

**February/March 2017 Teacher's Guide for**

**No-Hit Wonder! D3O®**

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# About the Guide

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Articles from past issues of *ChemMatters* and related Teacher’s Guides can be accessed from a DVD that is available from the American Chemical Society for $42. The DVD contains the entire 30-year publication of *ChemMatters* issues, from February 1983 to April 2013, along with all the related Teacher’s Guides since they were first created with the February 1990 issue of *ChemMatters*.

The DVD also includes Article, Title, and Keyword Indexes that cover all issues from February 1983 to April 2013. A search function (similar to a Google search of keywords) is also available on the DVD.

The *ChemMatters* DVD can be purchased by calling 1-800-227-5558. Purchase information can also be found online at:

<https://www.acs.org/content/acs/en/education/resources/highschool/chemmatters/products.html>.

# Student Questions

**No-Hit Wonder! D3O®**

* 1. What are "smart materials"?
	2. What was the inspiration for the invention of D3O®?
	3. Give a definition for viscosity, and list two substances with higher viscosity.
	4. What is a Newtonian fluid?
	5. List three factors that can influence the viscosity of non-Newtonian fluids?
	6. What is the name given to fluids that become less viscous when shaken or stirred? List three examples of this type of fluid.
	7. Name two places that synovial fluid is found in the body. Why does synovial fluid protect you from injury?
	8. List a) three synthetic polymers; b) three natural polymers.
	9. Explain why shear-thickening fluids become more viscous under sudden stress.
	10. Why is D3O® effective material in protective knee and elbow pads?
	11. How might D3O® provide better protection from concussions than impact protection helmets currently in use?
	12. What is perhaps the most important use of D3O®, according to the article?

# Answers to Student Questions

**(taken from the article)**

**No-Hit Wonder! D3O®**

* + 1. **What are "smart materials"?**

*"Smart materials" are materials that change in response to their environment, such as D3O®.*

* + 1. **What was the inspiration for the invention of D3O®?**

*D3O® was invented by Richard Palmer to protect himself from bumps and bruises from wipeouts suffered while snowboarding.*

* + 1. **Give a definition for viscosity, and list two substances with higher viscosity**.

*Viscosity is a measure of a fluid's resistance to flowing. Two materials with higher viscosity are syrup and honey.*

* + 1. **What is a Newtonian fluid?**

*A Newtonian fluid is a material whose viscosity remains constant, no matter how fast it is forced through a pipe or channel. Its viscosity only changes in response to temperature.*

* + 1. **List two factors that can influence the viscosity of non-Newtonian fluids.**

*Two factors that can influence the viscosity of non-Newtonian fluids are agitation and pressure. (Students might also say, “temperature”, but that is not specifically stated in the article.*

* + 1. **What is the name given to fluids that become less viscous when shaken or stirred? List three examples of this type of fluid.**

*Fluids that become less viscous when shaken or stirred are called shear-thinning fluids. Three examples of shear-thinning fluids mentioned in the article include*

1. *ketchup,*
2. *shaving cream,*
3. *toothpaste, or*
4. *paint.*
	* 1. **Name two places that synovial fluid is found in the body. Why does synovial fluid protect you from injury?**

*Synovial fluid can be found in the elbow and knee joints in your body. Synovial fluid protects you from injury because it is a shear-thickening fluid that becomes more viscous and cushions the joint when you bump your knee or elbow.*

* + 1. **List a) three synthetic polymers and b) three natural polymers.**
1. *Synthetic polymers include*
2. *plastic*
3. *rubber*
4. *polyester*
5. *Spandex™*
6. *D3O®*
7. *Natural polymers include*
8. *DNA*
9. *proteins*
10. *starch*
	* 1. **Explain why shear-thickening fluids become more viscous under sudden stress.**

*Shear-thickening fluids become more viscous under stress because the polymer chains in the fluid do not have time to quickly rearrange themselves and move out of the way of each other. So, they become entangled, more viscous, and more like a solid.*

* + 1. **Why is D3O® effective material in protective knee and elbow pads?**

*D3O® is an effective knee and elbow pad material because it is a shear-thickening fluid that flows easily under normal conditions and becomes more viscous when sudden stress is applied to the knee or elbow, as in a fall.*

* + 1. **How might D3O® provide better protection from concussions than impact protection helmets currently in use?**

*D3O® might provide better protection from concussions than current helmets by preventing rotational acceleration that causes side-to-side and front-to-back movements of the brain within the skull.*

* + 1. **What is perhaps the most important use of D3O®, according to the article?**

*Perhaps the most important use of D3O® is in bulletproof vests and body armor, protecting the lives of police officers and members of the military.*

# Anticipation Guide

Anticipation guides help engage students by activating prior knowledge and stimulating student interest before reading. If class time permits, discuss students’ responses to each statement before reading each article. As they read, students should look for evidence supporting or refuting their initial responses.

**Directions:**  *Before reading*, in the first column, write “A” or “D,” indicating your agreement or disagreement with each statement. As you read, compare your opinions with information from the article. In the space under each statement, cite information from the article that supports or refutes your original ideas.

|  |  |  |
| --- | --- | --- |
| **Me** | **Text** | **Statement** |
|  |  | 1. D3O® is n more than 100 products.
 |
|  |  | 1. D3O® is available in several neon colors.
 |
|  |  | 1. Fluids with a high viscosity (resistance to flow) also have a high density.
 |
|  |  | 1. Isaac Newton described the effect of heating on the viscosity of fluids.
 |
|  |  | 1. Non-Newtonian fluids change viscosity due to agitation or pressure.
 |
|  |  | 1. Fluids that thicken when shear stress is applied quickly are not found in nature.
 |
|  |  | 1. Both shear-thinning fluids and shear-thickening fluids are polymers.
 |
|  |  | 1. D3O® is a colloid, a polymer suspended in an oily liquid without separating.
 |
|  |  | 1. D3O® flows easily until a sudden shear stress is applied.
 |
|  |  | 1. D3O® can be used in bulletproof vests and helmets.
 |

