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Using 3D Printing for the Instruction of Petrophysical Properties

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Using 3D Printing for the Instruction of Petrophysical Properties

by

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Report

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Dedication

To my loving husband Jeff.

Without your patience and support,

none of my adventures would be possible.

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Abstract

Using 3D Printing for the Instruction of Petrophysical Properties

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The University of Texas at Austin, 2014

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With the recent increase in natural gas production, the demand for college educated petroleum engineers has increased. A greater number of high school graduates are now applying to petroleum engineering degree programs, however, the admission requirements to petroleum engineering schools are becoming increasingly stricter. Secondary educators have a greater challenge to better prepare students to compete for these positions and there is a need to introduce petrophysical concepts to students in the most effective manner. One petrophysical concept is porosity of rock. In this report, background information on rock formation and porosity of rocks is provided along with a brief summary on how 3D printers operate. But primarily, a lesson plan is presented to teach rock porosity in a novel way using 3D printed enlargements of porous rock from x-ray microtomography images of packed sand.

The hypothesis was that students will gain greater understanding of petrophysical properties when using 3D prints of rocks. The porosity lesson with a lab using the 3D printed rocks was taught to a treatment group of 20 upcoming 6th graders. A porosity lesson without the use of 3D printed rocks was didactically taught to a control group of 14 additional 6th graders. Because of time limitations, not all of the students from the

treatment group were able to experience all elements of the lab. However, every student in the control group received instruction and practice on how to calculate porosity of rock. The treatment group showed greater gain in learning the abstract concept about porosity that rocks of similar structure will have equivalent porosity regardless of grain size. However, the control group indicated greater gain learning the fundamental concepts of the definition of porosity, how to calculate porosity, and at being able to transfer their knowledge of percent porosity to a general problem about percentages. Despite the limited sample size and other sources of error, using 3D printed enlargements of rock was found to enhance students' abilities to visualize abstract petrophysical properties. However, benefits from didactic instruction of fundamental concepts of petrophysical properties were found as well.

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Chapter 1: *Introduction*

Students today require a deep understanding of science, technology, engineering, and math in order to be able to successfully function in an increasingly complex world. As a result, more is required of educators in order to facilitate the needs of today's students. Orion and Trend, editors of the *Journal of Geoscience Education* state that "the educational process requires teachers to unravel and mediate the meaning of learning and to tailor their teaching to that which will best exploit the learning characteristics of the students. One of the main challenges of science education is to develop thinking skills among learners in order to strengthen their scientific understanding: this should be an empowering and liberating process for both students and teachers. Steps towards the achievement of this goal include the identification of the meaning of learning and the development of appropriate curriculum materials and teaching strategies that address learning characteristics across various populations of learners" (Orion and Trend, 2009). To this end, educators must not only possess in-depth knowledge of disciplines, but we must also be open to utilizing newly available technologies in order to deliver instruction.

A recent resurgence of oil & gas development particularly in the state of Texas (Fig. 1) has increased the number of students seeking degrees in petroleum engineering, while the capacity of degree programs are remaining relatively unchanged. Thus the admission requirements of many schools including the University of Texas (UT) petroleum engineering program are becoming increasingly stricter. It is interesting to note that in 2004 the number of applicants to UT whose first choice of major was petroleum engineering was lower than the number of students admitted to the petroleum engineering program. There are several factors that impact the final admit counts including second choice majors, major changes by the student, and impacted majors. Since the school of engineering has many impacted majors, there were 24 additional students admitted to petroleum engineering who either were not able to get into other engineering majors or who listed petroleum engineering as their second choice and were cascaded into the major by the end of the admissions cycle and ultimately accepted their admission into the petroleum engineering major. From 2004 to 2013, the number of applications increased from 114 to 987. (Fig. 2).

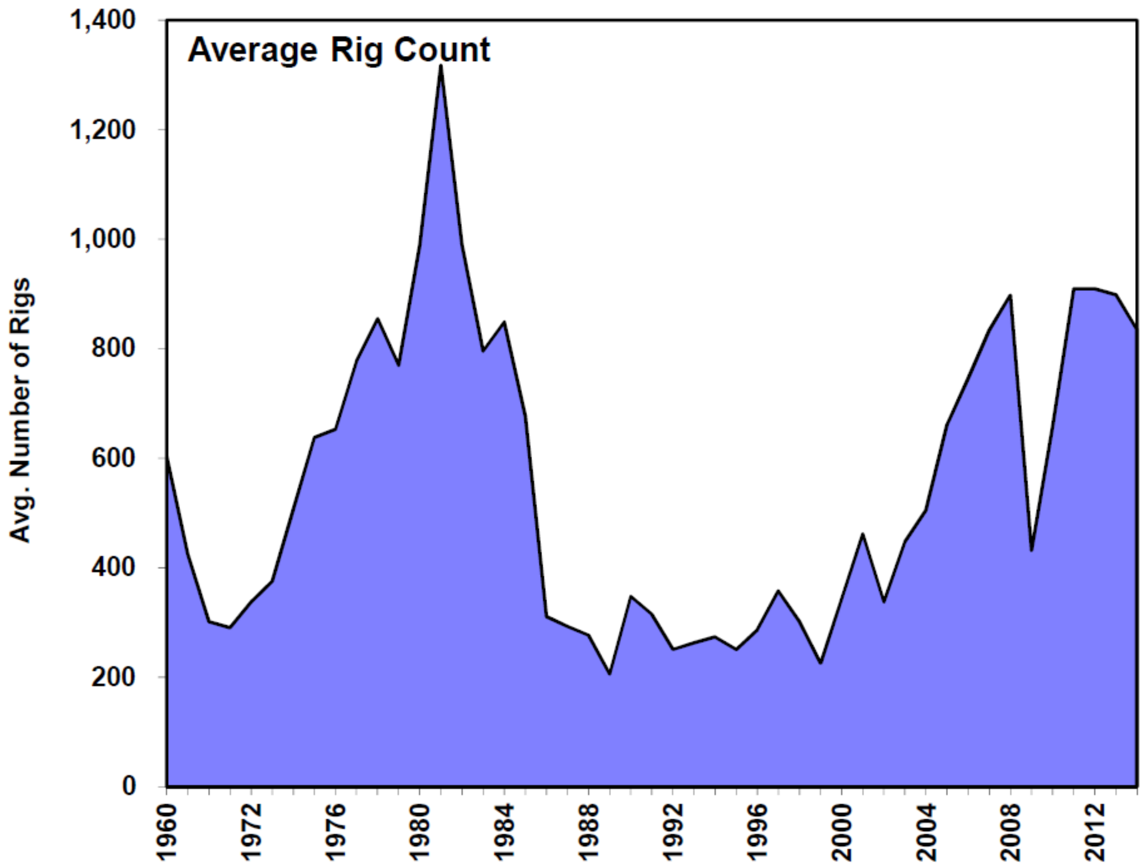


Figure 1: Average drilling rig count in Texas (Railroad Commission of Texas, 2014)

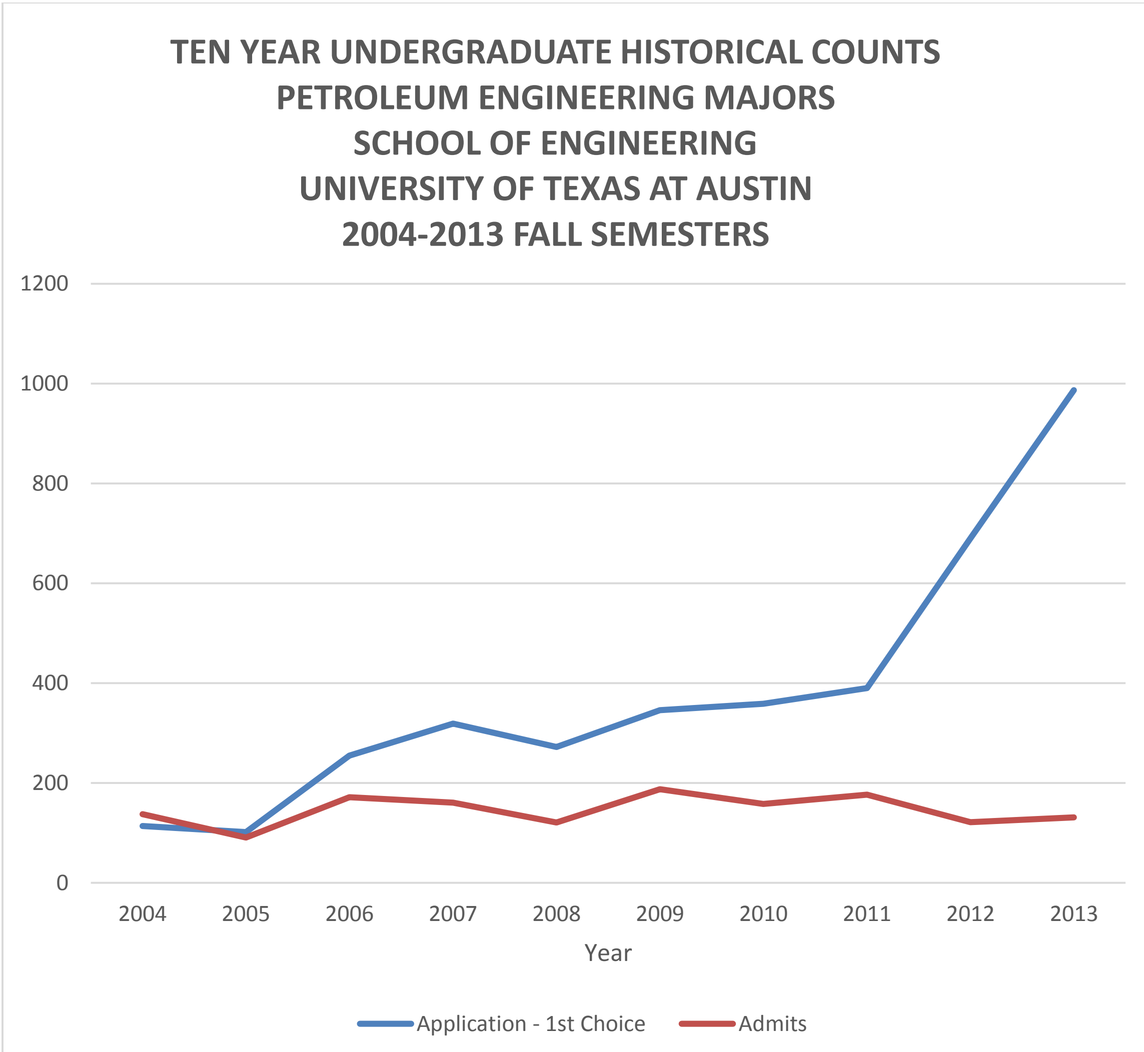


Figure 2: Number of students applying to the department of petroleum engineering at the University of Texas at Austin compared to the number accepted. (Office of Admissions, University of Texas, Austin, 2014)

Thus, K-12 educators have an increased responsibility to ensure their students have the tools available to them to compete with those seeking post high school study in the field of petroleum engineering which include skills related to both geology and classical engineering. Geophysical skills students require to compete include: "(1) geology-related spatial visualization, (2) understanding absolute geologic time, including the concepts of physical and temporal correlation of stratigraphic units, (3) actualistic thinking, or the ability to interpret ancient environments through comparison with modern ones, (4) geological field strategies and techniques, and (5) scientific reasoning" (Almquist et al., 2011). The purpose of this report is to focus on the development of this first skill – improving geology-related spatial visualization.

Teaching and improving spatial reasoning can be difficult particularly as it relates to what is unseen below ground. For example, it is common for students to have misconceptions about how groundwater is stored and how it moves (Schwartz et al., 2011). It has, however been established that through the study of geology, a student's spatial ability can be improved (Titus and Horsman, 2009). This is particularly true when lessons integrate hands-on modeling exercises (Drennan and Evans, 2011). Modeling also plays an important role in engineering. "The creation and use of representations is a central aspect of modeling, and students who are learning to model often use a variety of representations to express, test, revise, and communicate their own thinking. Consequently, model development often depends on representational fluency and the ability to translate between and within different representational forms (Moore et al., 2013). "Explicit learning experiences about models and the modeling process need to be embedded into the engineering curriculum, specifically in the teaching of engineering design. Teaching modeling will improve student use and understanding of modeling as an important and pervasive engineering tool" (Carberry and McKenna, 2014).

Many efforts in geology education try to help students visualize things that are too big to see or conceptualize. This work is concerned with helping student to visualize things that are too small for them to see, yet play a crucial role in geological processes, specifically the elements of geology that determine the transport of water and the filtration of water.

This is accomplished through the creation of geological models imbedding microstructure details into a larger conceptual picture using newly available technology, namely three-dimensional printers.

Chapter 2: *Review of the Literature*

HISTORICAL APPLICATIONS OF INSTRUCTIONAL MODELS

Models have traditionally been utilized in classrooms to assist students' visualization of abstract concepts or to assist visualization of items too small to be visible with the unaided eye. Before the development of computers, these models were concrete and tangible – 3-dimensional items that could be held and manipulated. From the 1930's through the 1950's many different types of physical models were promoted for use in classrooms. There were electrical models used to teach vibration theory (Kemler and Freberg, 1943). Rubber models were used to teach the principles of elasticity (Durelli, 1950). Airplane models were created with Tinker Toys (Larson, 1959). There were various types of "loaded models" with a variety of applications (Gilkey, 1935). The use and development of models was so common that model factories were developed in universities created for the purpose of building models for the engineering colleges (Gwiazdowski, 1930). Papers have been written on the use and construction of models (Hartenberg, 1950). In the 1930's, there were even conferences held for the express purpose of sharing and demonstrating the latest models created for technical education (Plummer, 1935).

INSTRUCTIONAL MODELS IN THE COMPUTER ERA

With the advent of computers, the modeling of geological structures has been greatly enhanced. The list of applications is extensive. Global Positioning Systems, Geographic Information Systems, and total station laser surveying (Almquist et al., 2011) are among the tools that have been used. There are countless computer simulations where individuals control various parameters in order to construct geological scenarios to model various structures and geophysical activity (Fraser et al., 2007). There are many websites dedicated to archiving the many various geological software available. One such website is maintained at North Dakota State University. Not only does it contain links to a multitude of geological software, but it also contains links to other sites that maintain such lists (Saini-Eidukat, 2014). Computer technologies not only have improved the capabilities of geologists, but they have also enhanced student learning.

Computer applications are used in a wide variety of engineering disciplines. One such scaffolded software environment is ChemProV which is used by beginning chemical engineering students. Its purpose is to assist students in solving material balance problems by providing dynamically-generated feedback on syntactic and semantic correctness of students' evolving disciplinary diagrams and mathematical equations with a goal of improving engineering students' problem-solving abilities. After a recent study using ChemProV, researchers concluded that the software "can serve as a valuable aid in helping students learn engineering problem-solving skills. Its software design approach can be used as a model for designing educationally-effective software environments for other engineering disciplines" (Hundhausen et al., 2011).

Computer simulation-based learning improves motivation as well as their performance. Recent use of computer simulation-based learning in a Machining Technology course by mechanical engineering students found that "the students perceived their psychological needs to be satisfied and had high levels of self-determined motivation." These students also had higher mean performance test scores. The researchers concluded that "students perceived their basic psychological needs to be met and that simulation-based learning can potentially enhance self-determined motivation as well as improve learning in general" (Koh et al., 2010).

Another study of computer applications in a stochastic groundwater modeling course followed students for one week in an effort to strengthen groundwater education.

In addition to learning key vocabulary, the educational objectives of this course were to "explain spatial correlation, produce realizations of groundwater flow, and critique deterministic groundwater models." These goals were accomplished through guided, hands-on computer exercises provided by Processing Modflow for Windows (PMWIN). The study found "students reported significant improvement in their ability to perform a majority of the educational objectives" (Mays, 2010).

One additional example of using computers in an educational setting is seen in a classroom for optical mineralogy. The course requires students to "integrate a complex theory with microscope manipulations and image interpretation." To facilitate instruction, digital photomicrographs were uploaded to individual student Tablet PCs that not only allowed students to view the images up close, but also allowed digital annotations. The results of this study found student visualization of the minerals improved (Hoisch et al., 2010). These various classroom examples of computer modeling suggests that providing models and simulations to students can improve engagement and enhance learning.

PHYSICAL INSTRUCTIONAL MODELS IN THE 21ST CENTURY

Despite the prevalent use of computers, there are still recent applications of hands-on manipulatives. It has been said that "quality, multimodal instruction will help to clarify students' misconceptions and assist them in constructing accurate mental models" (Schwartz et al., 2011). Additionally, "activities rich in object-visualization could provide an opportunity to motivate and empower a population – object visualizers – who may have disliked prior science courses" (Kastens, 2010). Therefore, even though current electronic devices provide very accurate and realistic representations, there remains a need for physical hands-on manipulatives.

A recent study introduces an interesting instructional method to model complex Earth systems. "Students are provided with a mechanism for explicitly following matter as it moves through the environment, and describe this movement pictorially in box-and-arrow diagrams. This approach raises awareness of the underlying causes for the dynamic nature of systems, and encourages reasoning, thoroughness, and transferability of skills. Preliminary data suggest that this method is effective with post-secondary students" as well and the methods are encouraged to be adapted to other courses (Clark et al., 2009). Even though this process does not utilize manipulatives, it does demonstrate a use of representations that are not generated using computers.

There is one unique and interesting study of the use of a physical underground mine mapping simulation to build geospatial skills. "A physical (non-virtual) underground mine mapping simulation in a building on the Adams State College campus in Alamosa, Colorado, provides an excellent cost-effective and efficient learning tool to prepare students for actual field mapping, while improving spatial thinking using a physical hands-on setting. In this simulation, students act as mine geologists, completing simulated mine mapping work tasks. Mapping and interpretive skills are enhanced in an adaptable, flexible, and easily implemented simulation that is software independent. The mine simulation is well received by students as an effective training and learning tool" (Benson, 2010). This application of geological instruction seems very intriguing yet very massive.

One additional example of using tactile objects to teach space science to grade school students is for the benefit of students with visual impairments. Eleven students at a week-long residential summer camp received "Earth and planetary science lessons on rotation/revolution, silhouettes of objects from different views, contour maps, impact craters, asteroids, and topographic features of Mars. The materials are recommended for use with sighted students as well as those with visual impairments because of their concrete, tactile nature" (Rule, 2011).

