Physics of Incline Plane Fluid Droplets

Subject Area(s)	**Physics**
Associated Unit	**Linear Dynamics, Forces, Friction, Newton's Laws of Motion, Fluid Dynamics, Surface Tension**
Lesson Title	**Predicting the motion and limits of droplets down incline planes**

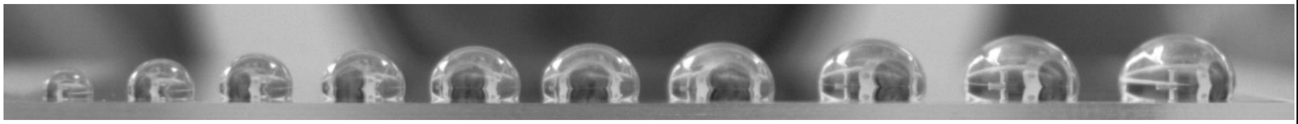


Image 1: Shows the resting position of different sized droplets on a smooth surface coated with CYTOP™

Grade Level	11-12
Lesson #	1 of 1
Lesson Dependency	N/A
Time Required	100 Minutes (Two 50 minutes)
Group Size	3 students
Cost per Group	$0.99

Summary: In this lesson, students will learn that different size-fluid droplets behave differently than solid-rigid objects sliding down incline planes. The students will use different surfaces like bare glass, Rain-X® coated glass and a surface coated with Teflon™ tape (other smooth surfaces may be used) to explore the forces between each surface and deionized water droplets. The students will use different sized droplets and vary the angle of the surface to estimate the coefficient of friction. The students will find that unlike solid-rigid objects, the motion of fluid droplets cannot be predicted the same way using Newton's Laws of linear motion. There are additional energies and forces involved in the motion of a droplet of fluid. The lesson is a great review of incline plane motion with linear dynamics, introduction to fluids dynamics, or science practice of experimentation.

Engineering Connection: Engineers have always been interested on materials which provide low friction and hydrophobic properties. Flouropolymers such as Teflon™ and Cytop™ are two widely used substances because they are corrosive resistant, withstand high temperature and smooth hydrophobic surfaces. Teflon™ is widely used as thread sealer, gasket maker, and pan coatings: Cytop™ has proven to be of great benefit as a coating of electric components [ATTACHMENT: Cytop™ paper] . During this investigation, students are exposed to the smooth texture of Teflon™ tape and Rain-X® in exploring fluid dynamics on incline planes. The lesson may also be expanded into a research paper where students can learn more on the dynamics of fluid droplets using calculus [Read "Rolling droplets" under references] or applications of flouropolymers in electronics.

Engineering Category

#1: Relating science and/or math concept(s) to engineering

Keywords: Friction, incline plane, Newton's Laws, fluid dynamics, surface tension

Educational Standards

State STEM Standard

Florida: Math [2010] Grades 9-12

- High School — Algebra
- High School — Functions
- Similarity, Right Triangles, and Trigonometry

Florida: Science [2008] Grades 9-12

- Nature of Science Standard 1: The Practice of Science
- Physical Science Standard 10: Energy
- Physical Science Standard 12: Motion

ITEEA Standard

- Technology and Society [2000] Standard 6. Students will develop an understanding of the role of society in the development and use of technology. *(Grades K - 12)*
- The Designed World [2000] Standard 19. Students will develop an understanding of and be able to select and use manufacturing technologies. *(Grades K - 12)*

NGSS Standard

Next Generation Science Standards: Science [2008] Grades 9-12

- SC.912.P.10.1 Differentiate among the various forms of energy and recognize that they can be transformed from one form to others.
- SC.912.P.12.3 Interpret and apply Newton's three laws of motion.
- SC.912.P.12.2 Analyze the motion of an object in terms of its position, velocity, and acceleration

Pre-Requisite Knowledge

Prior to this lesson, student should know basic concepts relating to friction. Friction depends on the coefficient of friction between the surface and normal force on the object ($f \approx \mu n$). There are also two types of friction forces, static and kinetic forces. The experimental errors involved in this lesson will allow the students to treat static and kinetic as almost being equal and no distinction will be made here. Furthermore, the student should be able to use Newton's 1st Law ($\Sigma F = 0$) when the object is in static or translational equilibrium. The droplet here will be assume to be in translational equilibrium when moving down the incline plane and thus a system of equation will yield that the coefficient of friction (μ) depends on the angle only like rigid objects.