# Reading Strategies

These graphic organizers are provided to help students locate and analyze information from the articles. Student understanding will be enhanced when they explore and evaluate the information themselves, with input from the teacher if students are struggling. Encourage students to use their own words and avoid copying entire sentences from the articles. The use of bullets helps them do this. If you use these reading and writing strategies to evaluate student performance, you may want to develop a grading rubric such as the one below.

|  |  |  |
| --- | --- | --- |
| **Score** | **Description** | **Evidence** |
| 4 | Excellent | Complete; details provided; demonstrates deep understanding. |
| 3 | Good | Complete; few details provided; demonstrates some understanding. |
| 2 | Fair | Incomplete; few details provided; some misconceptions evident. |
| 1 | Poor | Very incomplete; no details provided; many misconceptions evident. |
| 0 | Not acceptable | So incomplete that no judgment can be made about student understanding |

***Teaching Strategies:***

* Links to **Common Core State Standards for Reading**:
	+ ELA-Literacy.RST.9-10.1:Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.
	+ ELA-Literacy.RST.9-10.5: Analyze the structure of the relationships among concepts in a text, including relationships among key terms (e.g., force, friction, reaction force, energy).
	+ ELA-Literacy.RST.11-12.1:Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account.
	+ ELA-Literacy.RST.11-12.4: Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 11-12 texts and topics.
* Links to **Common Core Standards for Writing**:
	+ ELA-Literacy.WHST.9-10.2F: Provide a concluding statement or section that follows from and supports the information or explanation presented (e.g., articulating implications or the significance of the topic).
	+ ELA-Literacy.WHST.11-12.1E: Provide a concluding statement or section that follows from or supports the argument presented.
* **Vocabulary** and **concepts** that are reinforced in this issue:
	+ Chemical and physical properties
	+ Chemical reactions
	+ Viscosity
	+ Personal and community health
	+ Oxidation states
	+ Elements
	+ Conservation of matter
	+ Consumer choices
	+ Recycling
* Most of the articles in this issue provide opportunities for students to consider how understanding chemistry can help them make informed choices as consumers. The articles also connect chemistry and engineering.
* Consider asking students to read “Open for Discussion” on page 4 to extend the information in “The Drive for Cleaner Emissions” on pages 5-7.
* The infographic on page 19 provides more support for the article “Brush Up on Toothpaste!” on pages 14-15.
* To help students engage with the text, ask students which article **engaged** them most and why, or what **questions** they still have about the articles.
* You might also ask them how information in the articles might affect their choices as consumers. Also ask them if they have different ideas to solve some of the problems discussed in the articles.
* The Background Information in the *ChemMatters* Teachers Guide has suggestions for further research and activities.

***Directions*:** As you read the article, complete the graphic organizer below to describe fluids, including D3O.®

|  |  |  |
| --- | --- | --- |
| **Fluid** | **Examples with Properties** | **Uses** |
| **Newtonian fluid** |  |  |
| **Shear-thinning fluid** |  |  |
| **Shear-thickening fluid** |  |  |
| **D3O®** | **Shear-thinning or Shear-thickening?** |  |

**Summary**: On the back of this page, write a short summary describing 3 new things you learned about D3O.®

# Connections to Chemistry Concepts

**(for correlation to course curriculum)**

1. **Liquids**—Typical liquids follow Newton's law of viscosity. Non-Newtonian liquids include D3O®, and they have unique and useful properties which are a cross between solids and liquids.
2. **Viscosity**—When discussing viscosity, D3O® would be an excellent example to use because its viscosity changes with stress. Chemists have used D3O®'s unique properties to make useful materials that students may know or use.
3. **Polymers**—These natural and synthetic molecules are found or used in almost every aspect of our lives including foods, fuels, clothing, sports and protective gear, surface coatings, living cells, and the entire plastics industry.
4. **Colloids**—Students may be aware of common colloids, but they may not think of non-Newtonian materials such as D3O® and oobleck as colloids. Linking the idea that polymers are the dispersed phase in many colloids may provide a connection to biochemistry.
5. **Solutions**—Compare and contrast colloids and solutions, using D3O® and oobleck as examples of colloids.
6. **Intermolecular attractions**—Using viscosity, rather than evaporation rates or boiling points, may provide students with a different method of understanding intermolecular forces. These intermolecular attractions are typically viewed as weak forces; but, by using water, cooking oil, and corn syrup as examples, students may better grasp the concept of intermolecular attractions and their collective effect.

# Possible Student Misconceptions

**(to aid teacher in addressing misconceptions)**

1. **“Thick liquids have a high density.”** *Viscosity and density are two different concepts. Viscosity relates to the rate of flow of a fluid—less viscous materials (e.g., water) flow more easily than more viscous materials (e.g., honey). Density relates to the quantity of mass per unit of volume. Dairy cream is viscous, it flows slowly; milk is not as viscous, it flows more easily. However, cream is less dense than milk (it floats to the top of whole milk). So cream is both more viscous and less dense than milk. Liquid mercury is another example of a material with high density and low viscosity.*
2. **“Fluids flow faster when they are warm.”** *Typical liquids (Newtonian fluids) do flow faster (more easily) when they are warmer. Warm honey certainly pours more easily than cold honey. However, not all fluids are liquids; fluids also include gases. For gases, viscosity is controlled by the number of molecular collisions between gas particles. Therefore, at higher temperatures there are more collisions, so the viscosity of gases will increase with increasing temperatures. In common liquids, the relationship between temperature and viscosity is inverse, but with gases the relationship is directly proportional.*