Our research is centered on the teaching of the concepts of porosity and permeability of rocks in a concrete manner. The American Society of Civil Engineers has published a book of classroom demonstrations for water concepts. The editors Hilton and Neupauer provide a chapter on teaching groundwater concepts through 9 interactive lessons. One lesson in the groundwater chapter is titled "Porosity" and is taught using Grape-Nuts cereal and milk to demonstrate that "aquifers are not like underground rivers but more like a cereal bowl" (Hilton and Neupauer, 2013). The lesson is concrete and simple to implement. However, due to the loose nature of the cereal, a student could lose sight of the idea that the aquifer is contained in rock and that the pore spaces are very small. In this work, porosity is demonstrated utilizing a product that more closely resembles actual rock.

USES OF THREE-DIMENSIONAL PRINTERS

One of the greatest technological advances thus far in this century is the creation of three-dimensional printers. A new phase has emerged – "Internet of 3D Printed Products." Via 3D printers connected to the internet, "we are looking at not only intangible services, but tangible goods will be delivered as well to our computers over the Internet. We will be able to receive or create goods in digital form, and we will be able to 3D print them and turn them into physical objects." There are also a variety of applications of 3D printed material. This includes but is not limited to "3D printing of specialized robot parts, 3D printing of transplanted jaws, 3D printing helping grow new bones with scaffolding, and 3D printing drugs, and newer models for training of engineers." This particular study also recognizes "3D printing of tactile aids for visually impaired" (Kaur, 2012).

Another application of using 3D printers in the instruction of geosciences has been for the creation of terrain models. Before 3D print technology was available, construction of physical models involved expensive, labor-intensive sculpting or molding. Using data from "topographical maps, radar data, altimetry, and digital terrain models," terrain models can be created within hours at a lower cost. Printing terrain models can allow a person to visualize distant places they may never visit especially terrains of lunar and planetary surfaces. There are even greater benefits to the visually impaired making space sciences accessible to more (Horowitz and Schultz, 2014). Interestingly enough, we were unable to find evidence of 3D printing being used to create models of petroleum reservoirs.

In this work, 3D printers are used to enlarge common objects, namely rocks, in a similar fashion that a 2D image would be enlarged, in order to gain understanding of their structure and properties. In doing so, not only will a student be able to visualize geological processes, but they can also perform simplified experiments with rock models that previously were only possible with time consuming and expensive equipment. Most soils and sandstones have grains with diameter on the order of 62.5 to 1000 micrometers. As a result, their intergranular pore spaces are commonly 0 to 100 micrometers in diameter (Peters, 2012). Diagenetic processes in sandstones (compaction, partial dissolution, and recrystallization) during burial can further reduce the pore space sizes. Thus high resolution imaging is required to understand the microstructure. X-ray microtomography has revolutionized our understanding of the three-dimensional rock pore spaces by allowing non-destructive imaging (Flannery et al., 1987). Recent advances in these imaging practices have been reported by Wildenschild and Sheppard (2013). The level of detail obtained is great, however it takes fairly specialized knowledge to translate the image's geometries to so-called STL files required by 3D printers (Szilvási-Nagy and Mátyási, 2003).

Chapter 3: *Petrophysics*

The source of most of the information contained in this chapter comes from Ekwere J. Peters' Advanced Petrophysics textbook. Petrophysics is the study of physical properties and behavior of rocks, including how fluids move through rocks. This study is of particular importance to petroleum and geosystems engineers because the majority of the fluids in the rock are either water or hydrocarbons. Despite Hubbert's prediction that the production of oil has reached its peak (Hubbert, 1956), strong demand continues for petroleum products in the United States. World use of oil may be declining, but the consumption of natural gas appears to be on the rise (Fig. 3). It is the job of the petroleum and geosystems engineers to locate and extract these fluids from the rock; therefore, their professions remain very important to our society.

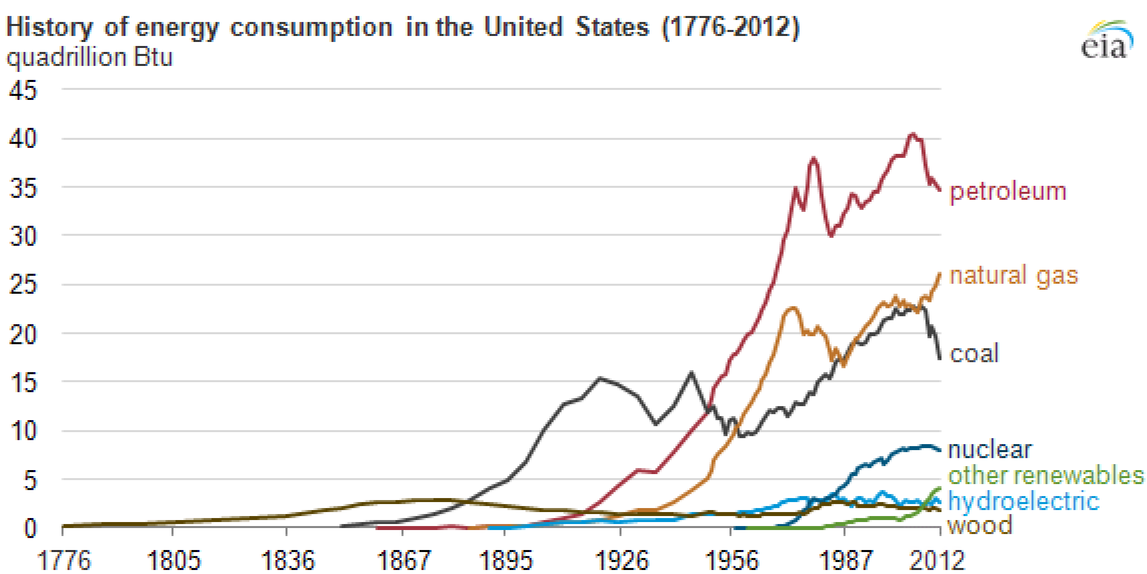


Figure 3: History of energy consumption in the United States (U. S. Energy Information Administration, 2013).

ROCKS

There are three basic types of rocks: sedimentary, metamorphic, and igneous rocks. The most common form of sedimentary rocks include sandstones and carbonate rocks. Their name describes how they are formed. For instance, sediment in water settles to the bottom of lakes and oceans. Sedimentary rocks can also be formed land and wind might be the sediment carrier. As more and more sediments are deposited, the layers below get compacted and cemented, and their resident water migrates out. High pressures and temperatures at depth ultimately form rocks. We see sedimentary rocks form in layers on the Earth's crust over time. Often these sedimentary rock layers are visible above ground in canyons or in outcrops of various formations after uplift or erosion (Fig. 4). Petroleum is formed when dead organisms (e.g. plankton) are buried with the sediments and exposed to great pressures and temperatures (Fig. 5).

Figure 4: Sedimentary rock layers at Canyonlands National Park (Herbert, 2014).

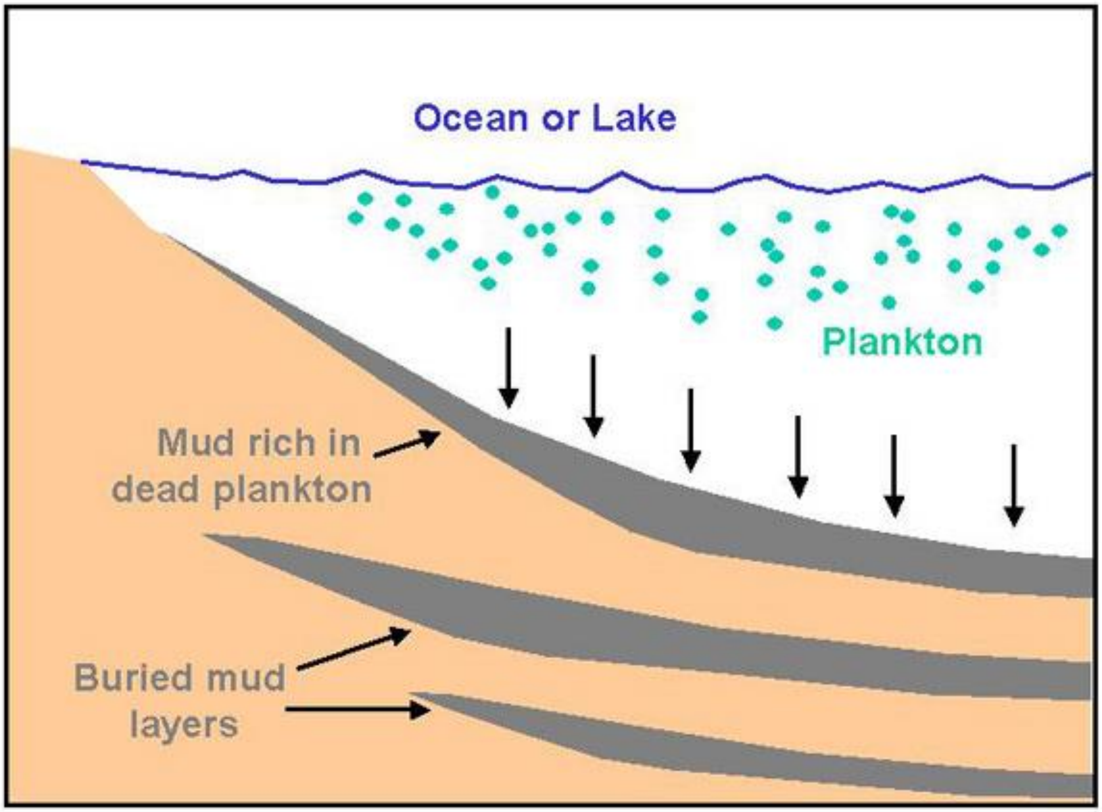


Figure 5: Plankton sediment forming layers of sedimentary rock (Bratton, 2003).

Sedimentary rock can be transformed into metamorphic rock due to high heat and pressure causing physical and chemical changes. Examples of metamorphic rock include quartzite and marble. Igneous rocks are formed by cooling of volcanic lava or magma. Granite is an example of an igneous rock. Of the three, sedimentary rock is typically where hydrocarbons exists.

Because sedimentary rock is found closer to earth's surface and typically has not been subject to high heat or pressures, there is less compaction of the grains of the rock. Therefore, sedimentary rock is often more porous than other types of rocks allowing for a greater percent of empty space in the rock for fluids. Additionally, much of the sediment that creates sedimentary rock is organic material. This organic material, primarily diatoms, commonly called plankton, is the building blocks for hydrocarbons. Therefore, it is within sedimentary rock that we find the majority of our fossil fuels.

Fossil fuels reservoirs are formed from the organic material found in sedimentary rock. The settled diatoms decompose into hydrocarbon fluids, primarily oil and natural gas. The density of oil and gas is less than the rock and water trapped in the rock. Therefore, if the rock is both porous and permeable, the oil and gas will seep upward towards the surface of the Earth. If the oil and gas reach rock that is not permeable, it will collect in a subsurface reservoir (Fig. 6).

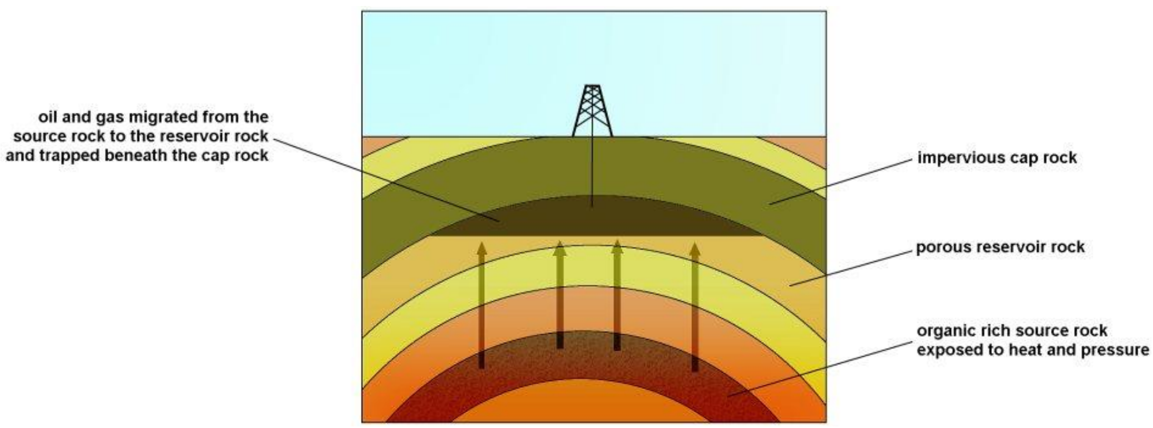


Figure 6: Formation of an oil and gas reservoir (Shepherd, 2002).

Permeability refers to the ability of rock to transmit fluids, and it depends on porosity as well as sizes and connectivity of pore spaces. Porosity refers to the percent of pore space within a rock. The lesson developed in this work deals with the measurement of porosity.

POROSITY

Porosity is the ratio of the volume of the pore space compared to the total volume of the rock. Often the pores of a rock are isolated and not connected. If so, the effective porosity will be less than the total porosity of the rock. The effective porosity of rock is more important in controlling flow than the total porosity.

The porosity of sandstone, a type of sedimentary rock, is affected by packing sorting, and cementation. Packing refers to the arrangement of the grains in the rock and effects pore space connectivity. The square packing in Figure 7 has a greater percent of pore space (47.6%) than the hexagonal packing's pore space (39.5%).

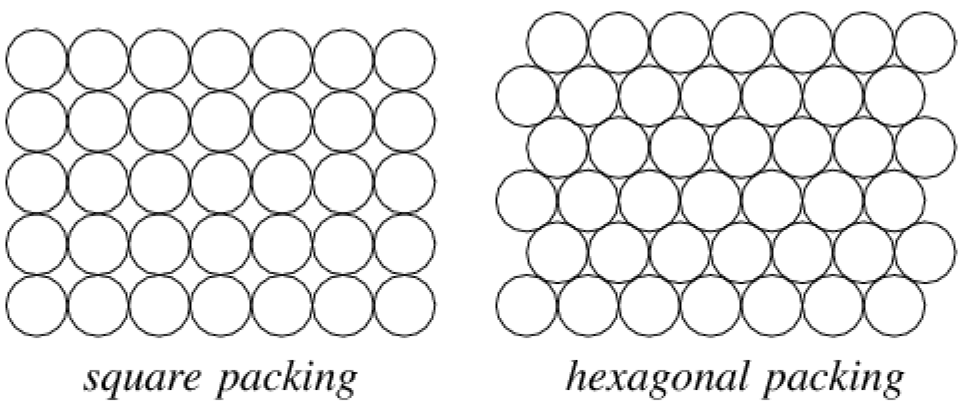


Figure 7: Idealized packing arrangements of sand grains in sandstone (Wolfram Math World, 2014).

47.6 39.5

Sorting refers to the variability of grain sizes within a rock. If a rock has a variety of grain sizes, smaller grains will fill in the pore space around the larger grains. Therefore, rocks with a variety of grain sizes will have less porosity than rock with uniform grain sizes (Fig. 8).

Figure 8: Example sorting arrangements of sand grains in sandstone (The Open University 2014).

Cementation also affects the porosity of sandstone. Cementation occurs when cement precipitates from water and fills the pore space (Fig. 9). Cement is usually made of quartz or carbonates.

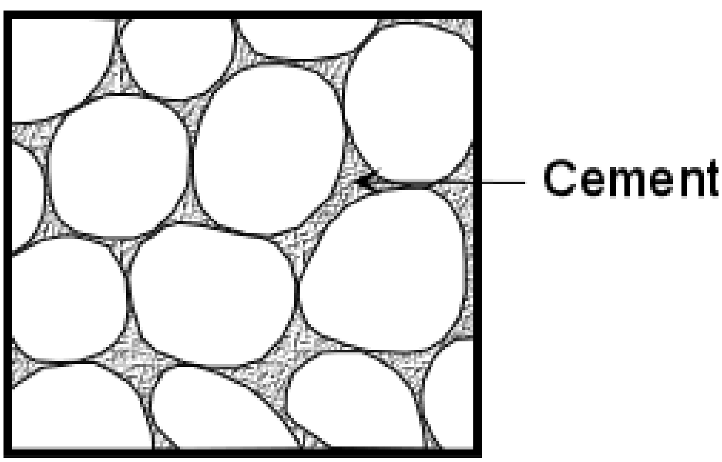


Figure 9: Cementation in sandstone (Nelson, 2014).

Porosity of sub-terrain rock can be measured both directly on a rock sample in a laboratory or indirectly on location at the well site. One method to measure the porosity directly is to find the mass of a clean and dry rock and compare it to the mass of the rock when it is saturated with fluid. Then calculate the volumes of each by dividing their mass by their density. The porosity is the difference in the volumes divided by the volume of the sample. This process can take time that is not always available for classroom labs.

There are various porosity calculating devices that inject a sample with fluids to achieve saturation. Various fluids are also used for this analysis. For some of these fluids, it is not possible to expel them from the rock sample once injected into the pores. Other fluids can be caustic, causing the sample to become more porous the longer the fluid remains in the rock. In both of these cases, the sample would not be suitable for further study. All of these methods calculate effective porosity as opposed to total porosity. To calculate total porosity, the sample would have to be crushed and compacted. The volume of the crushed sample would be compared to the volume of the sample in its original state. This process would depend on the crushed particle size, however.

An additional way to measure the porosity of a rock sample is to use X-ray computed tomography (CT) imaging. The grayscale colors of voxels (volume elements, the 3D equivalent of 2D pixels) in the image are normalized on a scale of 0 to 1 with 0 representing white and 1 representing black. Typically, there is enough separation between greyscales corresponding to pores and rock to separate them. This process is called segmentation.

Porosity can also be measured at the well site indirectly using logs. A log of the well is produced using sound or electromagnetic waves. A logging tool is placed in the well bore at the depth of the target formation. The tool contains transmitters and receivers. Waves emitted from the transmitter echo back to the receiver from the formation. The time the sound takes to return to the receiver from the transmitter is noted. Sound waves are typically used to measure elastic properties of rock. For porosity, a neutron source is used more often. If using sonic logs for porosity, then the porosity and sonic transit time are related as

$$\Delta t = \phi \Delta t_{fluid} + (1 - \phi)\Delta t_{solid}$$

where ϕ is the total porosity, Δt is the measured interval travel-time, Δt_{fluid} is the interval travel-time of the saturating fluid, and Δt_{solid} is the interval travel-time of the rock matrix. This estimation equation is called Wyllie's equation (Wyllie et al., 1956). Therefore, it follows that a greater echo time will indicate a formation with a greater porosity (Peters, 2012).