$$\Sigma F = 0$$

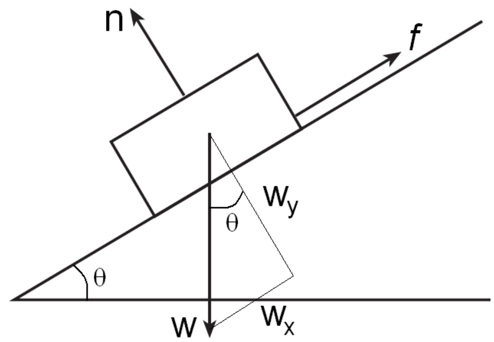
$$W\sin(\theta) - f = 0$$

$$mg\sin(\theta) - \mu n = 0$$

Where $n = W\cos(\theta) = mg\cos(\theta)$ so…

$$mg\sin(\theta) = \mu mg\cos(\theta)$$

$$\sin(\theta)/\cos(\theta) = \tan(\theta) = \mu$$



Rigid object in translational equilibrium

However, students will find that the above approach does not work for droplets since they are not rigid objects. Each droplet (10µL through 100µL) will give a different angle and thus prove that the coefficient of friction is different due to the surface tension of water. In fact, surface tension will dominate smaller droplets (1µL - 40µL) and weight dominates larger droplets (larger than 40µL). It is important to note that there are many factors involved with fluid dynamics and it is not expected students understand all these factors. However, the lesson should be presented for the purpose of introducing students to these factors that are not covered in high school physics and why we have to consider ideal scenarios (i.e. no friction, no air resistance, ideal fluids, etc.). Additional material is provided on the dynamics of fluid droplets on an incline plane to use for reading an extension to the objectives.

Learning Objectives

After this lesson, students should be able to:

- know that fluid dynamics involves surface tension in dynamics of droplets
- know that roughness of a surface yields different coefficients of friction
- know that droplets size plays a critical role in the motion of incline planes
- apply Newton's Laws of motion to derive formulas for forces acting on droplets
- apply Newton's Laws to calculate coefficient of friction between the droplets and different surfaces

Materials List (per group)

1 Micropipette, protractor, coated surface (Rain-X®, Teflon™ tape, bare glass, etc.), deionized water

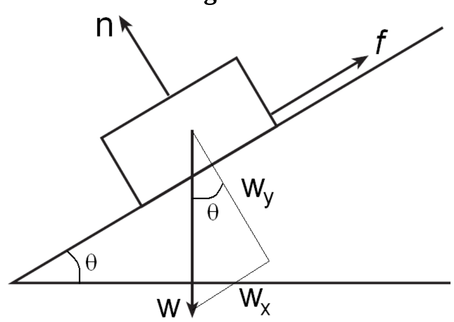
Introduction / Motivation (5E – Engage)

Start by opening up with an open ended question, what determines which drops fall (or streak) on a window during the rain? Does size matter? Does surface matter? Gather some thoughts and then show this video[1] to reinforce some of the answers. Proceed to explain that they will explore different surfaces (bare glass, Teflon™ tape and Rain-X® covered surface) to determine the coefficient of friction between each surface and different water droplet sizes. Also they will learn that droplet motion is greatly influenced by surface tension and other intermolecular forces.

Lesson Background & Concepts for Teachers (5E – Explain)

Students have already learned that friction is affected by different coefficients of friction between two surfaces. Here they will determine how each of the surfaces (bare glass, Teflon™, and Rain-X®) affects the friction force acting on a droplet on an inclined plane. Students will place a droplet of deionized water on each surface to slowly incline the plane until the droplet starts moving. The angle will be used to estimate the coefficient of friction treating the droplet as solid-rigid body. Each group of students will do one surface and vary the size of the droplet from 10μL to 100μL. Figure 1 illustrates the forces acting on a typical rigid object; for this part, the droplet will be treated as a rigid object. When the drop slides (even briefly), the force of friction (*f*) is equal to the weight component (Wx) that is along the direction of the plane. Therefore, the coefficient (μ) may be estimated to be equal to tangent (θ) as proven on "prior knowledge."

Figure 1



Vocabulary / Definitions

Word	Definition
coefficient of friction (μ)	ratio of friction force to normal force; "roughness" between two surfaces ranging from 0-1 (0 smoothest and 1 roughest)
friction force	force that acts in the opposite direction to an objects motion; static friction when object is not moving and kinetic if object is sliding
surface tension	cohesive force between molecules which keeps them "squeezed" together
normal force	force due to a surface directed in the direction perpendicular (normal) to surface
weight	force provided by Earth's gravitational field due to an object's mass. Always directed downward (to center of Earth).
translational equilibrium	state in which an object is moving at a constant velocity due to the forces "equating" to zero
static equilibrium	state in which an object is at rest due to the forces "equating" to zero

Associated Activities (5E – Explore)

- See ATTACHMENT "Droplets on Incline Planes" for student activity worksheet

Lesson Closure

- Here are additional small video clips for the purpose of closing the lesson. Both are performed on RainX® coated glass. The angle is slowly increased as with incline planes.
- The first video shows the way water droplets streak through a cascading effect where the larger one displaces the smaller ones held together by tension forces [video][3].
- The second video shows the opposite order of the droplets where the larger one is displaced first and the smaller ones require a greater angle to move [video][4].