# Anticipating Student Questions

**(answers to questions students might ask in class)**

1. **Why do animals (or people) that fall into quicksand sink deeper as they struggle to escape?** *Quicksand is a non-Newtonian fluid; it does not react to stress like more common liquids (water) might react. As an animal struggles to get free from the quicksand, the pressure applied on the quicksand makes it become more fluid, and the animal sinks deeper as it struggles harder. In reality, many animals die from exposure (heat and dehydration) when trapped in quicksand, rather than sinking and suffocating.*
2. **“Why can you run on wet sand on the beach, but you start to sink in the wet sand if you stand still?”** *Wet sand is a non-Newtonian fluid. When running on the wet sand, the pressure of your foot quickly hitting the sand does not allow the sand to move, so it feels hard and solid. However, when standing on the wet sand, the constant pressure of your feet causes the sand particles to slowly shift in the wet environment, causing your feet to slowly sink. This is similar to quicksand, but less dramatic.*
3. **“Is ketchup really a polymer? Yuck!”** *I hate to tell you this, but YES, ketchup is a polymer. A polymer is just a large molecule made of repeating units (monomers). The polymers in ketchup include small amounts of sugars, proteins, pectins, starches, and an additive called xanthan gum. The xanthan gum is added in concentrations of less than one percent, and it enhances the shear-thinning properties of the ketchup. Other foods that you consume made of polymers include pasta (starches), fruits (complex sugars and starches), and meats (proteins). So consuming polymers is really not so bad.*

# Activities

**Labs and Demos**

1. **Lab—making a cross-linked poly(dimethylsiloxane) polymer:** Silly Putty™ is poly(dimethylsiloxane) that has been cross-linked with boric acid. “The Synthesis of Bouncing Putty” describes the history, chemistry, and properties of Silly Putty™ and provides the experimental procedure for making a non-Newtonian bouncing polymer with a composition similar to Silly Putty™. The starting material, poly(dimethylsiloxane), is quite expensive; however, the generic end product would be interesting to compare to the name brand Silly Putty™. (<http://www.wou.edu/las/physci/ch462/BouncingPutty.htm>)
2. **Lab—making a non-Newtonian fluid with cornstarch and water:** Students enjoy making and exploring non-Newtonian fluids like oobleck, cornstarch and water. In “Cornstarch Ooze”, simple background information on non-Newtonian fluids accompanies the procedure and assessment for making this fluid. The activity is targeted at grades 3–8, but the activity complements the Rohrig article. (<http://teachers.egfi-k12.org/activity-cornstarch-ooze/>)
3. **Demonstrating oobleck and a relationship to liquid body armor:** The Children's Museum of Houston provides a scripted demonstration for exploring the molecular behavior of oobleck and explaining how nanotechnologists and material researchers apply these behaviors to protective fabrics in Liquid Body Armor. This demonstration is thorough and includes background, references, standards, an explanation of non-Newtonian fluids, and five demonstrations—including one with D3O®, if it is available. (<http://www.nisenet.com/sites/default/files/catalog/uploads/8379/liquid_body_armor.pdf>)
4. **Making “gak” and “slime” lab:** For teachers with a more modest budget, it is possible to produce a non-Newtonian material using white school glue, or poly(vinyl alcohol) (from a science supplier), and a borax solution. While this is a common activity conducted at many elementary and middle schools, “Hands-on Activity: Let's Make Silly Putty™”, is targeted at grades 10–12. The activity provides an engineering connection, and it references standards based on NGSS and the International Technology and Engineering Educators Association. The lesson is very complete and includes an introduction, vocabulary, procedure, background with chemical formulas and structures, teacher tips, safety, assessments, and extensions. (<https://www.teachengineering.org/activities/view/csu_polymer_lesson01_activity1>)
5. **Demonstrating and making “gak”:** This is another take on making a cornstarch and water (gak) non-Newtonian fluid. This Web site invites you to make a kiddie-pool amount of gak, and then directing family groups to make a smaller quantity of both gak and a white glue/borax mixture for experimentation. The site also suggests a demonstration of liquids with various viscosities running down a plastic board. (<http://www.leaps.ucsb.edu/forms/FUSEII_%20Nonnewtonian_fluids.pdf>)
6. **Lab—making slime:** This is a variation on a white glue and borax slime activity. Steve Spangler Science provides a short video and simple instructions for making a generic Silly Putty™. “Easy Slime Recipe” includes a simple explanation, along with an extension to the activity where students can vary the quantity of borax solution used to make the slime more or less runny (vary the viscosity). ([https://www.stevespanglerscience.com/lab/experiments/glue-borax-Gak/](https://www.stevespanglerscience.com/lab/experiments/glue-borax-gak/))
7. **Experimenting with density and viscosity lab:** Some students may need a refresher on the concepts of density and viscosity. This experiment, “Density and Viscosity”, is targeted at the eighth grade, but it may be useful for some high school students. The 5E model investigation is provided in a guided inquiry format written for teachers; there is no student materials list provided because it is an inquiry approach. However, the Web site provides a materials list, hints for teachers, extensions, and possible accommodations. (<http://www.cpalms.org/Public/PreviewResourceLesson/Preview/21223>)
8. **Studying fluid viscosity lab:** This three-part lab, “Viscosity: The Fluids Lab”, studies viscosity (with regular and advanced student portions), drag, and polymers. “Part I – Viscosity”, is most appropriate for the Rohrig article. Students drop balls of clay into water, vegetable oil, and hand soap to measure the time for the clay to drop and relate the time to the viscosities of the liquids. Student materials and answers are provided. (<http://web.stanford.edu/group/lpchscience/cgi-bin/wordpress/images/Viscosity-T.pdf>)
9. **Lab—exploring viscosity:** The Royal Society of Chemistry provides a classic experiment with the viscosities of common liquids in “Viscosity”. Students use identical tubes containing water, cooking oil, ethanol, liquid hand soap, motor oil, or bubble bath. Students measure the time it takes for an air bubble to ascend in the inverted tubes of liquid. Students answer a few questions and then are asked to design a different experiment to compare the viscosities of liquids. (<http://www.rsc.org/learn-chemistry/resource/res00000387/viscosity?cmpid=CMP00000456>)
10. **Lab to compare the viscosities of Newtonian and non-Newtonian fluids:** If teachers and students have access to a vacuum apparatus, a milligram balance, and assorted glassware, they can design a low-cost experiment to test the viscosity of Newtonian and non-Newtonian fluids. While the article states that it is low-cost, it would still be a challenging activity for most high schools. (Dolz, M, Delegido, J., Casanovas, A., Hernández.M. A Low-Cost Experiment on Newtonian and Non-Newtonian Fluids. *J. Chem. Educ.*, 2005, *82* (3), pp 445–447; <http://pubs.acs.org/doi/pdf/10.1021/ed082p445>; note that this link is a brief abstract only, the full article is only available to American Chemical Society members or subscribers to the journal.)
11. **Lab—synthesizing biodiesel and measuring viscosities:** For an environmental approach to viscosity, students can prepare and test the viscosity of biodiesel fuel synthesized from new and used vegetable oils. One of the problems with biodiesel is the changing viscosity with temperature extremes. This activity uses an inquiry approach to the student methodology. Supplemental notes for teachers and students are available for this article at *JCE Online*. (Clarke, N., Casey, J., Brown, E., Oneyma, E., Donaghy, K. Preparation and Viscosity of Biodiesel from New and Used Vegetable Oil. *J. Chem. Educ.*, 2006, *83* (2), pp 257–259; <http://pubs.acs.org/doi/pdf/10.1021/ed083p257>; note that this link is a brief abstract only, the full article is only available to American Chemical Society members or subscribers to the journal.)
12. **Lab to measure viscosities, and calculating molecular weights, of motor oils:** The viscosities of petroleum oils are measured and the molecular weights of the oils are calculated in a procedure described in this *JCE* article. The equipment and procedures are more complex than typical high schools would have available, but schools with access to college or university laboratories might perform this experiment, which is targeted at a college-level introductory physical chemistry (Maroto, J., Quesada-Pérez, M., Ortiz-Hernández, A. Use of Kinematic Viscosity Data for the Evaluation of the Molecular Weight of Petroleum Oils. *J. Chem. Educ.*, 2010, *87* (3), pp 323–325; <http://pubs.acs.org/doi/pdf/10.1021/ed800090h>; note that this link is a brief abstract only, the full article is only available to American Chemical Society members or subscribers to the journal.)
13. **Computer-based lab to analyze viscosity and temperature of a fluid:** In another college-level physical chemistry activity, students determine the viscosity of a fluid as related to its temperature using computer-based learning. This technique uses molecular dynamics simulations to gather the data for student analysis. The activity uses commercially available software with prepackaged scripts available through the online links in the article. (Eckler, L., Nee, M. A Simple Molecular Dynamics Lab to Calculate Viscosity as a Function of Temperature. *J. Chem. Educ.*, 2015, *93* (2), pp 927–931; <http://pubs.acs.org/doi/pdf/10.1021/acs.jchemed.5b00587>; note that this link is a brief abstract only, the full article is only available to American Chemical Society members or subscribers to the journal.)