Chapter 4: *3D Printers and STL Files*

Three-dimensional printers create objects by adding one layer at a time, and are thus also referred to as additive manufacturing. The creation of the first 3D printer is credited to Charles W. Hull of 3D Systems Corp. in 1984. There are a variety of technologies used to print in 3D. The most common technology is thermoplastic extrusion 3D printing (Barnatt, 2013).

The "ink" for thermoplastic extrusion printers is a polycarbonate plastic filament stored on a spool on the printer (Fig. 10). The plastic is threaded to the print head. The print head is heated and extrudes molten plastic to a build platform. Here the plastic cools quickly as it creates the solid print. The printer prints one layer at a time much the same way paper printer operates printing one row at a time. After printing a layer, the print head moves up to print the next layer (Barnatt, 2013).

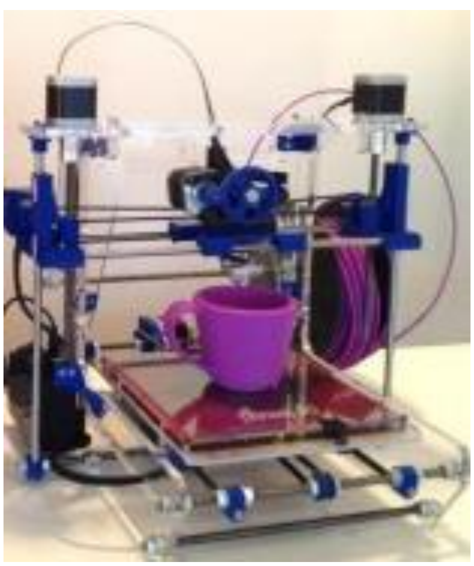


Figure 10: Airwolf 3D printer (Airwolf, 2013)

Sterolithography (STL) files are necessary to print an object on a 3D printer. The code defines a set of connected triangles in 3D space that represent the surface of the object to be printed. The vertices of these triangles can be calculated using Lorensen's and Cline's marching cubes algorithm. This algorithm was devised in 1987 to assist in creating 3D images from a series 2D medical images such as those in magnetic resonance imaging (MRI).

An STL file begins with an image of the object to be printed. The gradient shades of the colors of each voxel in the image of the object are assigned values. It is decided which color voxels are considered inside the solid and which represent outside the solid. The fifteen marching cubes are shown in Figure 11 below. Each of the 8 vertices in a marching cube represents 8 connected voxels in the image. Triangles divide the space in the marching cube between the inside voxels and the outside voxels. This process is repeated for all cubes of 8 voxels in the image beginning with the first row of the bottom layer of the image and continuing through the image to the last row of the top layer of the image. The combined triangles will form the isosurface of the object to be printed. When the printer knows where the surface of the object begins and ends, it knows where to print and where not to print. The printer simply prints from one surface of the object to the other (Lorensen and Cline, 1987).

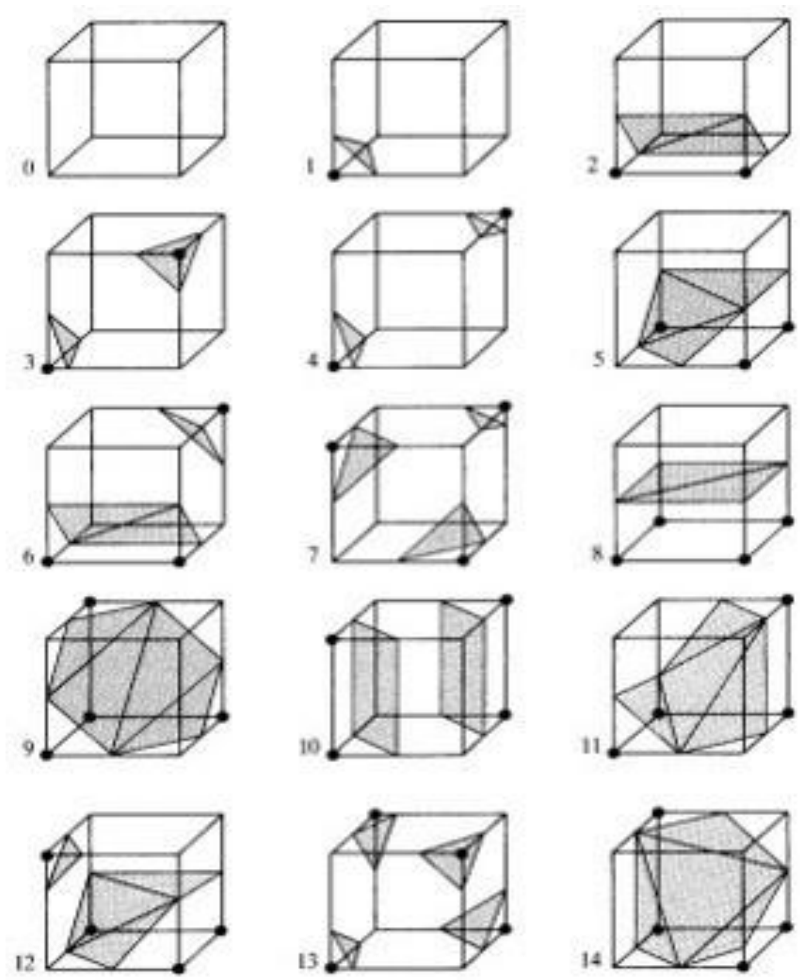


Figure 11: Marching cubes algorithm: possible configurations of triangles. (Lorensen and Cline, 1987).

There are many problems that can occur in developing STL files. Requirements of the triangles are that they must all be closed and every edge must be shared by exactly two triangles. Also every vertex must align with other vertices of other triangles. The vertices must not intersect another triangle on its edge. Triangles are also not allowed to intersect or overlap. Unwanted faces can occur from randomly placing triangles that are either inside or outside the solid. The algorithm will at times leave gaps in the surface. Also the algorithm can develop ill-defined surfaces. This can occur with lower resolutions in the original image. However, when the resolution is increased, the number of voxels increases creating more triangles in the surface. This can lead to more complications in creating excessively large files that some computers cannot facilitate. When the surface is created correctly, it will be represented by a smooth mesh of triangles. When there are errors in the STL files, there is mesh repair software such as MeshFix or MeshLab that seeks to average the distance between non-matched vertices and match them up (MeshRepair.org, 2012).

X-ray microtomography images of detailed rock microstructure can serve as input to construct STL files and this has been done for the creation of 3D prints used in this work. X-ray microtomography was first introduced in the late 1980's. X-ray microtomography is nondestructive and can create images with great accuracy and high resolution comparable to that of a light microscope (Flannery et al., 1987). Since then, the field has literally exploded. Imaging systems are now commonly available and have revolutionized research of processes on micron length scale in rocks. Recent advances in x-ray microtomography are now allowing understanding porous media flow and transport (Wildenschild and Sheppard, 2013).

The design of a microtomography system begins with a source of collinear x-rays (Fig 12). X-rays, as well as visible light rays, are waves of electromagnetic energy carried by photon particles. X-rays have a shorter wavelength but higher energy level than the visible light rays that human eyes can see. As such, x-rays can pass through objects. It is preferable that these x-rays be monochromatic, that is x-rays of a single wavelength. This helps to improve the resolution of the image. The x-rays of the microtomography system are directed at the sample to be imaged which sits on a rotatable stage. The sample absorbs some of the x-ray photons creating distinctions between the waves which represent the spatial differences in the density, and thus structure, of the sample. The remaining x-ray photons travel to a face plate consisting of lithographically fabricated phosphor plugs spaced approximately 2.5 μm apart. The phosphor plugs capture the optical photons converting the x-rays to visible light rays. A conventional lens system magnifies the image of the optical photons onto a charged-coupled detector (CCD). A CCD is a grid of capacitors that convert incoming photons into electron charges. Each capacitor represents a different pixel and each electron charge represents a different color hue. This data is recorded in multiple stacked planes. Three-dimensional images are reconstructed from this data which is stored in multiple stacked planes.

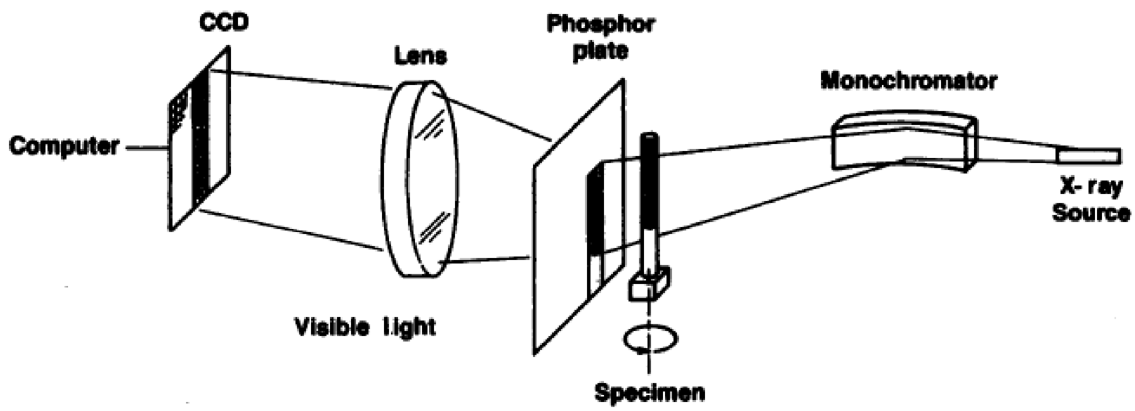


Figure 12: Illustration of an x-ray microtomography device (Flannery et al., 1987)

Creating products using 3D prints offers many advantages to traditional manufacturing processes. 3D printers offer shopping convenience. A product's print file can be downloaded via the internet and then printed at home on a 3D printer instead of traveling to a store or ordering products over the internet or by phone. The products can even be personalized and customized to you your own preferences (Barnatt, 2013).

Even though this technology has existed for 30 years, there are still disadvantages of their use. These printers have not always been very accessible, efficient, or fast enough for home use. Their price varies based on the printing resolution, size of the object to be printed, and the quality of filament material. 3ders.org report prices ranging from $249 for a very basic printer to $846,000 for a more sophisticated model. The polycarbonate filament is also quite pricy for everyday home applications. Prices of filament range from $18.96 to $175.20 per kilogram depending on the material, size, color, and quantity purchased (3ders.org, 2014). For reference, MakerBot claims one kilogram of filament will print 699.3 cm^3 or 392 standard size chess pieces with 5% infill. This could create 12 complete chess sets. MakerBot's filament cost $48 per 1 kilogram spool (MakerBot, 2012). Therefore each chess set would cost $4 each without a board. Considering that Amazon.com sells an inexpensive Pressman toy chess set for $7.96 with a board, MakerBot's chess set appears relatively affordable (Amazon, 2014). However, not all applications are as cost effective. But as with all new technologies, prices may drop as the industry gains efficiency of scale.

There are many applications of 3D prints. Their main advantage is arguably not printing objects that are already easily mass produced (such as chess sets), but printing customized objects and replacements for parts that possibly do not exist on the market. One of the most significant applications is how it has revolutionized modern medicine. Biomedical engineers are creating customized body parts. We also find 3D prints being used to make jewelry, art, and fashion. Architects and engineers now have the ability to quickly and efficiently create models, prototypes, and iterations of their designs. Candies are even being printed using chocolate and other sugars (Barnatt, 2013). However, there have been very limited applications found for 3D print applications in education. Segerman promotes the use of 3D printing for visualizing mathematics. Examples he proposes are printing 3D graphs such as a hyperbolic paraboloids or non-Euclidean surfaces such as inverted tori or Möbius strips (Segerman, 2012). But the majority of educational applications have been in engineering, robotics, and computer science classrooms to teach students how to use a 3D printer and how to create STL files for design purposes (Martin, et al., 2014).

Chapter 5: *Methods*

In this work, the use of 3D prints was used to develop a lab to teach porosity of rock. The hypothesis was that students will gain greater understanding of petrophysical properties when using 3D prints of rocks during instruction than without the 3D prints. The goals were that students would come to know the meaning of porosity, know how to compute porosity, and to understand a deeper concept of porosity that similar structured rocks will have the same porosity regardless of grain size. Prior to conducting the research, approval was obtained from the Institutional Review Board at the University of Texas at Austin. Both parental consent and the students assent were obtained. The lesson plan is presented in Appendix A. There is also an instructional presentation provided in Appendix B.

3D rocks were printed in the shape of a cylinder in order to emulate a core sample (Fig. 13). The print is an enlargement of the microtomography image of a sand packing (Fig. 14). This image was manipulated using ImageJ/Fiji software (Fiji, 2014) and the STL file was corrected using MeshFix (Dice Holdings, Inc., 2014). The STL file to create this print can be found online at the digital rocks portal https://pep.tacc.utexas.edu/projects/5/ (Unconsolidated sand project). A similar print for any other lithology could be produced using any number of other STL files posted on the mentioned digital rocks portal. Two magnifications of the 3D prints and customized containers to hold the prints were created (Fig. 15). The containers were used to calculate the volume of the pore space filled with water. Because the prints are made of polycarbonate, a petrochemical, their density is less than water and will float. It is important that the print fit tightly in the container to use friction to hold the print in place and to gain an accurate measurement of the water displaced. In the absence of customized containers, beakers can be used as long as the diameter of the print is the same as the internal diameter of the beaker.

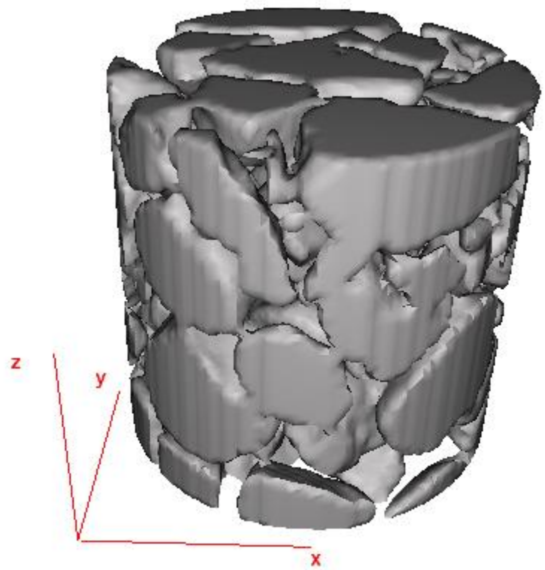


Figure 13: Snapshot of an STL surface for a cylindrical subsample with diameter and length both 180 voxels (Prodanović, 2014)

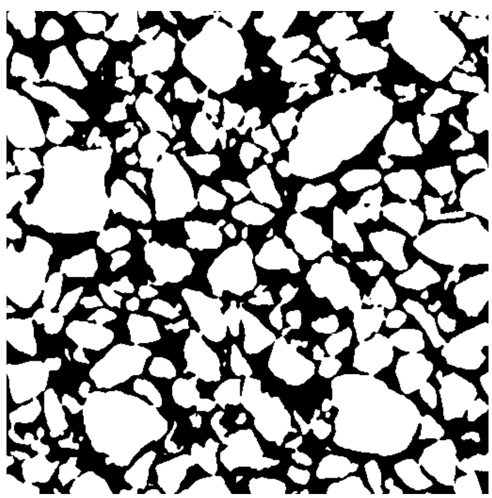


Figure 14: Cross-section of a volumetric segmented file (of unconsolidated sand, sand is in white, pore space is in black) used to create STL files for 3D printing of rock (Prodanović, 2014)

Figure 15: Photographs of 3D printed rocks used in our porosity lab (Dees, 2014)

The lab was designed for a 6th grader. In Texas, it is in 6th grade that students study the layers of Earth and learn about the different forms of rock and the rock cycle. These topics are not discussed again unless a student takes Earth & Space Science as a senior in high school. However, every year from kindergarten through 6th grade, some aspect of rocks are a part of the Texas science curriculum (Texas Education Agency (TEA), 2010). Therefore, this 3D printed rock lesson can be adapted to a variety ages to suit educational needs. The true power of this lesson is the visualization of the structure of rock made possible with a printed enlargement of rock (Fig. 16).

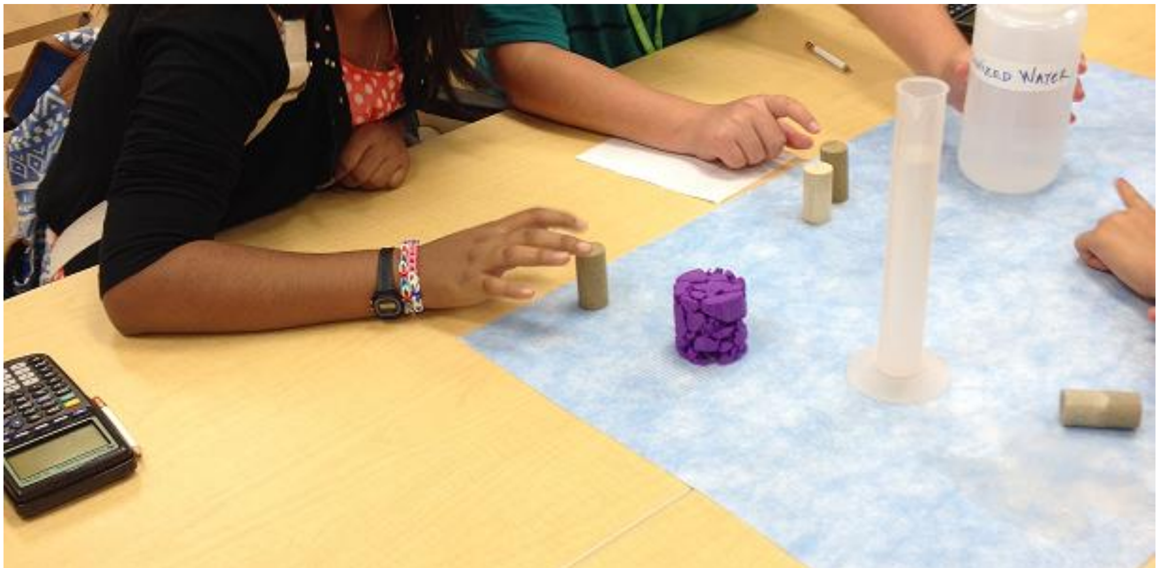


Figure 16: 6th grade students interacting with our lab materials (Dees, 2014)

The lesson creates a lab for groups of 3 to 4 students, ideally 4, where all students in the group assume different roles: a geologist, a petroleum engineer, a mathematician, and a statistician. The responsibilities of the geologist involve examining the rocks. They will take measurements of the 3D printed rock. We provided the geologist with a wash bottle so they can pour water over the rock to witness the water seep into the actual pore space of the rock. The geologist will also use a field lens or magnifying glass to compare the structure of the actual rock sample with that of the 3D printed rock.