Assessment (5E – Evaluate)

Pre-Lesson Assessment

1. Evaluate what students know about droplet motion through open ended questioning. Like describing the rain streaking on a window. Which droplets streak? Does size matter? Do they all streak? Do students know about surface tension?

Post-Introduction Assessment

1. What forces act on a rigid object sliding down an incline plane at a constant velocity?
2. What factors affect the coefficient of friction?
3. What additional forces might be acting on a droplet moving on an incline plane?
4. Are there any noticeable changes in droplet shape as it moves on incline plane?

Lesson Summary Assessment

1. Did the student get the same coefficient of friction between the droplet and surface?
2. How do students compare their coefficient of friction with other groups with different surfaces?
3. What additional factors influence the motion of a droplet on an incline plane?

Homework

N/A

Lesson Extension Activities (5E – Extension)

Read about applications of micro fluids in engineering. Focus on electrowetting (EW) applications in micro-lenses, display technology, lab-on-a-chip, etc. Printing of article and summary are encouraged but not mandated.

Additional Multimedia Support

Internet access for videos

References

1. Youtube. Rain Drops HD 1080p by MrKadappooran
   http://www.youtube.com/watch?v=4PMlj_8v8Ko 25 July 2014
2. L. Mahadevan and Yves Pomeau. Physics of Fluids: Rolling droplets Published September 1999

   http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CCsQFjAB&url=http%3A%2F%2Fwww.seas.harvard.edu%2Fsoftmat%2Fdownloads%2Fpre2000-09.pdf&ei=iVfYU7K2CdCmyATptYGwAw&usg=AFQjCNHOtmAKww2v7bQQ4HLi7WGen7MCeg&sig2=UMrcspp5cD1N_YJDY-Z-uQ&bvm=bv.71778758,d.aWw
3. Youtube. Microdroplets streak on RainX (40uL-10uL)

   https://www.youtube.com/watch?v=f9jn458ejzo 29 July 2014
4. Youtube. Microdroplets run on RainX (10uL-40uL)

   https://www.youtube.com/watch?v=SIorZ1kLjZk 29 July 2014

Attachments
Attachment 1: “Droplets on Incline Plane” student exploration worksheet for activity

Contributors
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Dr. Nathan B. Crane and Qi Ni at University of South Florida (USF): Mechanical Engineering.

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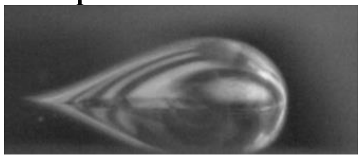
Classroom Testing Information
N/A

Attachments

“Droplets on Incline Plane” student exploration worksheet

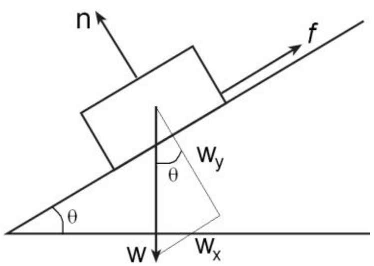
Droplets on Incline Planes



Objective: Determine factors affecting resistive forces on water droplets of different size.

Materials: 1 protractor, 1 micropipette, surface (bare glass, Rain-X® coated, Teflon™ coated, etc), and dionized water.

Prior Knowledge: Derive an expression for the coefficient of friction on the following rigid body in translational equilibrium.



μ = ____________________________

Data:

Surface Type: ____________________________________

Droplet Size (μL)	**Measure Angle to Move (^{0})**	**Calculate Coefficient "μ"**
10		
20		
30		
40		
50		
60		
70		
80		
90		
100		

Analysis/Interpretation:

1. Do you expect the same coefficient of friction for the same droplet/surface combination? Explain

2. Did you get the expected results? Explain

3. Compare/contrast your results with a different group member who did a different surface.

Expand:

1. Read the research publication titled "Incline droplets" and complete the following table.

What we knew about fluid dynamics?	What we learned from the research paper?

2. How might this knowledge be relevant or applicable in engineering? Read about applications of micro fluids in engineering. Focus on electrowetting (EW) applications in micro-lenses, display technology, and lab-on-a-chip.