**Simulations**

1. **Fluid pressure and flow:** The PhET simulation, “Fluid Pressure and Flow”, provides students with the opportunity to "explore pressure in the atmosphere and underwater" and "reshape a pipe to see how it changes fluid flow speed." Numerous teacher-submitted activities accompany the simulation on the PhET site. (<https://phet.colorado.edu/en/simulation/legacy/fluid-pressure-and-flow>)
2. **Fluid pressure:** This PhET simulation allows students to "explore pressure under and above water" and to "see how pressure changes as you change fluids, gravity, container shapes, and volume." Additional teacher-submitted activities are available for the simulation. (<https://phet.colorado.edu/en/simulation/under-pressure>)
3. **Density:** For students needing a refresher on density concepts, PhET provides a simulation titled “Density”. In the simulation, students "create a custom object to explore the effects of mass and volume on density" and collect mass and volume data to discover the relationship between the mass and the volume of an object. Numerous teacher-submitted activities accompany this simulation. (<https://phet.colorado.edu/en/simulation/legacy/density>)

**Media**

1. **YouTube video of D3O® on a shovel:** The Rohrig article references this YouTube video, *Smack Me on the Head with a Shovel! – D3O® Demonstration* (2:07). The video shows a man hitting the test subject on the head and knee (don't try this at home) while the subject is wearing D3O® protective pads. ([https://www.**youtube**.com/watch?v=U17MVtY0w5M](https://www.youtube.com/watch?v=U17MVtY0w5M))
2. **YouTube video of D3O® in motorcycle armor:** “D3O® Armor Demonstration” (5:02) shows D3O® used in motorcycle shoulder, elbow, and back armor products. (<https://www.youtube.com/watch?v=Z-PVNYt0Nqs>)
3. **YouTube video of D3O® vs Silly Putty™:** This video, "What's in the Box – D3O® vs. Silly Putty™ (by Hitfar)!" (4:34), compares the shock absorption of D3O® with that of Silly Putty™, when wrapped around a raw egg. The video continues with the use of D3O® in cell phone cases. (<https://www.youtube.com/watch?v=lk1vCIopa00&t=17s>)
4. **Silly Putty™ infographic:** The Web site, *Compound Interest*, provides an interesting infographic of the composition and functioning of Silly Putty™. Accompanying the infographic is a brief article with additional details on Silly Putty™. (<http://www.compoundchem.com/2015/11/10/sillyputty/>)
5. **Podcast explaining Silly Putty™:** *Chemistry World* magazine provides an audio-only podcast, “Polydimethylsiloxane” (6:11), explaining the science of this compound, which is the primary ingredient in Silly Putty™. A written transcript of the audio is provided on the Web page. (<https://www.chemistryworld.com/podcasts/polydimethylsiloxane/8774.article>)
6. **Video of Newtonian and non-Newtonian fluids:** “Comparison of Newtonian and Non-Newtonian Fluids” (3:36) from *Encyclopaedia* *Britannica* provides a simple explanation of these fluids with examples and demonstrations. (<https://www.britannica.com/science/fluid-physics/images-videos>)
7. **PowerPoint of Non-Newtonian fluids:** This 31-slide PowerPoint from University of California Berkeley, “Non-Newtonian Fluids”, provides a scholarly lesson (with advanced mathematics) and a few images of non-Newtonian materials. ([www.cchem.berkeley.edu/cbe150a/mom/**non**ewt.ppt](http://www.cchem.berkeley.edu/cbe150a/mom/nonewt.ppt))
8. **YouTube video of non-Newtonian fluids:** “Non-Newtonian Fluids” (4:53) is an overview of non-Newtonian fluids, with images, diagrams, and a clear explanation of the behavior and composition of non-Newtonian fluids. (<https://www.youtube.com/watch?v=DQoelYi6qfw>)
9. **Video webinar of Newtonian and non-Newtonian fluids:** “Viscosity Fundamentals Webinar: Newtonian and Non-Newtonian” (38:37) provides a thorough explanation with excellent illustrations of Newtonian and non-Newtonian behavior. The webinar is posted on YouTube and is provided by RheoSense, Inc., a company manufacturing and selling viscometers. However, there are only a few references or commercial portions to the presentation. (<https://www.youtube.com/watch?v=PdQyFVNjhgs>)
10. **High speed video of honey coiling due to viscosity:** *Smarter Every Day* provides this video on YouTube, “Amazing Honey Coiling High Speed Video!” (5:17), showing how honey forms coils as it is slowly poured. The liquid rope coil effect (looks like a spring) is due to honey's high viscosity (due to intermolecular forces). (<https://www.youtube.com/watch?v=zz5lGkDdk78>)
11. **PowerPoint of non-Newtonian fluids:** This 33-slide presentation provides another look at non-Newtonian fluid behavior and fluid statistics. It is a technical presentation, but the first ten slides may be useful for students and teachers. (<http://slideplayer.com/slide/9769275/>)