The petroleum engineer is responsible for conducting the experiment. This involves determining the water displaced by the rock in order to calculate the pore space of the rock. In addition to the 3D rock and its customized container, the engineer also needs a graduated cylinder filled with water that is at least the volume of the pore space. The engineer will note the initial volume of the water in the graduated cylinder. The student will then simply place the 3D printed rock in the container, pour water over the rock just to the top of the rock and tapping out air bubbles, and then note the volume of water in the graduated cylinder once more.

The mathematician is responsible for all calculations for the group. This can be done with a calculator or without a calculator. The statistician will record all the data on the data collection sheet. The job of the statistician is also to report the calculated porosity of their sample to the whole class data collection sheet.

There are also some general rules for the lab. If a group has only three members, the mathematician will also serve as the statistician. As groups complete the lab at one station, they will rotate to the next. As they rotate, the group members should also rotate their roles with a goal of students working at least four stations so that they can all assume each of the roles. The most important rule is that each group member is to be responsible to each other to make sure all are aware of and agree with everyone's discoveries.

There are several learning theories employed in the porosity lab. Within each lab group, a community of learners is created. A goal is to establish a student-centered learning environment where "everyone is involved in the collective and individual effort to understand" (Bielaczyc and Collins, 1999). The lab was designed so that each group acts as a practice field which is separate from the "real" field. A practice field offers "contexts in which learners, as opposed to legitimate participants, can practice the kinds of activities that they will encounter outside of school" (Barab and Duffy, 2012). Elements typically included in practice field include:

1. Learning by doing.

2. Realistic problems typical of what would be found outside of school.
3. Teachers aiding as a problem-solving expert in addition to being a content expert.
4. Opportunity for reflection and to correct misconceptions.
5. Working with ill-defined problems in order for student to take ownership of the process.
6. Collaboration with others.
7. Relevant problems that challenge and engage the students.

A realistic situation was created to learn porosity by students assuming occupations found in industry while doing our lab in a group setting with teacher support. At the end of the lesson, students had the opportunity to analyze the results of all groups in order to notice that all porosities calculated were relatively the same regardless of the size of the sample. This helped students to correct their misconceptions that one would be greater than the other. This captures the definition of a practice field with the lab.

A didactic lesson was also created for a control group of students. The Power Point presentation for this control group is included in Appendix C. In this lesson, every student was taught the definition of porosity and every student had the opportunity to practice calculating porosity twice. They also were shown two different sized enlargements of the same sandstone shown on slide 19 of Appendix C. Using this slide, the class discussed how both samples would have the same porosity regardless of their size because their structures were identical. The prescribed presentation was longer than the enacted due to time constraints. The formal instruction ended with slide 20 which gave an overview of the oil & gas industry. A demonstration was then provided involving two student volunteers to show how injection and production wells function (Fig. 17). This was followed by (slide 29) post-assessment.

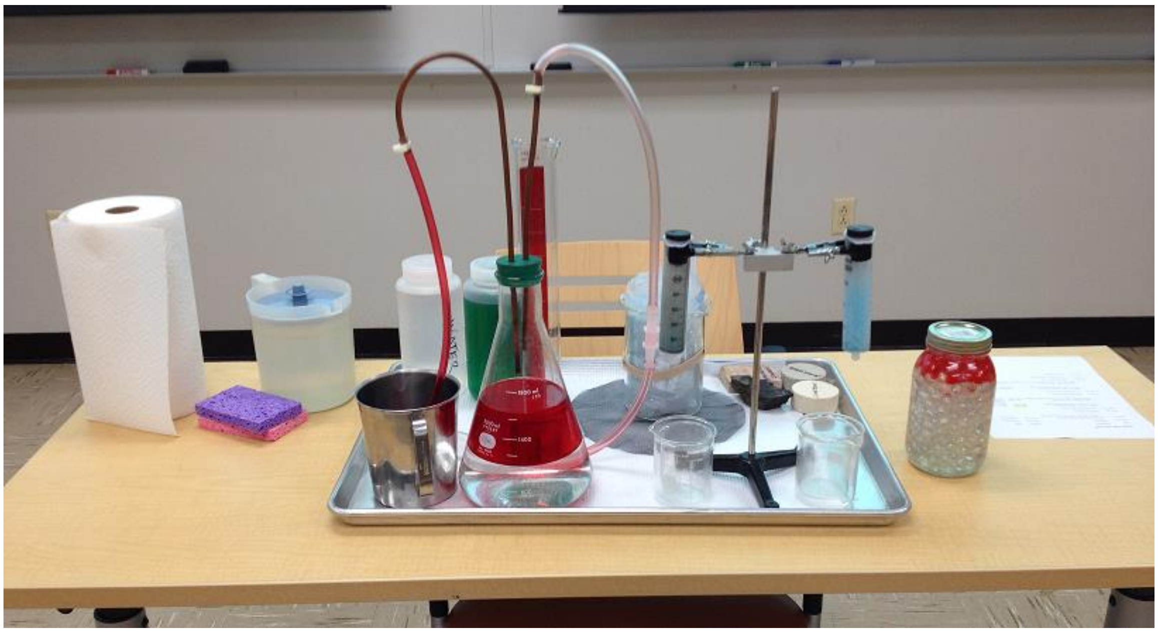


Figure 17: Injection and production well demonstration (Dees, 2014).

The lab was conducted on the campus of the University of Texas at Austin (UT) with incoming 6th graders from Manor ISD participating in Breakthrough Austin's summer program. Breakthrough is a not-for-profit organization serving low-income students from upcoming 6th graders through college with a goal to help them become the first college graduates in their families. Their philosophy is "built on the belief that there are no quick fixes and that early, long-lasting interventions can make the difference between dropping out of high school or going to college" (Breakthrough Austin, 2014).

There is an extensive process involved to have the opportunity to participate with Breakthrough. Staff from Breakthrough first conduct orientations on school campuses to raise awareness about their program. Students must complete an application along with essays about why they want to go to college and why they want to participate with Breakthrough. The students along with their parents must attend an interview as well as meet Breakthrough's admissions criteria. Typically, neither parent has completed a college degree in the United States. Students must have strong grades, however, Breakthrough does not target gifted and talented students. Students must also not have any behavior problems (Breakthrough Austin, 2014).

On the day of the lesson presentation, Friday, July 25, 2014, Breakthrough brought 4 classes of rising 6th graders to UT. Breakthrough reported that selection into each of the four classes was based on random assignment. Two of these four classes attended the porosity lab and Breakthrough randomly selected these two classes. The first group served as the control group and the second group who came an hour later were the treatment group. The order was not random – it was what was convenient to the additional helpers, students from the University of Texas at Austin's Petroleum & Geosystems Department, that came to assist during the treatment lab.

Prior to the beginning of instruction for both groups, all students were notified about the research study and gave them the option to participate or not. Those that chose to participate signed assent forms. A pre-assessment of the first four questions from the question bank found in Appendix E was given. Students were instructed to write "pre" at the top of a piece of paper to record their responses but not to put their name on their paper in order to maintain their anonymity. They were also reminded not to collaborate with their neighbor and to give their best answer. The option "I don't know" was offered as the last choice of every problem. They kept their pre-assessment until the end of the instruction. They then took a post-assessment on the back of their pre-quiz labeling the back of the paper “post”. Again they were instructed to not write their name on their paper. After the conclusion of the post-assessment, their papers were collected, stapled together, and labeled either control group or treatment group.

Chapter 6: *Results and Data Analysis*

The porosities calculated by the treatment group are summarized in Table 1 below. At station 1, students used the larger 3D printed rock and station 2 used the smaller 3D printed rock. It is interesting that when using smaller dimensions, the groups were more consistent in their calculations than those that used the larger print. One explanation could be that there is less room for error when using lower values. However with the limited sample of only 6 groups, it is not wise to draw conclusions. These results however were strong enough evidence for 60% of students to understand that porosity is not dependent upon grain size. Sixty percent of the control group answered correctly on the test question concerning this fact.

% Porosities
Whole Class Data Collection Sheet

Group Number	**Station Number**	
	1	**2**
1	68	
2		56.6
3	50.5	
4		56.6
5	54.5	
6		56

Table 1: Porosities calculated by treatment group.

Answers to all of the assessment questions are summarized in Table 2.

Assessment Results Fluids Playing Hide and Seek Below Ground Breakthrough Austin - Manor 6th Grade Program Engineering Day University of Texas at Austin Friday, July 25, 2014									
Question Number	**Response**	**Control Group 14 Students**				**Treatment Group 20 Students**			
		Pre-Assessment		**Post-Assessment**		**Pre-Assessment**		**Post-Assessment**	
		Number	**%**	**Number**	**%**	**Number**	**%**	**Number**	**%**
1	**A**	**1**	**7**	**12**	**86**	**0**	**0**	**11**	**55**
	B	0	0	1	7	1	5	7	35
	C	1	7	1	7	0	0	2	10
	D	0	0	0	0	1	5	0	0
	E	12	86	0	0	17	85	0	0
	No Ans.	0	0	0	0	1	5	0	0
2	A	11	79	6	43	11	55	6	30
	B	0	0	4	29	1	5	2	10
	C	**3**	**21**	**3**	**21**	**6**	**30**	**12**	**60**
	D	0	0	0	0	2	10	0	0
	E	0	0	1	7	0	0	0	0
3	A	8	57	5	36	8	40	4	20
	B	4	29	3	21	0	0	5	25
	C	**0**	**0**	**5**	**36**	**9**	**45**	**8**	**40**
	D	1	7	0	0	1	5	1	5
	E	1	7	1	7	2	10	2	10
4	A	0	0	2	14	1	5	2	10
	B	**2**	**14**	**9**	**64**	**2**	**10**	**7**	**35**
	C	0	0	0	0	2	10	1	5
	D	0	0	0	0	0	0	4	20
	E	11	79	3	21	15	75	6	30
	No Ans.	1	7	0	0	0	0	0	0

Table 2: Assessment Results – Correct answers are shaded.

The first question was asked to determine if students knew the definition of porosity. In the pre-assessment, one student in the control group indicated the correct answer where no one in the treatment group knew the answer. Interestingly, our control group was significantly more successful at learning the definition of porosity than our treatment group. After instruction, all but two or 86% of the control group were successful in answering the definition question. Eleven out of a larger sample of 20 in our treatment group got question 1 correct. It is possible this result was influenced by the student who shouted out his answer at the beginning of the post-assessment. He said out loud that he answered B for number 1. Seven student or 35% also answered B for number 1. We will not be able to determine if these students got the answer wrong due to lack of knowledge or due to the influence of this one peer.

Question 2 was a conceptual question about porosity. Rocks that have similar structure will have the same porosities regardless of the size of the grains in the rock. There were a few students in both the control and treatment groups that indicated they knew this idea before instruction. Three students in the control group and 6 students in the treatment group got this question correct in the pre-assessment. On the post-assessment, there was no change in number of correct responses in the control group. However, 2 of the 3 that got question 2 correct on the post-assessment were not the same individuals that got number 2 correct on the pre-assessment. Regardless, the control group showed little growth in learning this concept. But, the treatment group did show significant improvement on the post-assessment. The number of students in this group who answered correctly doubled.

Question 3 was asked to identify if students knew how to calculate percentages in isolation and not in the context of a problem situation. The question was also very visual. Our presentation to the control group was rather visual, a picturesque Power Point. No one in the control group was able to correctly answer question 3 on the pre-assessment. Five from this control group or 36% were able to answer correctly on the post-assessment. The treatment group showed no improvement on question 3. In fact, the results went down by one student. Nine students came into our lesson indicating that they did know how to calculate percent. However, only 8 students got question 3 correct after instruction.

Question 4 combined the ideas of questions 1 and 3. Students were asked to calculate the porosity of a rock. To do so requires a working definition of porosity and be able to calculate percent. Again the control group showed the most improvement on this question. Two of the 14 from the control group got the question correct on the pre-assessment. This number grew to 9 or 64% correct on the post-assessment. The treatment group did show improvement, but not as much as the control group. The treatment group's number changed from 2 or 10% correct on the pre-assessment to 7 or 35% correct on the post-assessment.

Chapter 7: *Conclusions*

In recent years, there has been an ongoing debate in education as to whether hands-on, problem-based learning is a superior instructional method over traditional didactic instruction (Jonassen and Land, 2012). This research does not answer these questions. But it does recognize that there are benefits to both points of view. It is interesting that the control group showed more improvement on three of our four questions. These three questions, numbers 1, 3, and 4 do have some correlations. The student must know the definition of porosity (question 1) and how to calculate percent (question 3) in order to calculate porosity (question 4). It makes sense that the control group would be more successful than the treatment group on question 4. The lesson practiced the computation of problem 4 twice with all members of the control group using different values. Only the mathematician had practice at calculating porosity in the treatment group. The statisticians might also glean insight to the process because they were responsible for the data collection sheet that contained the formulas. Despite the fact our instructions were to share their findings and understandings with all group members, the reality is that if the student does not do the work, they are less likely to understand. In addition, the program was a bit rushed since students had to make it through different labs.

There are questions that remain for the control group's success. First, the obvious, did the student from the treatment group who said his answer out loud during the post-assessment for question 1 unduly influence others in his group? But beyond this, will the control group still know the answers to questions 1, 3, and 4 a year from now? Or, did they just learn enough to pass the test? Did they receive enough experience with the subject to secure this knowledge into long-term memory?

Were the students of the control group more successful at calculating porosity because they gained a better understanding of the definition and how to calculate percent? Or, did their practice during instruction of how to calculate porosity help them to better understand how to calculate percent and to have a deeper understanding of the definition of porosity? Further research on these questions could greatly improve the process of instruction.

The real understanding the control group gained can be questioned, however. Sixty-four percent were successful in calculating percent porosity on the post-assessment. However, only 36% were able to transfer that knowledge to the general case of calculating percent found in question 3. So it would seem that the control group learned how to calculate percent for this one specific scenario. But it seems doubtful that they would be able to apply percent to a different situation. On the other hand, often students are able to visualize concepts in the context of a problem situation much more effectively than in the case of an abstract problem such as question 3. Here again, more research would be helpful in determining if the problem-based application helped students to have more success on question 4 than they did on problem 3 which was essentially void of context.

The hypothesis examined in this work was supported with question 2. It was proposed students would have more success if given hands-on experiences that helped them to visualize abstract concepts. The students in the treatment group who were allowed to use the 3D prints of enlarged rock received the opportunity to see firsthand that the porosities of rocks with similar structure will be the same independent of their grain size. This is counter-intuitive. In fact, in the post-assessment, more students of the control group (43%) said the rock with the enlarged diagram would have a greater porosity than that of the smaller image. Therefore, it follows that use of 3D prints to enlarge rock allows students to gain greater comprehension of the petrophysical properties of rock. It allows students the opportunity to easily visualize that that previously could not be seen or well understood.

However, with such a small sample size, these results are very preliminary. This research should be extended to a larger number of students. It would also be interesting to adapt the lesson to a wider range of ages. There are opportunities for grade school students to learn about rocks beginning as young as preschool age up to seniors in high school.

Another source of error was collusion during the quizzes. Before the quizzes, students were instructed not to consult their neighbor during the quiz. However, there were still students who looked at their neighbor's answers. Some even very quietly talked to their neighbor.

Our original lesson design was to have our treatment group conduct the lab 4 times, rotating through the stations, each time using a different 3D printed rock. Each time they rotated, they were to assume a new role giving students an opportunity to do every element of the lab. Helpers during the lab reported that students who assumed the role of mathematician or statistician were more likely to get the questions correct than the students who were the geologist or petroleum engineer. Treatment group results may have improved if more time were allowed for more rotations. Greater retention of the new knowledge may result if students are given the chance to learn these petrophysical process in such a visually rich and hands on manner. Another option to conducting this lab would be to have each student do everything on their own if printing enough models is not prohibitively expensive.

There are many improvements that could be made to the porosity lesson. On the original data collection sheet, a place to calculate radius was not provided, nor was a diagram of a cylinder with the dimensions labeled. These were items that students were expected to know prior to instruction, however, they did not. The data collection sheet has been amended and the revision is included in Appendix A.

Students were required to perform mathematics that was most likely not developmentally appropriate. The current mathematics Texas Essential Knowledge and Skills (TEKS) for 6^{th} graders include learning to add and subtract fractions and decimals, multiply and divide whole numbers, to use order of operations without exponents, and to only find volumes of a rectangular prisms (TEA, 2006). The lesson requires students to multiply decimals, use exponents, and calculate volume of a cylinder. However, the TEKS are currently under revision and the proposed 6^{th} grade mathematic skills include higher level skills such as multiplying and dividing positive rational numbers and using exponents. But, the new 6^{th} grade TEKS do not include calculating volume of a cylinder (TEA, 2012). Nevertheless, the lesson can be appropriate for upcoming 6^{th} graders when given a labeled diagram of a cylinder and the formula using 3.14 instead of π.

An additional way to improve the lesson would be to include impermeable samples for comparison with our porous rocks. This would allow students to compare and contrast porous and nonporous medium thus further strengthen their understanding of porosity. The lesson could be extended to include a lab to teach permeability using the 3D printed rocks.

The remaining question that needs to be asked is what are other applications of printing 3D models as an instructional aide for other educational disciplines? In education, 2D images are used to teach, especially when it is not possible to create a 3D representation with traditional technology. A random sampling of teacher opinions was solicited. An American Sign Language teacher asked for a cut away view of the ear and head to scale size. Geometry teachers wanted examples of polyhedrons such as a trapezoidal prism, an irregular cone, conic sections, and shapes that would answer the question of why 1/3 and 4/3 are constants used in the formulas of pyramids, cones, and spheres. The calculus teacher wanted solids of revolution. The biology teachers wanted an enlargement of a cross section of a leaf and a cell showing its organelles. The chemistry teacher requested representations of crystalline structures represented as a simple cubic, as a face-centered cubic, and as a body-centered cubic. The physics teachers wanted representations of electromagnetic waves and mechanical waves. They also wanted a cube, cylinder, and sphere with flux lines to teach Gaussian surfaces. And the health science teacher wanted prints of organs. These applications could potentially increase the visualization of sighted individuals, but consider how much greater these models could serve the visually impaired community. With 3D printers, imagination is our only limitation.

Chapter 8: Applications to Practice

For the purposes of this report, we are asked to reflect on four topics and to speak to how they relate to our experience at the University of Texas in the UTeach*Engineering* MASEE program. Within each topic we are to address specific questions as noted in each section.

DEVELOPING ENGINEERING AWARENESS

This section is to document how the MASEE program has prepared me to represent engineering careers and practices to my future students and why, as well as my specific plans for accomplishing this in my future classroom or other educational endeavors. As a high school mathematics teacher, my motivation to earn a master's degree in engineering education was not so that I could teach engineering. But rather that I want to understand applications of the advanced mathematics I teach to bring relevance and meaning to my instruction. A good number of high school students have no sense that the math they learn has any real importance to their future and will regularly ask, "Why do I need to learn this?" Since beginning this program, I routinely look for applications of their math in engineering and will share different engineering careers that use the math. Most often I do this by showing videos found on the internet to spark my students' interest.

This past school year, we did hold a petroleum engineering career day event at my high school campus. Dr. Maša Prodanović, assistant professor of petroleum engineering at the University of Texas at Austin, led a presentation titled Fossils in My Gas Tank. We invited students enrolled in Earth and space science, environmental science, advanced quantitative reasoning, and engineering courses. Dr. Prodanović talked about energy and its importance to society, where we find oil and gas, and how fluids move through rock.

The talk was very informative and seemed to spark the interest of many who attended. They were very intrigued to hear from a college professor and to learn from an expert in her field. I hope to offer engineering career days on an annual basis at my school and to expand the presentation to include a variety of different fields in engineering.

DEVELOPING ENGINEERING HABITS OF MIND

In this section, we are to include examples of how we have employed engineering habits of mind and how we will facilitate our students' development of these habits. I am a high school mathematics teacher. In a mathematics classroom, it is difficult to incorporate engineering habits of mind on a regular basis. However there are correlations of the engineering habits of mind to practices in mathematics (Engineering Your World, 2013). The mathematics standards of the Common Core begins with Standards for Mathematical Practice that include "processes and proficiencies" that are applicable to all levels of students. These standards have many commonalities with the UTeach-*Engineering* habits of mind (Common Core, 2014). The new Texas Essential Knowledge and Skills will include Process Standards that will be the same for every mathematics course in the state of Texas. These standards also have connections with engineering habits of mind (TEA, 2012). In addition to these standards, the Education Development Center, Inc. (EDC) established mathematical habits of mind that have used them to organize mathematics curriculum (Cuoco et al., 2010). In Table 3, I have attempted to organize the UTeach*Engineering* habits of mind and to find correlations to the EDC's mathematical habits of mind and to the mathematical process standards presented by the Texas Education Agency and the Common Core.

UTeach*Engineering* Habits of Mind	TEKS Mathematical Process Standards	Common Core Standards for Mathematical Practice	EDC Mathematical Habits of Mind
Systems Thinking Systems thinking is a set of habits or practices in a framework based on the belief that the parts of a system can best be understood in the context of relationships with each other and with other systems, rather than in isolation. Emphasis is placed on a top-down perspective, the system environment, and critical interfaces.	Apply mathematics to problems arising in everyday life, society, and the workplace.	Look for and make use of structure.	Performing thought experiments.
System Understanding and Quantification Students learn to characterize the system using quantitative techniques common in the practice of engineering, enabling a deeper understanding of the system.	Use a problem-solving model that incorporates analyzing given information, formulating a plan or strategy, determining a solution, justifying the solution, and evaluating the problem-solving process and the reasonableness of the solution. Analyze mathematical relationships to connect and communicate mathematical ideas.	Reason abstractly and quantitatively. Look for and express regularity in repeated reasoning.	Finding, articulating, and explaining patterns.
Creativity Engineers think creatively within well-defined constructs. Students experience a variety of design approaches using concept generation and selection techniques employed by engineers.	Create and use representation to organize, record, and communicate mathematical ideas.	Make sense of problems and persevere in solving them.	Creating and using representations. Generalizing from examples
Verification Engineers must verify that their selected concepts satisfies the design constraints, requirements, and customer needs.	Display, explain, and justify mathematical ideas and arguments using precise mathematical language in written or oral communication.	Model with mathematics.	Expecting mathematics to make sense.
Communication Students learn good communication skills and unique aspects of how engineers document and present design ideas and analytical results. Emphasis is placed on creating communication artifacts to ensure accurate interpretation by others (with an eye toward clarity, detail, precision of process, and completeness.)	Communicate mathematical ideas, reasoning, and their implications using multiple representations, including symbols, diagrams, graphs, and language as appropriate.	Construct viable arguments and critique the reasoning of others.	Articulating generality in precise language.
Collaboration Students learn the importance of working on multidisciplinary teams and understand what type of team member they are. Emphasis is placed on engineering personality types, integrated product teams, and examples of successful engineering teams.			
Common Engineering Tools and Techniques Students learn to use common tools and techniques that engineers employ to approach and solve problems and to manage projects. Approach and application are based on the design challenge at hand.	Select tools, including real objects, manipulatives, paper and pencil, and technology as appropriate, and techniques, including mental math, estimation, and number sense as appropriate, to solve problems.	Use appropriate tools strategically. Attend to precision.	

Table 3: Correlation of the UTeach*Engineering* Habits of Mind with Mathematical Habits of Mind and Process Standards.

It could be argued that the mathematical habits of mind and the mathematics standards presented above could be aligned differently to the engineering habits of mind. However, I believe there are sound correlations nonetheless. The only engineering habit of mind that is not shown in the mathematics standards is collaboration. Even though collaboration is not a written standard, we find argument for collaboration in mathematics as early as 1974 (Bagnato, 1974) and I see its application practiced in mathematics classrooms on a regular basis. Therefore, even though the standard for collaboration in mathematics is not written, I do believe it is an unspoken habit of mind in mathematics. Although I most likely will not be practicing official engineering habits of mind regularly in my classrooms, there are similar habits my students do experience every day in my classroom.

DEVELOPING AN UNDERSTANDING OF THE DESIGN PROCESS

In this section, we are to detail how our research or design project contributed to our understanding of the design process. We are also to include ways in which we feel that our work was not representative of the design process as presented by UTeach*Engineering*. My research for the purposes of this report was not a design project, therefore, developing the porosity lab did not encompass all aspects of an engineering design process. However, there are correlations of the creation of this lesson plan to the UTeach*Engineering* design process which is a circular plan as follows:

1. Identify the need.
2. Describe the need and characterize and analyze the system.

3. Generate and select a concept
4. Embody, test, evaluate, and refine the concept.
5. Finalize and share the design.
6. Evolve the design.

For this report, I was given a 3D print of an enlargement of a rock and asked to design a lesson plan that would be of benefit to grade school students. I began with a study of rocks and petrophysics and a study of the Texas Essential Knowledge and Skills to determine concepts that could be taught using the 3D prints. I determined there was a need for teaching the ideas of porosity and permeability. Through this process, I identified and described the need. We further narrowed down our concept selection to only porosity given our time constraints. We then began exploring appropriate pedagogy to teach porosity and embodied the lesson in a formal lesson plan. We then shared our lesson with the Breakthrough 6th grade program from Manor ISD. After presenting the lesson, we evaluated what went well and what needed improvements and adjusted our lesson plan. The revised lesson plan is included in Appendix A of this report. We also hope to extend this lesson to include permeability.

Developing Knowledge for and of Engineering Teaching

This section is to include specifics of how what we have learned in the MASEE program will affect (or has already affected) our practice in engineering education. In the Advanced Quantitative Reasoning (AQR) class I teach at Vista Ridge High School, we have two units that students find rather challenging. These are the study of functions and recursion through analyzing linear, exponential, logistic, and sinusoidal patterns. In order to attempt to create greater interest in these units, for the past two school years I have integrated the Fuel Efficient Vehicle Challenge from our Engineering Design Methods course. I have students extend the challenge to create data tables and graphs of the speeds and accelerations of their cars to find quadratic and linear patterns. In my year end survey to kids, many tell me this project is their favorite activity of the year. I am continuing to revise and improve this lesson and hope to share it with others in the state of Texas who also teach this course. I would also like to add the earthquake simulation challenge from our Engineering Energy Systems course of the MASEE program to AQR during our sinusoidal unit. I recently attended National Instruments' NI Week to learn about the equipment necessary for this project. I also gained additional ideas on creating a new project using data collecting cameras to observe the growth of bacteria in a petri dish over time. Similar to how STL files are created, we could count pixels to calculate the area of space occupied by the bacteria and develop the logistics trends evident with growth in restricted spaces.

Functional relationships exist in petrophysics as well. Specifically, correlations between permeability and porosity are very common. Henry Darcy established a proportional relationship expressing permeability as a function of grain diameter squared. Darcy's Law has been generalized as:

$$k = f_1(s)f_2(n)d^2$$

where $f_1(s)$ is called the shape factor, $f_2(n)$ is the porosity factor, and d is the average diameter of the grains. The expression $f_1(s)f_2(n)$ has been recognized as a single dimensionless coefficient C giving us the quadratic relationship:

$$k = Cd^2$$

There are possibilities to explore these relationships using our 3D printed rocks specifically for AQR. See Figure 18 (Bear, 1988).

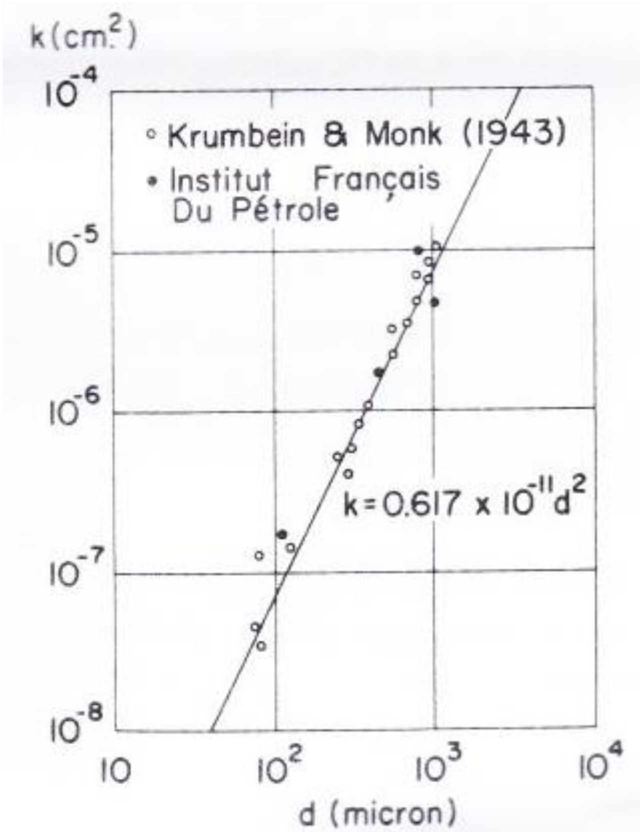


Figure 18: Variation of intrinsic permeability (k) with grain diameter (d) in granular porous media (Bear, 1988).

In April 2014, my advising professor Maša Prodanović organized a kitchen lab exhibit at the Thinkery, Austin's newest children's museum that emphasizes STEM disciplines. We created several stations to teach petrophysics to the young patrons of the Thinkery. Children completed a pre- and post-assessment using question 21 found in Appendix D and we did find that some of the older children improve their understanding of rocks. However most of the younger ones simply drew the same picture of a big blue cavern underground in the post-assessment that they did in the pre-assessment.

While at the Thinkery, I was inspired to consider the possibilities of creating a two story transparent water well. See Appendix E for our preliminary proposal that we plan to present to the Thinkery. We wish to install a well that would allow children to hand pump water from a simulation of the Edwards Aquifer and to be able to view the mechanics of the well. This idea led me to reach out to the Barton Springs/Edwards Aquifer Conservation District (BSEACD) to gain knowledge about the best educational stance we would like to promote and to learn of potential sources of funding. Robin Gary, the Senior Public Information and Education Coordinator of the BSEACD, was a wealth of information about the Edwards Aquifer and helped me to narrow the message we would teach which should be conservation of water and avoidance of water pollutants. I have also contacted a former student of mine, Kaitlin Kyle, who is currently a student in the Fine Arts School at the University of Texas at Austin. Kaitlin is creating a translucent design to cover the two story windows in front of our well and Edwards Aquifer to illustrate our structure and to give location perspective. It is art that gives meaning to our science, technology, engineering, and math changing the acronym STEM to STEAM. It was Harvey White who first used the phrase STEAM in 2010 to promote the creativity and innovation that art adds to STEM (Eger, 2010). I am very excited about this project and hope to continue working with the BSEACD to hopefully see its instillation. I have one additional upcoming opportunity to teach engineering. But this one will be for the instruction of teachers. At the urging of Dr. Prodanović and Dr. Olson, I applied to present my porosity lesson plan at the annual Conference for the Advancement of Science Teaching (CAST). I was accepted and will be a presenter at CAST in November of this year. I hope to add a lesson on permeability by this time. I am looking forward to this conference and the future opportunities my work with UTeach will bring.

Appendix A

Porosity Lesson Plan

Learning Outcomes:

1. The learner will comprehend the structure of water and fossil fuel reservoirs.
2. The learner will understand the meaning of porosity of rock.
3. The learner will calculate porosity of sub-terrain rock.

Essential Questions:

1. How are water and fossil fuels stored below the Earth's surface?
2. What is porosity of rock and why is it important to geologist and petroleum engineers?
3. How do you calculate the porosity of rock?

Key Vocabulary:

Porosity
Permeability
Sedimentary Rock
Igneous Rock
Metamorphic Rock

Materials:

At each lab station of 3-4 students:

- Number each station
- Lab Roles – provided below
- Magnified 3-D printed rock – cylindrical shape like a core sample
  - Each station should have a different 3D printed rock
  - Samples should include two different levels of magnification of each type
- A beaker or other open water tight container
  - Must be the same diameter as the 3D printed rock
- An actual core sample that has a similar structure to the 3D printed rock
- Graduated cylinder filled with water
  - Capacity should be at least the same as the volume of pore space of the 3D printed rock
- Ruler
- A wash bottle filled with water
- Geologist field lens or magnifying glass
- Calculator
- Data collection sheet – provided below
- Scratch paper
- Writing utensils

Material (continued):

Pitcher of water
Bucket to collect used water
Paper towels
Natural Sponges
Whole class data collection sheet – provided below
Instructional Power Point – provided in Appendix B
For each student: Assessment – question bank provided in Appendix D

TEKS:

Kindergarten

(7) Earth and space. The student knows that the natural world includes earth materials. The student is expected to:

(A) observe, describe, compare, and sort rocks by size, shape, color, and texture;

(C) give examples of ways rocks, soil, and water are useful.

1st Grade

(7) Earth and space. The student knows that the natural world includes rocks, soil, and water that can be observed in cycles, patterns, and systems. The student is expected to:

(A) observe, compare, describe, and sort components of soil by size, texture, and color;

(C) gather evidence of how rocks, soil, and water help to make useful products.

2nd Grade

(7) Earth and space. The student knows that the natural world includes earth materials. The student is expected to:

(A) observe and describe rocks by size, texture, and color.

3rd Grade

(7) Earth and space. The student knows that Earth consists of natural resources and its surface is constantly changing. The student is expected to:

(A) explore and record how soils are formed by weathering of rock and the decomposition of plant and animal remains.

4th Grade

(7) Earth and space. The students know that Earth consists of useful resources and its surface is constantly changing. The student is expected to:

(B) observe and identify slow changes to Earth's surface caused by weathering, erosion, and deposition from water, wind, and ice; and

(C) identify and classify Earth's renewable resources, including air, plants, water, and animals; and nonrenewable resources, including coal, oil, and natural gas; and the importance of conservation.

5th Grade

(7) Earth and space. The student knows Earth's surface is constantly changing and consists of useful resources. The student is expected to:

(A) explore the processes that led to the formation of sedimentary rocks and fossil fuels;

(D) identify fossils as evidence of past living organisms and the nature of the environments at the time using models.

6th Grade

(10) Earth and space. The student understands the structure of Earth, the rock cycle, and plate tectonics. The student is expected to:

(A) build a model to illustrate the structural layers of Earth, including the inner core, outer core, mantle, crust, asthenosphere, and lithosphere;

(B) classify rocks as metamorphic, igneous, or sedimentary by the processes of their formation.

Earth & Space Science

(8) Earth in space and time. The student knows that fossils provide evidence for geological and biological evolution. Students are expected to:

(A) analyze and evaluate a variety of fossil types such as transitional fossils, proposed transitional fossils, fossil lineages, and significant fossil deposits with regard to their appearance, completeness, and alignment with scientific explanations in light of this fossil data.

(12) Solid Earth. The student knows that Earth contains energy, water, mineral, and rock resources and that use of these resources impacts Earth's subsystems. The student is expected to:

(B) describe the formation of fossil fuels, including petroleum and coal.

Process:

A. Opening the Lesson – As a whole group discussion, ask students to describe their understanding of how water is held underground. Show a sponge and demonstrate how a sponge can hold water. Ask students if they believe rocks can also hold water like a sponge and ask students to raise their hand if they say yes and then have a show of hands of those who say no. Then share the learning objectives and essential questions and explain that today, students will assume the role of geologists. Ask students to recall the rock cycle. Explain porosity and how sedimentary rock can be porous. Explain how the 3D printed rock is an enlargement of actual rock, similar to how you would see rock when under a microscope. Show all through a power point presentation. See Appendix B.

B. Lab Instructions – Describe what students will find at each lab station. Groups of 4 will assume the roles listed below. After the lab is completed at one station, groups will rotate to a station with a 3D printed rock of a different size. As they rotate, students should switch roles. Groups should attempt to rotate 4 times so that all students will get to assume each role. Each group member is responsible to each other to make sure all are aware of and all agree with their discoveries.