12. **Video explaining viscosity:** Khan Academy provides “Viscosity and Poiseuille Flow” (11:05) as a part of the *Fluid Dynamics* unit. The video discusses viscosity, viscous forces, and Poiseuille's Law in typical Khan Academy form, with mathematical formulas, simple drawings, and an audio explanation. (<https://www.khanacademy.org/science/physics/fluids/fluid-dynamics/v/viscosity-and-poiseuille-flow>)
13. **PowerPoint on viscosity:** This 26-slide presentation from the Department of Engineering at Rochester University, “Fluid Dynamics – Viscosity”, starts with an overview of fluids and viscosity and applications of fluid dynamics, and then progresses through Newton's Law of Viscosity, and on to Newtonian and non-Newtonian fluids. (<http://www.che.rochester.edu/users/dafoster/ChE243/Fluid%20Dynamics%20Viscosity.pdf>)
14. **Video of Bear Grylls in quicksand:** YouTube hosts a video, “Bear Grylls Sahara Quicksand” (3:29), showing the television actor in a pool of quicksand, a non-Newtonian fluid. Grylls discusses how to escape from quicksand. (<https://www.youtube.com/watch?v=MJTGwZM05lQ>)
15. **Video of ketchup pouring and accompanying lesson support:** This TED Ed Talk video, “Why is Ketchup So Hard to Pour?” (4:28), provides an interesting explanation about a problem most people have experienced. The video with interesting graphics is accompanied by a brief set of ten follow-up questions, additional resources, and a guided discussion question. ([http://ed.ted.com/lessons/why-is-ketchup-so-hard-to-pour-george-zaidan#review](http://ed.ted.com/lessons/why-is-ketchup-so-hard-to-pour-george-zaidan%23review))
16. **Shear-thickening in non-Newtonian fluids video:** This YouTube video, “Fluid Mechanics, Shear Thickening” (3:07), provides a brief and simple explanation of fluid behavior, including shear-thickening, with graphics and video clips. (<https://www.youtube.com/watch?v=tE3TjXpWPmo>)
17. **Non-Newtonian fluids and viscosity video:** This brief YouTube video, “Non-Newtonian Fluids and Viscosity” (4:30), shows the reactions of oobleck, Silly Putty™, and water react to forces including vibration, an airsoft gun, and other forces. (<https://www.youtube.com/watch?v=bLiNHqwgWaQ>)
18. **Thixotropy slides:** “Thixotropy – A Review”, is a 15-slide presentation in pdf, with graphics of common thixotropic fluids, a history of thixotropy, behavior of these materials, and mathematical theories. (<https://nnf.mit.edu/sites/default/files/documents/sr-2006-1.pdf>)

**Lessons and Lesson Plans**

1. **Making polymers with cornstarch, laundry starch, guar gum, and poly(vinyl alcohol):** The focus of this seven-day lesson unit, *Playing with Polymers*, is making and exploring polymers. However, the polymers are non-Newtonian fluids including cornstarch and water, white glue and borax, liquid laundry starch and white glue, guar gum and borax, and poly(vinyl alcohol) and borax. The lesson is targeted at the eighth grade and the illustrations and side notes may be childish for high school students, but the lesson ideas and directions may supply ideas for high school teachers and students. Teachers would need to add the content about non-Newtonian fluids to the activities. In addition, the content level of the lesson could be increased by allowing students to experiment with the recipes provided to create the best non-Newtonian fluid, given specific criteria. The lesson unit includes teacher notes, student packet, a PowerPoint on polymers, and additional resources. ([http://sciencespot.net/Pages/classchem.html#Anchor-poly](http://sciencespot.net/Pages/classchem.html%23Anchor-poly))
2. **Reviewing states of matter, viscosity, and non-Newtonian fluids:** *Strange Liquids: Newtonian and Non-Newtonian Liquids in the Primary School Classroom* is a New Zealand unit of lessons reviewing the states of matter (solid, liquid, gas, plasma, Bose-Einstein condensates); activities with Newtonian liquids, viscosity, and non-Newtonian liquids; transfer or application of these concepts to the real world; and an evaluation. The unit does not specify how many days are required for completion. Links to supporting documents and resources are provided, along with learning outcomes and student objectives. (<http://sciencelearn.org.nz/Teacher-Ideas/Unit-plans-and-planning/Unit-plan-Strange-Liquids>)
3. **Oobleck activity and writing assignment:** “Oobleck and Beyond” is a 10th grade physical science lesson on the states of matter and non-Newtonian fluids. The activity is typical of standard oobleck labs, but this lesson goes a step further with a lab report writing assignment including a rubric. (<http://www.nsta.org/publications/news/story.aspx?id=51279>)
4. **Viscosity:** “Viscous Fluids” is a 50-minute lesson with optional extensions for grades 10–12. The lesson is correlated to standards and is very organized (it comes from an engineering organization, Teach Engineering). Objectives, background for teachers, and assessments are some of the supports provided. Additional resources include a PowerPoint presentation, worksheets, and answers. Related lessons include “Measuring Viscosity”, “Viscoelasticity”, and “Creepy Silly Putty™”. (<https://www.teachengineering.org/lessons/view/cub_surg_lesson03>)