C. Lab Roles

a. Geologist – responsible for examining the rocks.

i. Measure the diameter and height of the 3D printed rock in centimeters.

ii. Use the wash bottle to pour water over the actual rock and witness the water seep into the rock.

iii. Use the field lens or magnifying glass to observe the structure of the actual rock and compare it to the structure of the 3D printed rock.

b. Petroleum Engineer – responsible for conducting the experiment.

i. Place the 3D printed rock in the container.

ii. Note the initial volume of water in the graduated cylinder.

iii. Pour water from graduated cylinder to the top of the 3D Printed rock.

iv. Note the final volume of water in the graduated cylinder.

v. Empty the container after taking your measurements and shake out water from the 3D print and container.

c. Mathematician – responsible for all calculations.

i. Calculate the radius.

ii. Calculate volume of the 3D printed rock using the formula $V = 3.14r^2h$.

iii. Calculate the volume of the pore space by subtracting the final volume of the water in the graduated cylinder from the initial volume of the water.

iv. Calculate the percent porosity of the 3D printed rock by dividing the volume of the pore space by the total volume of the 3D printed rock and then multiply by 100.
% Porosity = Vol. of Pore Space ÷ Total Vol. of Rock x 100

d. Statistician – responsible for completing the data collection sheet.

i. Record the station number.

ii. Record the diameter and height of the 3D printed rock in centimeters.

iii. Record the calculated radius.

iv. Record the calculated volume of the 3D printed rock in cubic centimeters.

v. Record initial volume of water in the graduated cylinder.

vi. Record the final volume of the water in the graduated cylinder.

vii. Record the calculated volume of the pore space.

viii. Record the calculated porosity.

ix. Report porosity to the whole class data collection sheet.

D. Whole Group Summary – When all have completed the stations, collect students for a whole group discussion. Examine the whole class data collection sheet and look for outliers, errors produced by rounding, or errors in the data. Ask students to compare/contrast the porosity findings of the different stations. We should observe that all porosities of 3D printed rocks with similar structures are very close in value. Seek to clarify understandings or misunderstandings.

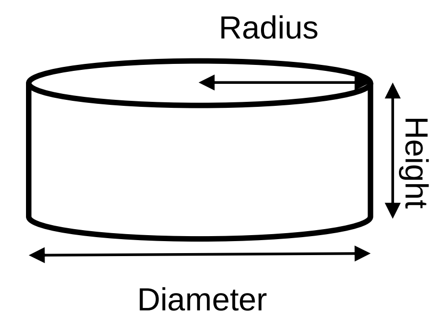
Note: The Data Collection Sheet that follows is a corrected version from that used during our study as discussed in our conclusions in chapter 7. The original form did not include the calculation for radius. It also did not include the diagram of a cylinder.

Name ______________________________

Date ________________ **Period** ______

Porosity Lab
Data Collection Sheet

Note that $1cm^3 = 1ml$



Station Number	Total Volume of 3D Printed Rock (cm^3)				Volume of Pore Space of 3D Printed Rock (ml)			% Porosity of 3D Printed Rock
	Diameter (cm)	Radius (r) (cm) Diameter ÷ 2	Height (h) (cm)	$V = 3.14r^2h$ (cm^3)	Initial Volume of Water (ml)	Final Volume Of Water (ml)	Initial Volume – Final Volume (ml)	Volume of Pore Space ÷ Total Volume ×100

% Porosities
Whole Class Data Collection Sheet

		Station Number					
		1	2	3	4	5	6
Group	1						
	2						
	3						
	4						
	5						
	6						

STATION No. ____

Lab Roles

Geologist – responsible for examining the rocks.

1. Measure the diameter and height of the 3D printed rock in centimeters.
2. Use the wash bottle to pour water over the actual rock and witness the water seep into the rock.
3. Use the field lens or magnifying glass to observe the structure of the actual rock and compare it to the structure of the 3D printed rock.

Petroleum Engineer – responsible for conducting the experiment.

1. Place the 3D printed rock in the container.
2. Note the initial volume of water in the graduated cylinder.
3. Pour water from graduated cylinder to the top of the 3D Printed rock.
4. Note the final volume of water in the graduated cylinder.
5. Empty the container after taking your measurements and shake out water from the 3D print and container.

Mathematician – responsible for all calculations.

1. Calculate the radius of the 3D printed rock.
2. Calculate volume of the 3D printed rock using the formula V=3.14r^2 h.
3. Calculate the volume of the pore space by subtracting the final volume of the water in the graduated cylinder from the initial volume of the water.
4. Calculate the percent porosity of the 3D printed rock by dividing the volume of the pore space by the total volume of the 3D printed rock and then multiply by 100.
   % Porosity = Vol. of Pore Space ÷ Total Vol. of Rock x 100

Statistician – responsible for completing the data collection sheet.

1. Record the station number.
2. Record the diameter and height of the 3D printed rock in centimeters.
3. Record the calculated radius of the 3D printed rock in centimeters.
4. Record the calculated volume of the 3D printed rock in cubic centimeters.
5. Record initial volume of water in the graduated cylinder.
6. Record the final volume of the water in the graduated cylinder.
7. Record the calculated volume of the pore space.
8. Record the calculated porosity.
9. Report porosity to the whole class data collection sheet.

The Rules

1. If you have only 3 in your group, the Mathematician will also serve as the Statistician.
2. Work quickly, we want you all to go to at least 4 stations.
3. As you rotate to a new station, you will also rotate your roles.
4. Each group member is responsible to each other to make sure all are aware of and all agree with your discoveries.

Appendix B

Porosity Lesson Power Point Presentation – Treatment Group

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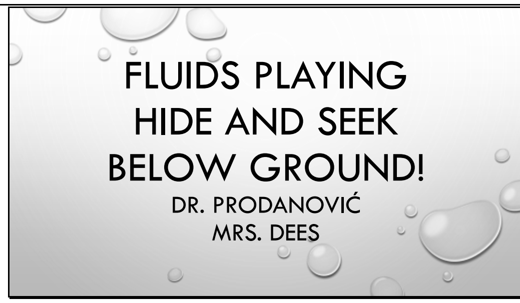
<tr><td>Slide 1</td><td>
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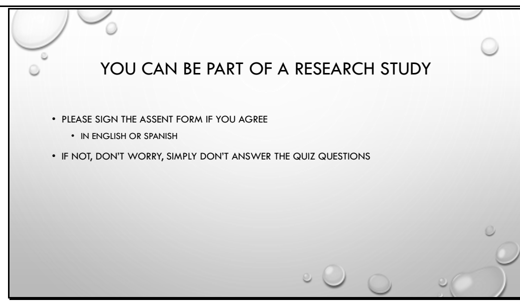
<tr><td>Slide 2</td><td>
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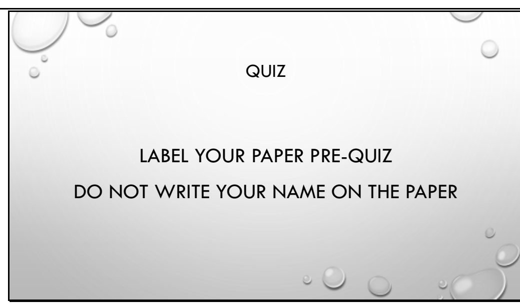
<tr><td>Slide 3</td><td>
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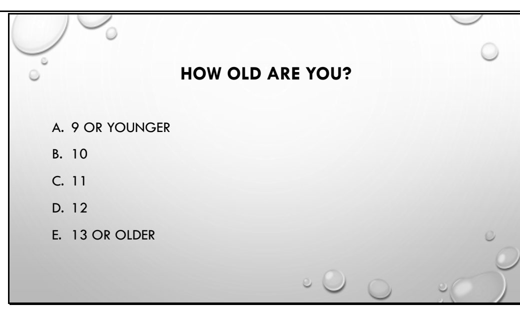
<tr><td>Slide 4</td><td>
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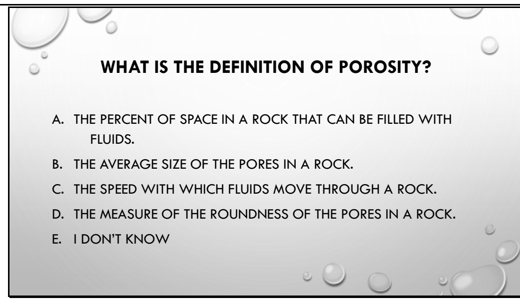
<tr><td>Slide 5</td><td>
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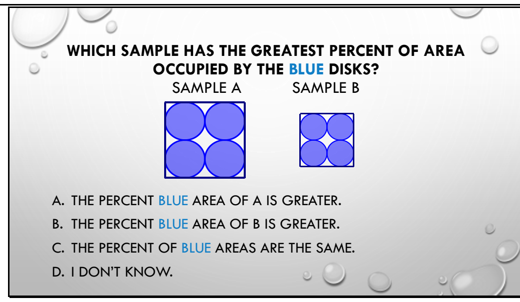
<tr><td>Slide 6</td><td>
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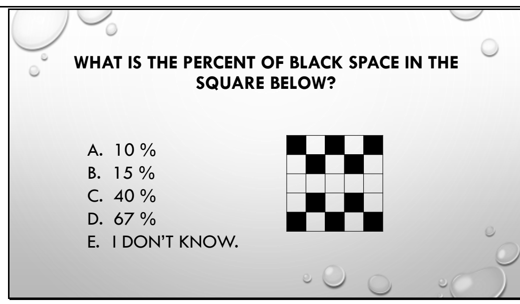
<tr><td>Slide 7</td><td>
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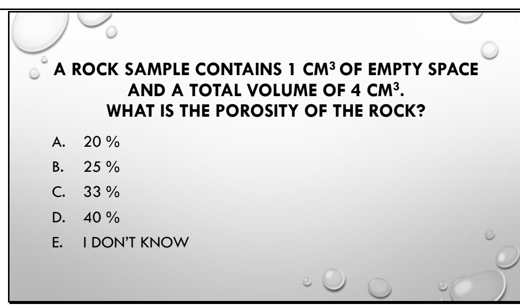
<tr><td>Slide 8</td><td>
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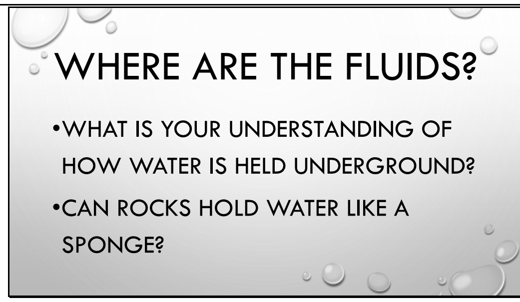
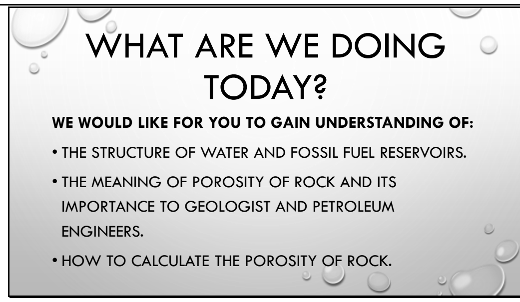
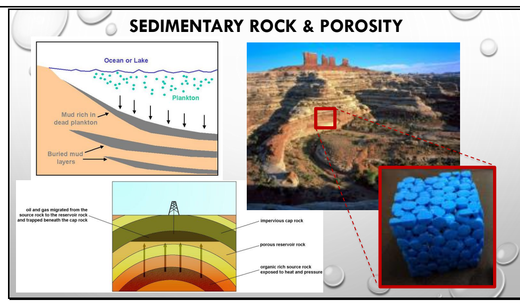
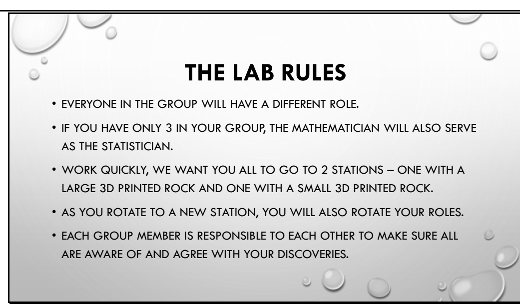
Slide 9	 	
Slide 10	 	
Slide 11	 Sources: Top-Left: Bratton, 2010 Top-Right: Herbert, 2014 Bottom-Left: Shepherd, 2002 Bottom-Right: Prodanović, 2014	Plankton, sand, cement, and other sediment in bodies of water settle. Over time, layers of sediment become cemented together creating sedimentary rock. We see the layers when the water recedes forming canyons. Also over time, the plankton decomposes to form fossil fuels. Because of their low densities, fossil fuels will migrate towards the Earth's surface until contained by an impervious cap rock creating an oil and gas reservoir. Today in your lab, you will use 3D printed rocks that are an enlargement of actual rock so that you can learn the structure of sedimentary rocks. Define porosity.
Slide 12	 	

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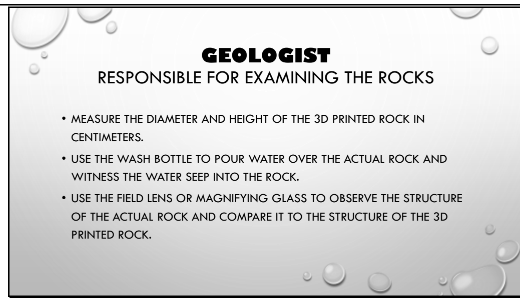

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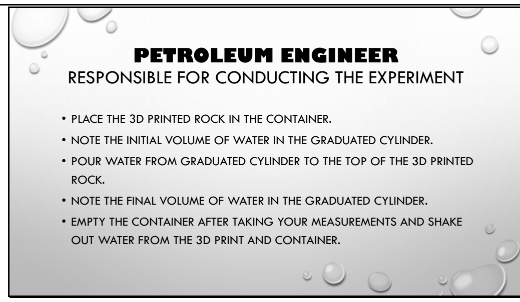

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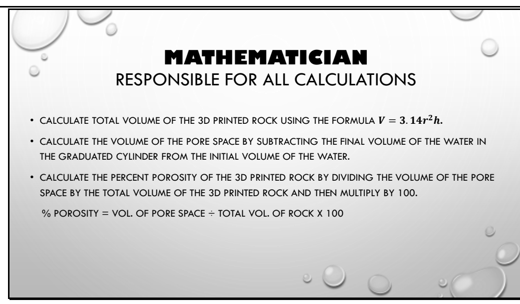

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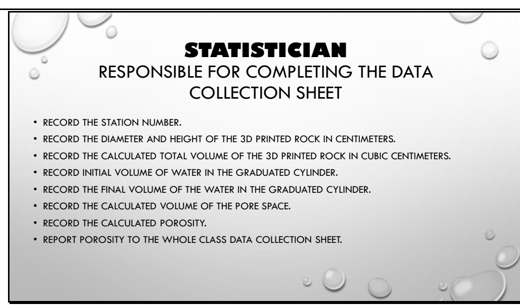

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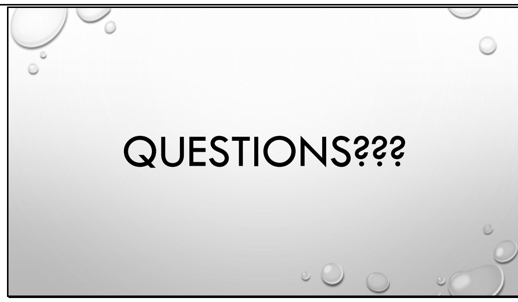
<tr><td>Slide 17</td><td>
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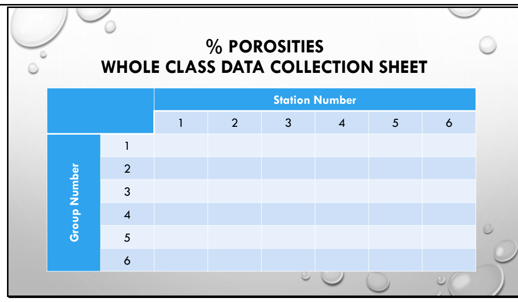
<tr><td>Slide 18</td><td>
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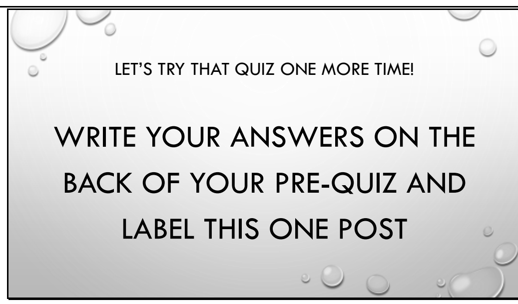
<tr><td>Slide 19</td><td>
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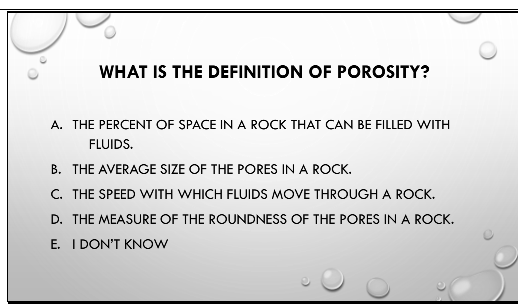
<tr><td>Slide 20</td><td>
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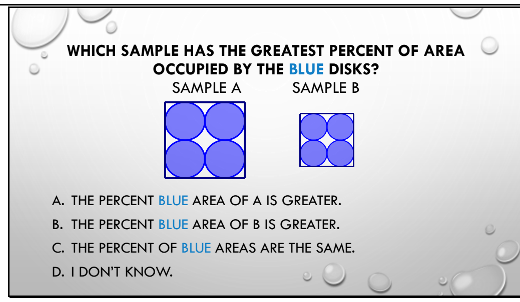

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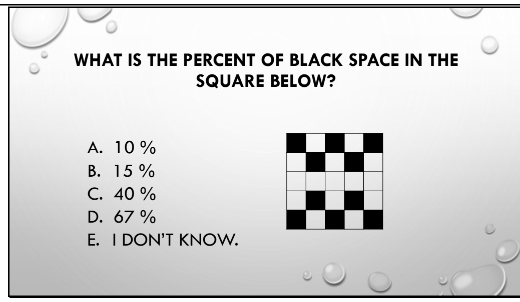

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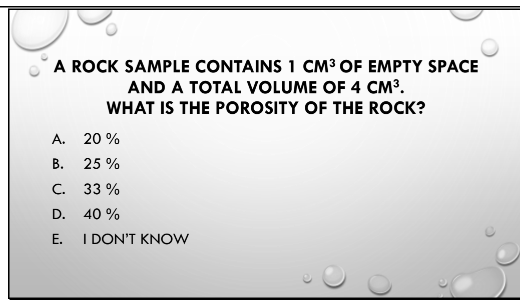