**Projects and Extension Activities**

1. **The egg drop:** Students could design a non-Newtonian material experiment to test the effectiveness of dropping an egg protected with D3O®compared to an egg protected with Silly Putty™ similar to what is seen at 0:53 in the video, “What's in the Box – D3O® vs. Silly Putty™” (by Hitfar): <https://www.youtube.com/watch?v=lk1vCIopa00&t=17s>. An alternative to this project (if D3O®is not easily available) would be to compare the protection provided by commercial Silly Putty™ with that of gak made from white glue and borax. Other non-Newtonian materials could be tested for their effective protection, as well. Students would design and conduct the experiments, collect and analyze data, and prepare a presentation.
2. **Isaac Newton research:** Isaac Newton is widely known for the story of the apple dropping on his head leading to an understanding of gravity and for his laws of motion. He was an inquisitive and complex man. Students could research and prepare a presentation (PowerPoint, video, story board, play in-character) on the contributions that Newton made to science as well as some of his idiosyncrasies.
3. **Making moon sand:** For an activity that students can do at home using inexpensive, readily available materials to study non-Newtonian materials other than oobleck, see “How to Make Moon Sand”. This Web site provides three different ways to make moon sand (using various combinations of cornstarch, flour, sand, water, or baby oil), and it provides simple directions and pictures that students can easily follow unsupervised at home. Teachers could design this into an inquiry lesson or assign students a task to complete with their moon sand. (<http://www.wikihow.com/Make-Moon-Sand>)
4. **Making kinetic sand:** Another version of a non-Newtonian fluid is kinetic sand—which can be purchased commercially, but can be prepared at school or at home with the simple directions on this Web site. One version uses fine sand dimethicone (can be purchased online), while the other version uses fine sand and cornstarch. Teachers may choose to structure some student activity with the kinetic sand, or allow students to experiment and free-play with the material. (<http://chemistry.about.com/od/chemistryactivities/fl/Kinetic-Sand-Recipe.htm>)

# References

**(non-Web-based information sources)**

**The references below can be found on the *ChemMatters* 30-year DVD, which includes all articles
published from the magazine’s inception in October 1983 through April 2013; all available Teacher’s Guides, beginning February 1990; and 12 *ChemMatters* videos. The DVD is available from the American Chemical Society for $42 (or $135 for a site/school license) at this site:** [**http://ww.acs.org/chemmatters**](http://www.acs.org/chemmatters)**. Click on the “Teacher’s Guide” tab to the left, directly under the “*ChemMatters Online"* logo and, on the new page, click on “Get the past 30 Years of *ChemMatters* on DVD!” (the icon on the right of the screen).**

**Selected articles and the complete set of
Teacher’s Guides for all issues from the past three
years are available free online at the same Web site, above. Click on the “Issues” tab just below the logo, *“ChemMatters Online”*.**

***30* Years of *ChemMatters !***

Available Now!

 An early issue in *ChemMatters* included an article on Silly Putty™. The article discusses the discovery and chemistry of this favorite toy which is a dilatant material. (Marsella, G. Silly Putty™. *ChemMatters*, 1986, *4* (2), pp 15–17)

 This “Mystery Matters” article describes the phenomenon of St. Januarius's centuries-old alleged blood liquefying from a clotted mass. What has been described as a miracle by some has been explained by scientists as a non-Newtonian thixotropic mixture. Read more about the mystery and the chemistry of this changing blood. (Meadows, R. Mystery Matters: Saint's Blood. *ChemMatters*, 1993, *11* (1), pp 11–15)

 Color-changing Silly Putty™ is included in an article on encapsulated pigments in products. The Silly Putty™ is addressed in a one-page section titled A Successful Failure. (Goldfarb, B. Mystery Color in a Capsule. *ChemMatters*, 1998, *16* (1), pp 10–12)

 Tied closely to the D3O®article is an entire article on slime, also written by Rohrig. The viscosity, non-Newtonian properties, polymer cross-linking, and an activity for making slime are highlighted in the article. The shear-thinning and shear-thickening properties of non-Newtonian materials are discussed, also. (Rohrig, B. The Science of Slime. *ChemMatters*, 2004, *22* (4), pp 13–16)

 The Teacher's Guide for “The Science of Slime” (above) is rich source of content related to this Rohrig article. Background information included in the Teacher's Guide includes viscosity, Newtonian and non-Newtonian fluids, Silly Putty™, and activities for making slime.

 Honey is often used as an example of a viscous (as compared to water) material. An entire article was devoted to honey in 2005. While the article does not address viscosity or other topics in the Rohrig article, honey is just a sweet topic. (Haines, G. Honey: Bee Food Extraordinaire! *ChemMatters*, 2005, *23* (5), pp 13–16)

 Rohrig strikes again with the article, “Serendipitous Chemistry”, which includes the section, “Silly Putty™: Serious Fun”. A brief history, the chemistry and properties of Silly Putty™ are discussed as an example of scientific discoveries made by accident. (Rohrig, B. Serendipitous Chemistry. *ChemMatters*, 2007, *25* (3), pp 4–6)

# Web Sites for Additional Information

**(Web-based information sources)**

**D3O®**

 Visit the D3O® Web site for additional pictures, product designs, news, and testing at <https://www.d3o.com/>.

 Wikipedia has a short article on D3O® with links to related topics and references. (<https://en.wikipedia.org/wiki/D3o>)

 For a comparison between D3O® and the conventional foam used in motorcycle protective gear and winter sports equipment, with a video clip and images, see <http://newatlas.com/d3o-motorcycle-armour-trauma-test/14227/>.

 This article discusses D3O® uses in shock protection for people, cell phones, and computers. It includes images and links to two short videos, as well. (<http://www.dailymail.co.uk/news/article-2261147/D30-Unique-orange-goo-wrap-round-fingers-whack-mallet.html>)

 For more information on energy-absorbing materials, check out this link which includes a discussion of non-Newtonian materials including D3O® and a similar material, Dow Corning®'s Defexion™. Images and explanations are included at the site. (<http://www.explainthatstuff.com/energy-absorbing-materials.html>)

 A variety of products containing D3O® are found at this site. Two of the more unusual products include ballet pointe shoes and polo knee guards. (<http://inventorspot.com/articles/gel_cushions_falls_can_also_stop_bullets_d3o_24587>

**General** **non-Newtonian fluids**

 For an in-depth discussion of the stretching and mixing of non-Newtonian fluids in polymer solutions, see <http://scholarship.haverford.edu/cgi/viewcontent.cgi?article=1093&context=physics_facpubs>.

 This site is the lecture notes for a lesson on rheology. It refers to a textbook chapter and a few other materials not available, but the lecture notes and information provided are very useful without the other materials. Non-Newtonian fluids, soils and clays, and blood, are subheadings that are discussed with a variety of figures. (<http://www.physics.usyd.edu.au/super/life_sciences/PM/PM5.pdf>)

 This article explains non-Newtonian fluid flows with diagrams and accompanying mathematics: <http://web2.clarkson.edu/projects/subramanian/ch330/notes/Non-Newtonian%20Flows.pdf>.

 This scholarly discussion of non-Newtonian fluids provides an introduction to these unusual materials. Included in the article are examples, classification, behavior, and models of non-Newtonian fluids. The article address different types of non-Newtonian fluids. (<http://www.physics.iitm.ac.in/~compflu/Lect-notes/chhabra.pdf>)

 This Web site introduces fluid mechanics and fluid properties and then proceeds into a discussion of Newtonian and non-Newtonian fluids including a differentiation between liquids and gases. (<http://www.efm.leeds.ac.uk/CIVE/CIVE1400/PDF/Notes/section1.pdf>)

 This in-depth article explains codimensional non-Newtonian fluids. These codimensional features include the furrows made by a brush moving through paint, the strands of cheese on a pizza, and the thin filaments in toothpaste. Colorful pictures and a scholarly explanation which include mathematics make this an informative article. (<http://web.stanford.edu/~mjlgg/cnnf.pdf>)

 In this article, readers will learn about the microscopic structure of shear-thinning and shear-thickening colloids and how the rate of shear affects the non-Newtonian properties. (<https://ecommons.cornell.edu/bitstream/handle/1813/30467/2011-06%20Publication%20-%20Itai%20Cohen%20-%20Imaging%20the%20microscopic%20structure.pdf?sequence=2>)

 This article provides another description of non-Newtonian fluids with heavy mathematics. The simultaneous elastic and viscous nature of non-Newtonian fluids is discussed. (<http://www.thermopedia.com/content/986/>)

 For an explanation of honey as an example of a non-Newtonian fluid including a discussion of its viscosity, see [https://blogs.scientificamerican.com/cocktail-party-physics/an-ti-ci-pa-tion-the-physics-of-dripping-honey/#](https://blogs.scientificamerican.com/cocktail-party-physics/an-ti-ci-pa-tion-the-physics-of-dripping-honey/%23).

**Shear-thinning fluids**

 An experiment on a 2002 space shuttle, Critical Viscosity of Xenon-2, sought to better understand the viscosity of fluids like ketchup. Learn more about it at <http://www.firstscience.com/SITE/ARTICLES/ketchup.asp>.

 To read about NASA's version of the Critical Viscosity of Xenon-2 experiment above, see <https://science.nasa.gov/science-news/science-at-nasa/2002/07jun_elastic_fluids>.

 This site features the profile of a Texas Advanced Computing Center scientist, Dr. William L. Barth, who studies shear-thinning materials. Read about his career and work at <https://www.tacc.utexas.edu/documents/13601/138850/secrets_of_shear_thinning.pdf>.

 This NASA Web page educates readers on the physics of whipped cream, a shear-thinning material and was linked to the Critical Viscosity of Xenon-2 experiment. Note that whipped cream is a shear-thinning fluid, while whipping cream is a shear-thickening fluid.) (<https://science.nasa.gov/science-news/science-at-nasa/2008/25apr_cvx2>)

 An article concerned with the instability of shear-thinning and shear-thickening fluids and their flow is located at <https://www.mech.kth.se/~luca/papers/iman_cyl.pdf>.

 This scholarly article (a term paper at Notre Dame) describes models for predicting shear-thinning behavior in polymer fluids. (<http://www3.nd.edu/~cpaolucc/termpaper.pdf>)

**Shear-thickening (dilatants) fluids**

 This link is a great resource for a more complete look at shear-thickening materials including oobleck and other colloidal dispersions. (<http://authors.library.caltech.edu/16539/1/Wagner2009p6165Phys_Today.pdf>)

 This Web site explains the action of shear-thickening fluids as used in liquid body armor. It includes useful graphics and brief descriptions of colloids and hydroclusters. (<http://science.howstuffworks.com/liquid-body-armor1.htm>)

 This site provides an examination of two shear-thickening mixtures, glycerin with glass bubbles and water with cornstarch. The report analyzes the ballistic resistance of these two materials. ([http://www.me.rochester.edu/courses/ME241.gans/ShearThickening(2).pdf](http://www.me.rochester.edu/courses/ME241.gans/ShearThickening%282%29.pdf))

 For a formal analysis of cornstarch and water (oobleck) as a shear-thickening fluid, see <http://physics.wooster.edu/JrIS/Files/Price_Web_Article.pdf>

 For a brief, but clear explanation of non-Newtonian fluids with an emphasis on dilatants, visit <http://www.azom.com/article.aspx?ArticleID=6113>.