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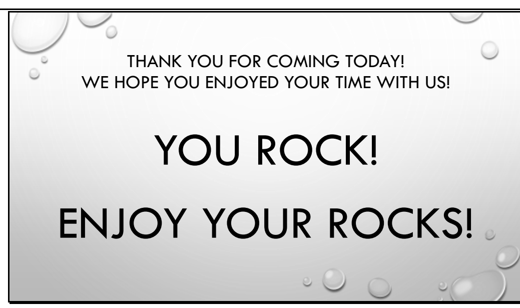
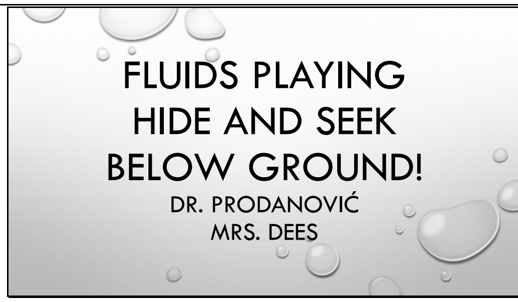
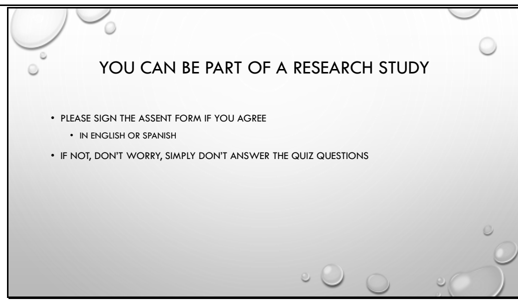
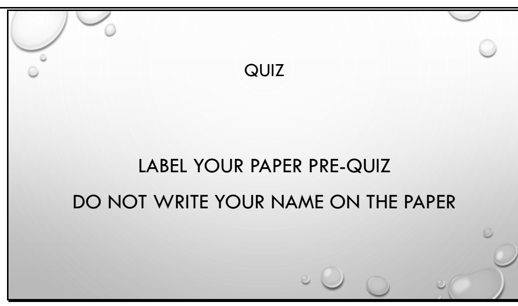
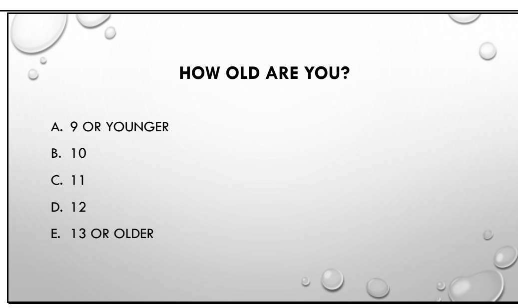


Appendix C

Porosity Lesson Power Point Presentation – Control Group

Slide 1		
Slide 2		Allowing the time to sign the assent form or not.
Slide 3		
Slide 4		

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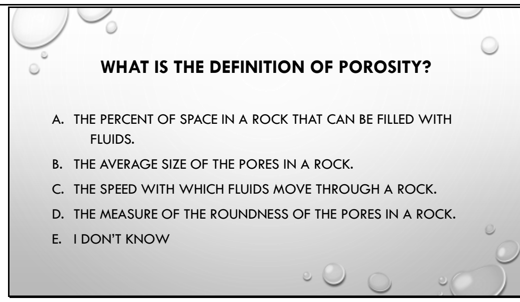
<tr><td>Slide 5</td><td>
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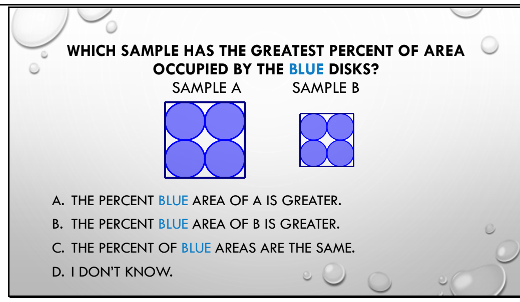
<tr><td>Slide 6</td><td>
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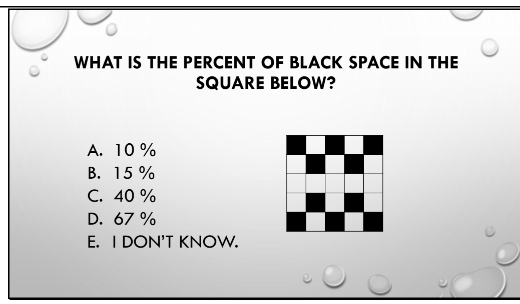
<tr><td>Slide 7</td><td>
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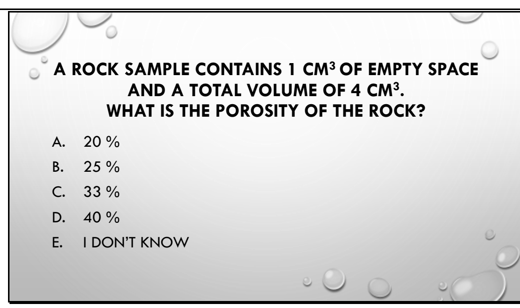
<tr><td>Slide 8</td><td>
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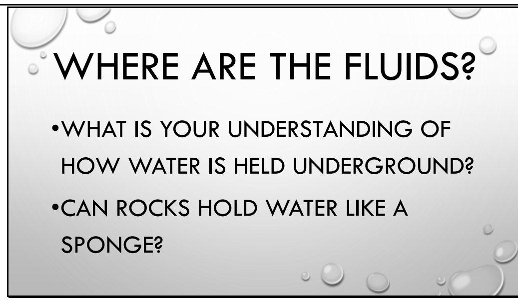
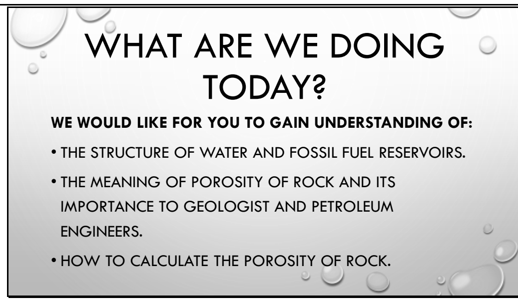
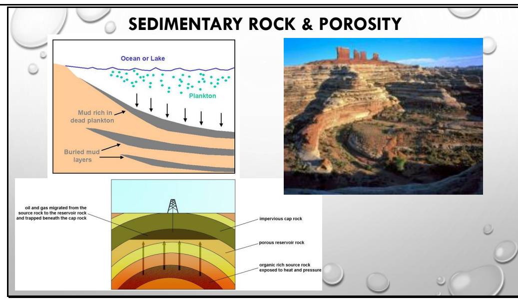
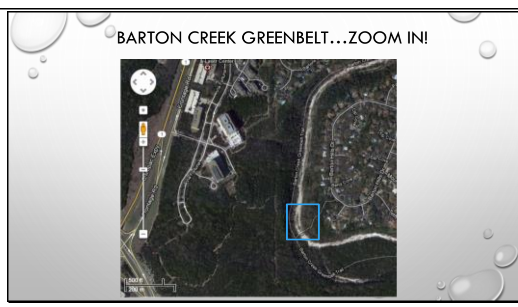
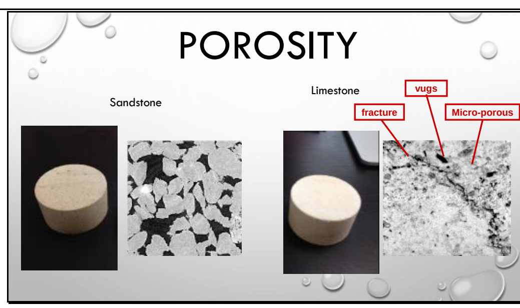
Slide 9	 	
Slide 10	 	
Slide 11	 Sources: Top-Left: Bratton, 2003 Top-Right: Herbert, 2014 Bottom-Left: Shepherd, 2002	Plankton, sand, cement, and other sediment in bodies of water settle. Over time, layers of sediment become cemented together creating sedimentary rock. We see the layers when the water recedes forming canyons. Also over time, the plankton decomposes to form fossil fuels. Because of their low densities, fossil fuels will migrate towards the Earth's surface until contained by an impervious cap rock creating an oil and gas reservoir.
Slide 12	 Source: Google Maps	When it rains it pours, and the water moves through fractures and out of the system exceedingly fast (thereby causing flash-flooding); after a dry period, due to water/air competition in this heterogeneous reservoir, the storage matrix might be 90% full, but wells go dry.

Slide 13	 Source: Prodanović, 2014	When it rains it pours, and the water moves through fractures and out of the system exceedingly fast (thereby causing flash-flooding); after a dry period, due to water/air competition in this heterogeneous reservoir, the storage matrix might be 90% full, but wells go dry.
Slide 14	 Source: Prodanović, 2014	Core samples of sandstone (left) and limestone (right).
Slide 15		
Slide 16	 Source: Prodanović et al., 2009 & 2014	Porosity: There is empty space within rocks, called pores, where fluids hide. Porosity – The percent of pore space in a rock. To Calculate Porosity – Divide the volume of the Pore Space by the Volume of the Rock.

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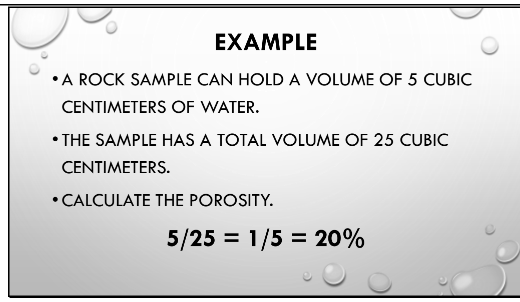
<td>
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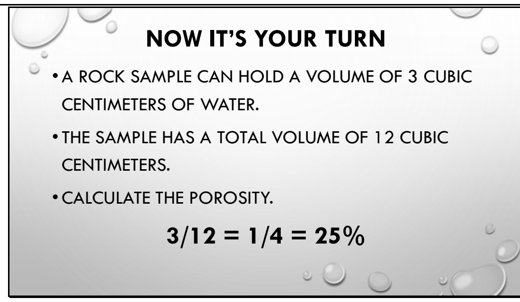
<td>
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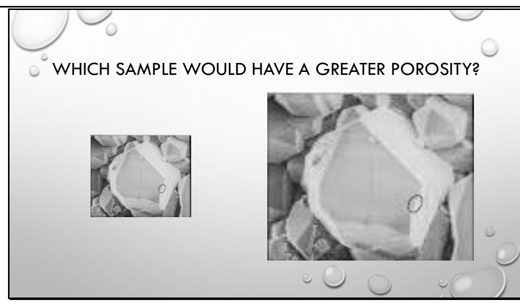
<td>

Source: Jordan & Kelloes, 2014</td>
<td>The porosities of similarly structured rocks are the same regardless of their size. They both contain the same percentage of empty space.</td>
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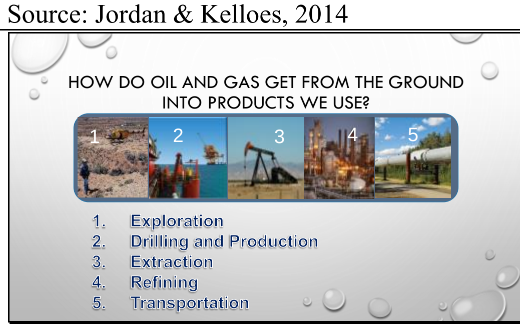
<td>

Source: Energy 4 Me, 2014</td>
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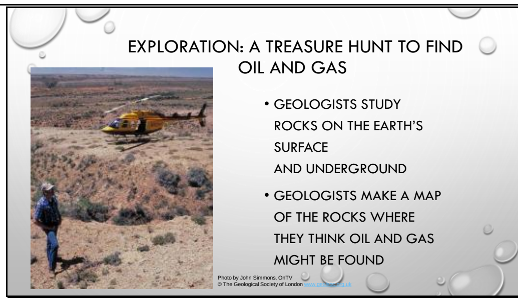
<td>

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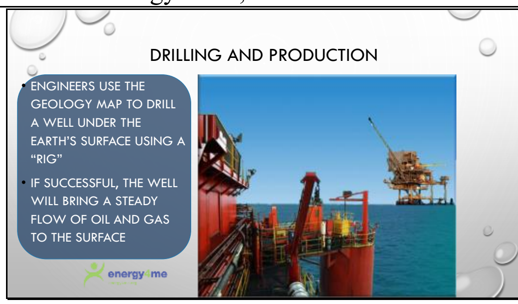
<td>

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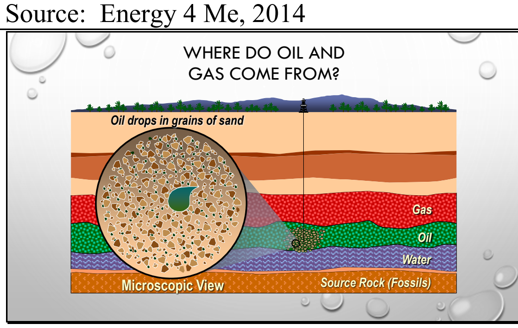
<td>

Source: Energy 4 Me, 2014</td>
<td>Oil and gas aren't found in a big underground lake! Engineers drill down through layers of sand and rock to reach the rock formations that contain oil and gas.</td>
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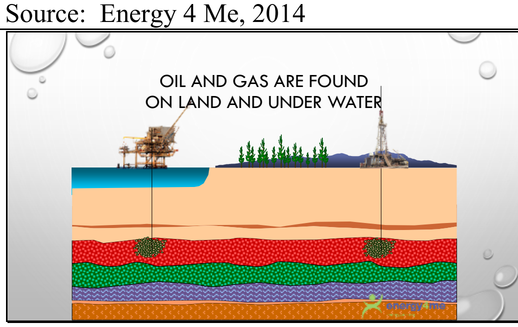
<td>

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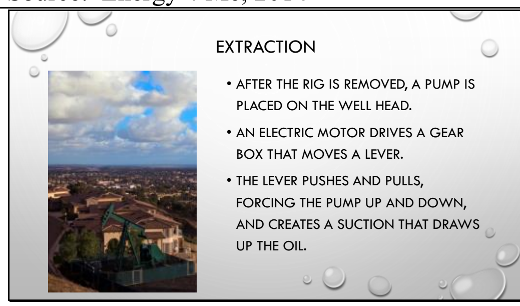
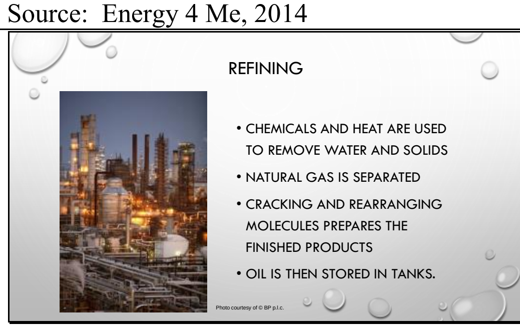
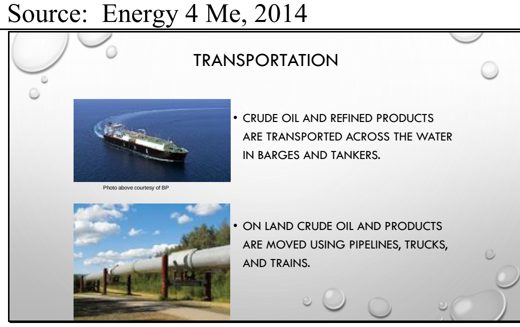
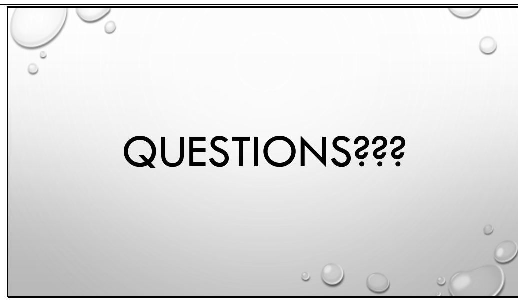
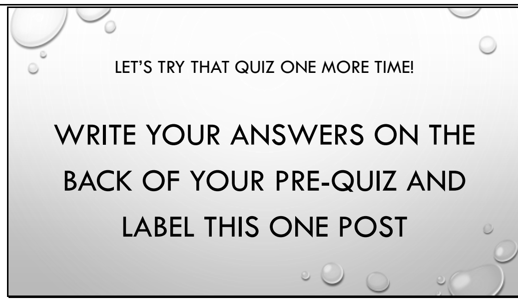
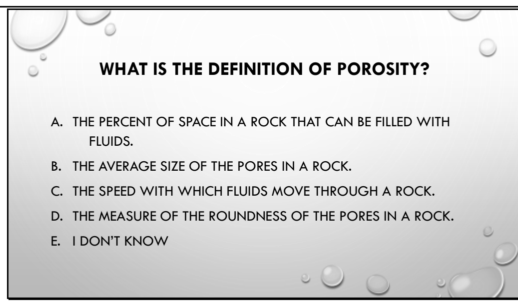
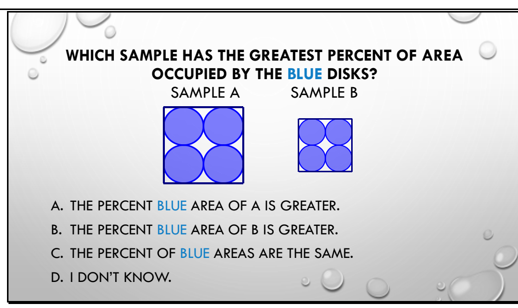
Slide 26	 Source: Energy 4 Me, 2014	
Slide 27	 Source: Energy 4 Me, 2014	
Slide 28	 Source: Energy 4 Me, 2014	

Slide 29		
Slide 30		
Slide 31		
Slide 32		

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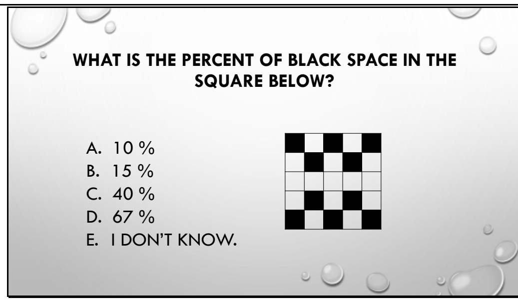
<tr><td>Slide 33</td><td>
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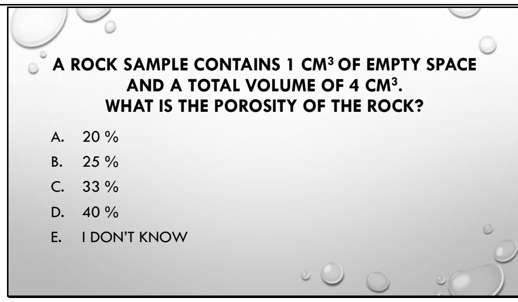
<tr><td>Slide 34</td><td>
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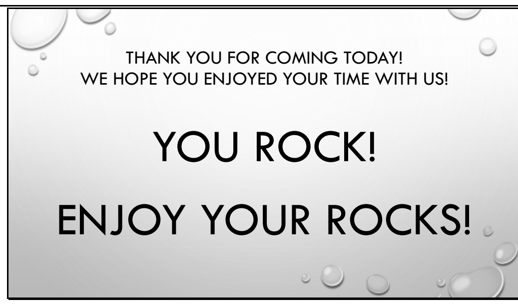
<tr><td>Slide 35</td><td>
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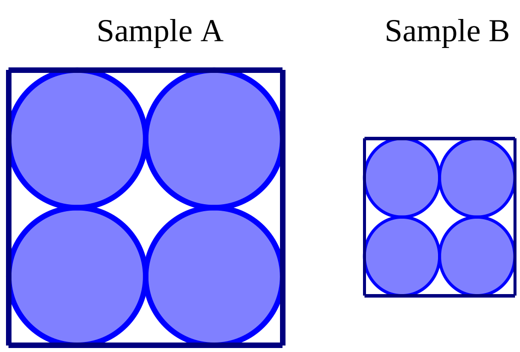
Appendix D

Porosity and Permeability Question Bank

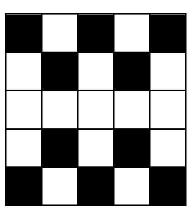
1. What is the definition of porosity?
   A. The percent of space in a rock that can be filled with fluids.
   B. The average size of the pores in a rock.
   C. The speed with which fluids move through a rock.
   D. The measure of the roundness of the pores in a rock.