 This Web site reports on why non-Newtonian fluids harden on impact. It includes two short video clips to support the explanation. (<http://phys.org/news/2012-07-duo-non-newtonian-fluids-harden-impact.html>)

 For an explanation of why the shear-thickening behavior of oobleck may be more complex than only shear compression, and may be more properly related to the inability of cornstarch grains to quickly move, see <http://www.sciencemag.org/news/2012/07/cornstarch-physics-shear-nonsense>.

**Thixotropic fluids**

 For an overview of non-Newtonian fluids, including ketchup (considered a thixotropic material) see <http://www.rheothing.com/2012/11/is-ketchup-really-thixotropic.html>.

 A complete discussion of thixotropy is provided at this Web site which includes a history, a mechanistic description, applications, and examples of thixotropy. (<http://www.dfi.uchile.cl/~rsoto/docencia/FluidosNoNewton2008/trixotropia.pdf>)

 An application of thixotropy is with soils, especially clay soils. Readers will learn about the thixotropic nature of the soils in Mexico City at <http://www.pmrl.ce.gatech.edu/papers/Diaz-Rodriguez_1999a.pdf>.

 A report on the stabilization efforts of the Leaning Tower of Pisa and the unstable, clay soils under it that probably caused the settling is found at <http://casehistories.geoengineer.org/volume/volume1/issue3/IJGCH_1_3_2.pdf>.

**Rheopectic fluids**

 This Web site give a brief bit of information on the rarest of the non-Newtonian fluids, rheopectic, at <http://io9.gizmodo.com/this-pole-climbing-rheopectic-fluid-might-one-day-keep-1505594148>.

 Wikipedia provides a short article on rheopectic materials and explains the difference between rheopectic and dilatants fluids at <https://en.wikipedia.org/wiki/Rheopecty>.

 This Wikipedia page gives additional information on both thixotropic and rheopectic fluids. (<https://en.wikipedia.org/wiki/Time-dependent_viscosity>)

**Viscosity**

 This Web site provides an excellent discussion of viscosity including definitions, factors affecting viscosity, motor oil, and non-Newtonian fluids. The topic is treated mathematically as well as descriptively. (<http://physics.info/viscosity/>)

 Lean about the factors affecting viscosity including laminar or turbulent flow conditions, shear rate, temperature, and pressure at <http://www.viscopedia.com/basics/factors-affecting-viscometry/>.

 Stress, strain, and viscosity as applied to the San Andreas Fault are discussed in a slide presentation in pdf at <http://www.csun.edu/~dsw/lect5_geodyn_stress.pdf>.

 A scholarly, 32-page report on the temperature dependence of a viscosity of non-Newtonian fluid, toothpaste, is located at <https://www.ifm.tu-berlin.de/fileadmin/fg49/AbschlussarbeiteundProjekte/messungen/internship_report_FannyRoziere_Temperature_dependence_of_viscosity_of_non_Newtonian_materials.pdf>.

 This Web site provides an in-depth study of viscosity, Newtonian and non-Newtonian fluids, and several other rheological topics. ([http://www.brookfieldengineering.com/education/viscosity\_whymeasure.asp#newtonian](http://www.brookfieldengineering.com/education/viscosity_whymeasure.asp%23newtonian))

 A more scholarly look at the concept of viscosity with mathematical formulas and an estimation of gas viscosities is located at <http://www.columbia.edu/itc/ldeo/lackner/E4900/Themelis3.pdf>.

 Beautiful and useful posters with explanations related to understanding viscosity from the standpoint of foods is located at <https://ediblesciencefaire.wordpress.com/viscosity-poster/>.

 A short discussion explaining that there is not a relationship between viscosity and density (for non-superfluids) is found at <http://physics.stackexchange.com/questions/158133/is-viscosity-a-function-of-density-only>.

 This Web site features an archived webinar as a part of the detailed explanation of the viscosity of Newtonian and non-Newtonian fluids. Diagrams, mathematical formulas, and other relevant links are provided at <http://www.rheosense.com/applications/viscosity/newtonian-non-newtonian>.

**Motor oil**

 If you would like to know more about motor oil viscosity classifications, see <http://standards.sae.org/j300_201501/>.

 For help selecting the proper motor oil for your vehicle based on label codes, viscosity, and types, see <http://www.popularmechanics.com/cars/how-to/a53/1266801/>.

 Additional information on motor oil viscosities and understanding the SAE (Society of Automotive Engineers) codes such as 5W-30, visit <http://www.upmpg.com/tech_articles/motoroil_viscosity/>.

 A more technical explanation of SAE motor oil viscosities is located at <https://www.jcmotors.com/images/understanding_motor_oil_viscosity.pdf>.

 For a different explanation on motor oil numbers, see <http://abcnews.go.com/Technology/story?id=119270&page=1>.

 Measuring motor oil viscosity is explained at this site which includes a few links to related topics. (<http://auto.howstuffworks.com/fuel-efficiency/fuel-consumption/question1641.htm>)

**Quicksand**

For a simple explanation of how quicksand, a non-Newtonian fluid, works including some simple graphics, see <http://science.howstuffworks.com/environmental/earth/geology/quicksand.htm>.

 This site answers the question, Can quicksand really suck you to your death? (<http://www.bbc.com/future/story/20160323-can-quicksand-really-suck-you-to-your-death>)

 If a person is caught in quicksand, this site describes what not to do so that you will survive. (<http://science.howstuffworks.com/science-vs-myth/everyday-myths/quicksand-sinking1.htm>)