2. Which sample has the greatest percent of area occupied by the blue disk?



   A. The percent blue area of A is greater.
   B. The percent blue area of B is greater.
   C. The percent of blue areas are the same.

3. What is the percent of black space in the square below?



   A. 10 %
   B. 15 %
   C. 40 %
   D. 67 %

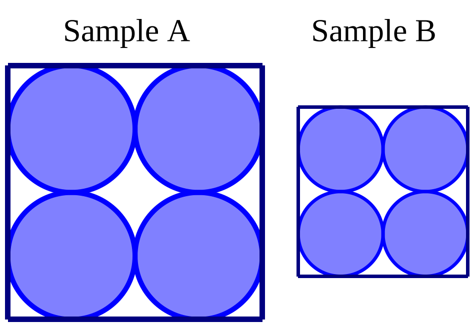
4. A rock sample contains 1 cm^3 of empty space and a total volume of 4 cm^3. What is the porosity of the rock?

   A. 20 %
   B. 25 %
   C. 33 %
   D. 40 %

5. What is the definition of permeability?
   A. The percent of space in a rock that can be filled with fluids.
   B. The average size of the pores in a rock.
   C. The speed with which fluids move through a rock.
   D. The measure of the roundness of the pores in a rock.

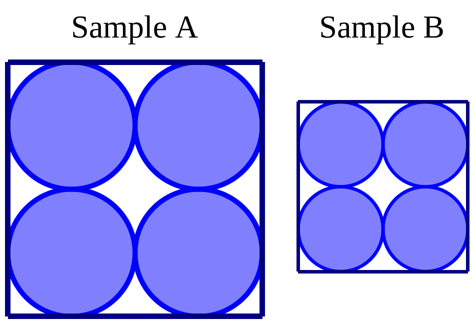
6. Which is most important in determining the amount of ground water, fossil fuel, or gas that can be stored within a rock?
   A. the rock's porosity
   B. the rock's permeability
   C. the rock's hardness
   D. the rock's geologic age

7. The diagram below represents rocks of the same size composed of the same material, but with different grain sizes. Which property is always the same for the two samples?



   A. Porosity
   B. Saturation
   C. Permeability
   D. Capillarity

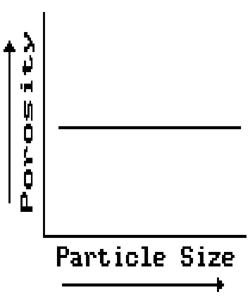
8. The diagram below represents two rocks cut with identical dimensions in the shape of a cube. The circles represent the grains and the spaces between the circles represent the pore spaces. Which of the below statements is true?



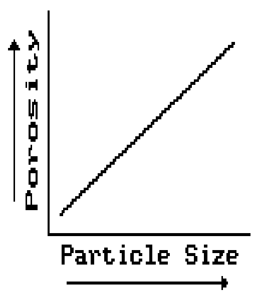
A. The porosity of Sample A is greater than the porosity of Sample B.
B. The porosity of Sample B is greater than the porosity of Sample A.
C. The porosity of Sample A is equal to the porosity of Sample B.

9. Which graph best represents the relationship between porosity and particle size for rock samples of uniform size, shape, and packing?

A,



C.



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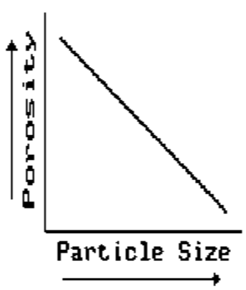
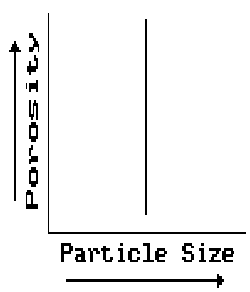
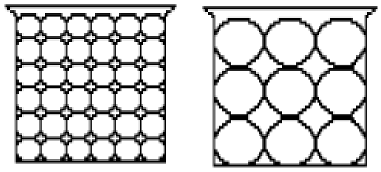


D.



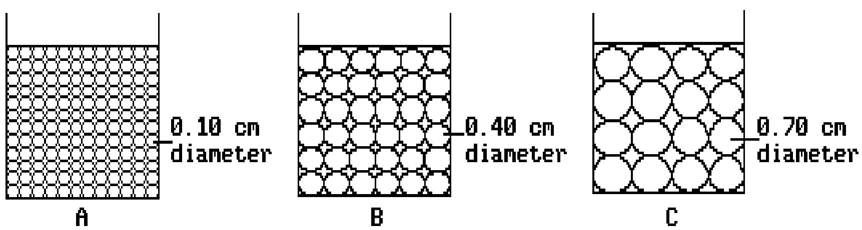
10. The diagrams below represent two identical containers filled with nonporous beads.



Compared to the model containing larger beads, the model containing smaller beads has:

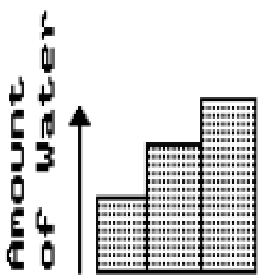
A. greater permeability and greater porosity
B. less permeability and greater porosity
C. greater porosity and greater capillarity
D. less permeability and greater capillarity

11. The diagrams below represent three identical beakers filled with nonporous beads.

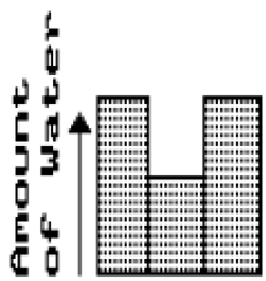


If water is added to each beaker to the level of the line, which graph best shows the amount of water added to each beaker?

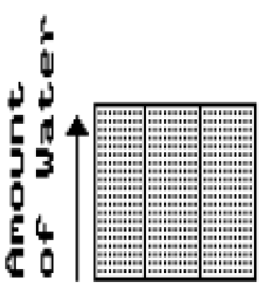
A.



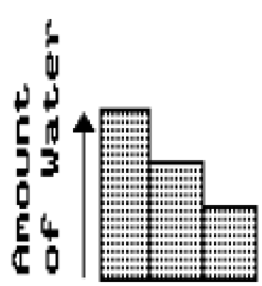
C.



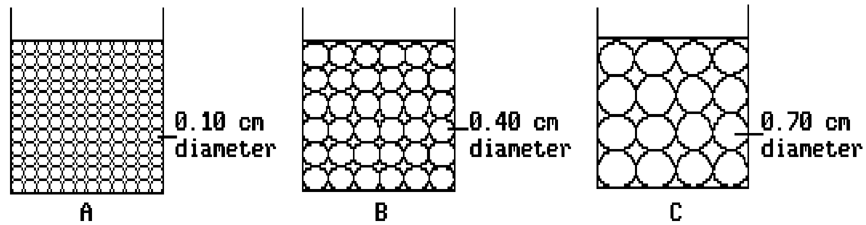
B.



D.



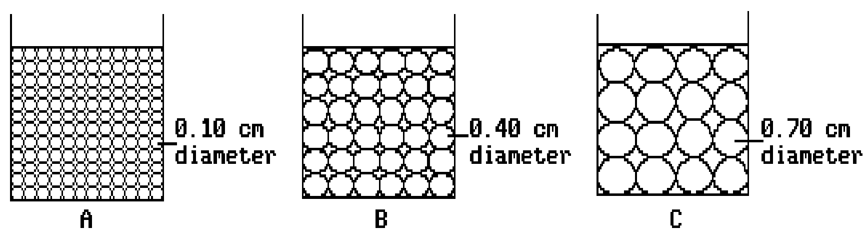
12. The diagrams below represent three identical beakers filled with nonporous beads.



There is also a 4th beaker, beaker D, containing a mixture of 0.10-centimeter spheres and 0.70-centimeter spheres. Compare to the porosity of the samples in the four beakers.

A. All four samples have the same porosity.
B. Sample A has the greatest porosity, Sample C has the least porosity, and samples B and D have the same porosity which is between A and C.
C. Sample A has the least porosity, Sample C has the greatest porosity, and samples B and D have the same porosity which is between A and C.
D. Samples A, B, and C have the same porosity and they are all greater than the porosity of Sample D.

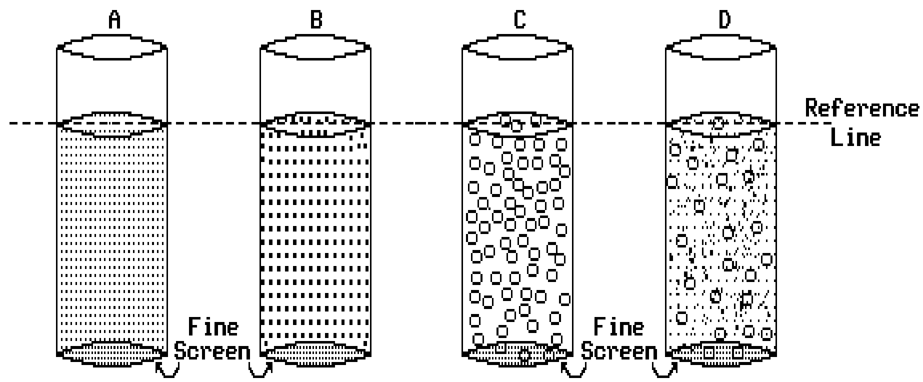
13. The diagrams below represent three identical beakers filled with nonporous beads.



Which beaker contains material with the greatest permeability?

A. Sample A
B. Sample B
C. Sample C

14. The diagrams below represent an investigation with core samples of various rocks. The core samples were placed in four similar tubes. Samples A, B, and C each contain rocks of uniform grain size, shape, and distribution. Sample D contained a conglomerate consisting of a mixture of the same grain sizes found in the other three samples. The investigation studied the effects that the different particle size has on porosity, capillarity, and permeability. Data collected is recorded in the table below.

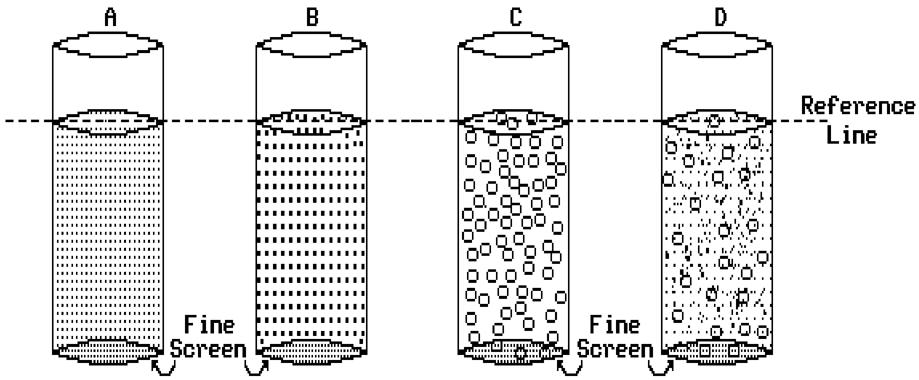


Tube	Paricle Size (diameter in cm)	Porosity (%)	Capillarity (mm)	Permeability (sec)
A	Fine (0.025 cm)	40	20	14
B	Medium (0.1 cm)	40	15	8
C	Coarse (0.3 cm)	40	7	6
D	Mixed (0.025 to 0.3 cm)	20	12	20

When water was poured into the top of each tube at the same time, which tube allowed the water to pass through most quickly?

A. Tube A
B. Tube B
C. Tube C
D. Tube D

15. The diagrams below represent an investigation with core samples of various rocks. The core samples were placed in four similar tubes. Samples A, B, and C each contain rocks of uniform grain size, shape, and distribution. Sample D contained a conglomerate consisting of a mixture of the same grain sizes found in the other three samples. The investigation studied the effects that the different particle size has on porosity, capillarity, and permeability. Data collected is recorded in the table below.



Tube	Paricle Size (diameter in cm)	Porosity (%)	Capillarity (mm)	Permeability (sec)
A	Fine (0.025 cm)	40	20	14
B	Medium (0.1 cm)	40	15	8
C	Coarse (0.3 cm)	40	7	6
D	Mixed (0.025 to 0.3 cm)	20	12	20

The bottom of each tube was closed and water was slowly poured into each tube until the water level reached the dotted line. Which statement best describes the amount of water held by the tubes?

A. Tubes *A* and *D* held the same amount of water and twice as much water as tubes *B* and *C*.
B. Tube *C* held more water than any other tube and tube held *D* the least amount of water.
C. Tubes *A*, *B* and *C* held the same amount of water and tube D contained half as much water.
D. Tube *D* held more water than any other tube and tube *A* the least.

Source of Questions 1-15: http://reviewearthscience.com/subjects/es/review/topic-spec/porosity.pdf

16. Ellen examined a sandstone sample under a microscope and counted the grains of sand she found at regularly spaced points. If the point contained void space, or empty space, she recorded the point as a pore. The table below shows her findings.

Element	Frequency
Sand	28
Pore	12
Total	40

Which percent most likely represents the porosity of this rock sample based on the measurements Ellen made?

A. 30 %
B. 42.9 %
C. 70 %

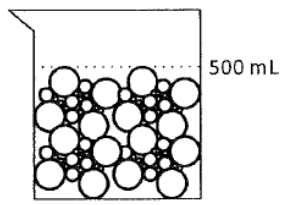
17. Alyssa examined a rock sample under a microscope and counted the rock grains she found at regularly spaced points. If the point contained void space, she recorded the point as a pore. The table below shows the elements she found, and how often they occurred. Quartz, feldspar, and clay are minerals that are found in rock grains.

Element	Frequency
Quartz	31
Feldspar	20
Clay	11
Pore	8

What fraction most likely represents the porosity of this rock sample based on the measurements Alyssa made?

A. 8/31
B. 8/62
C. 8/70

18. Mario has a 500-mL beaker that is filled with various sized round beads (see the figure below). He is able to pour 60 mL of water into the bead pack with no air bubbles trapped. What percent best represents the porosity of the bead pack?



A. 8.3%
B. 12%
C. 14%
D. 60%

19. A rock sample has a porosity of 25%, and has a total volume of 24 ml. If all of the pores are completely filled with water, what volume of water does the rock contain?
A. 1 ml
B. 6 ml
C. 18 ml
D. 49 ml

20. A rock sample has a porosity of 25%, and a total volume of 24 ml. In this case, however, only a fraction of the pore spaces are filled with water, and the rest are filled with oil. If the fraction of water in the pore spaces is 15%, what volume of oil does the rock contain?

Source of Questions 16-20: Breakthrough Austin, Summer, 2013, Example Math STAAR Questions

21. Draw a picture or describe with words what you think the Earth looks like underground below a water well.

    Questions to consider:

        Where does underground water come from?

        How is water stored underground?

Appendix E

STEAM'n Up the Edwards Aquifer a Proposal for a Permanent Exhibit at the Thinkery, Austin, Texas

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Overview

The acronym STEM (Science, Technology, Engineering, and Mathematics) is becoming more widely known as the standard for integration of the sciences. However, educators are increasingly adding Art to STEM to produce the acronym STEAM which recognizes the importance that art plays in the visualization and understanding of the STEM disciplines. Art helps to make STEM make sense to learners of all ages. Our proposal to the Thinkery is to create a permanent exhibit highlighting the Edwards Aquifer to teach geosystems engineering, hydrogeology, environmental science, geology, and math through a two story interactive water well. We have an artist working on developing a translucent visual display to serve as the lens through which the mechanics are viewed.

The exhibit we are proposing will occupy less than one foot of space deep along the interior of the north window of the atrium at the Thinkery. In the corner of the Currents exhibit room, we would like to install a hand operated water pump next to the atrium window. Water will be pumped out of a water well into a trough that will run the length of the window wall. The trough will be perforated to allow water to rain down to the 1st floor. A clear, narrow enclosure will capture the rain water to demonstrate how water is infiltrated through the Edwards Aquifer and back to our water well. We would like to add touch screen devices in the hallway outside the In My Family exhibit to inform patrons about the geology, ecology, engineering, and math of our exhibit. The art work we propose will cover the two story windows with a translucent vinyl film to illustrate the setting.

Another aspect of our research is utilizing 3D prints as instructional models for items that were previously impossible to create using traditional means. We have been printing enlargements of rocks in order to demonstrate the pore space that exists in rocks. We understand that the Thinkery has a 3D printer. We would like for this printer to be on public display behind a glass enclosure in the 1st floor hallway with our water well to print objects each day. Example objects that could be printed include our enlarged rocks or actual size replicas of the Barton Springs salamander. These items could then be added to the pond in the Our Backyard exhibit for patrons to enjoy. An explanation of the enlarged 3D rocks and salamanders could be added to the touch screen devices in the hallway. We would love for your 3D printer to be utilized on a regular basis to demonstrate to the public this new technology.

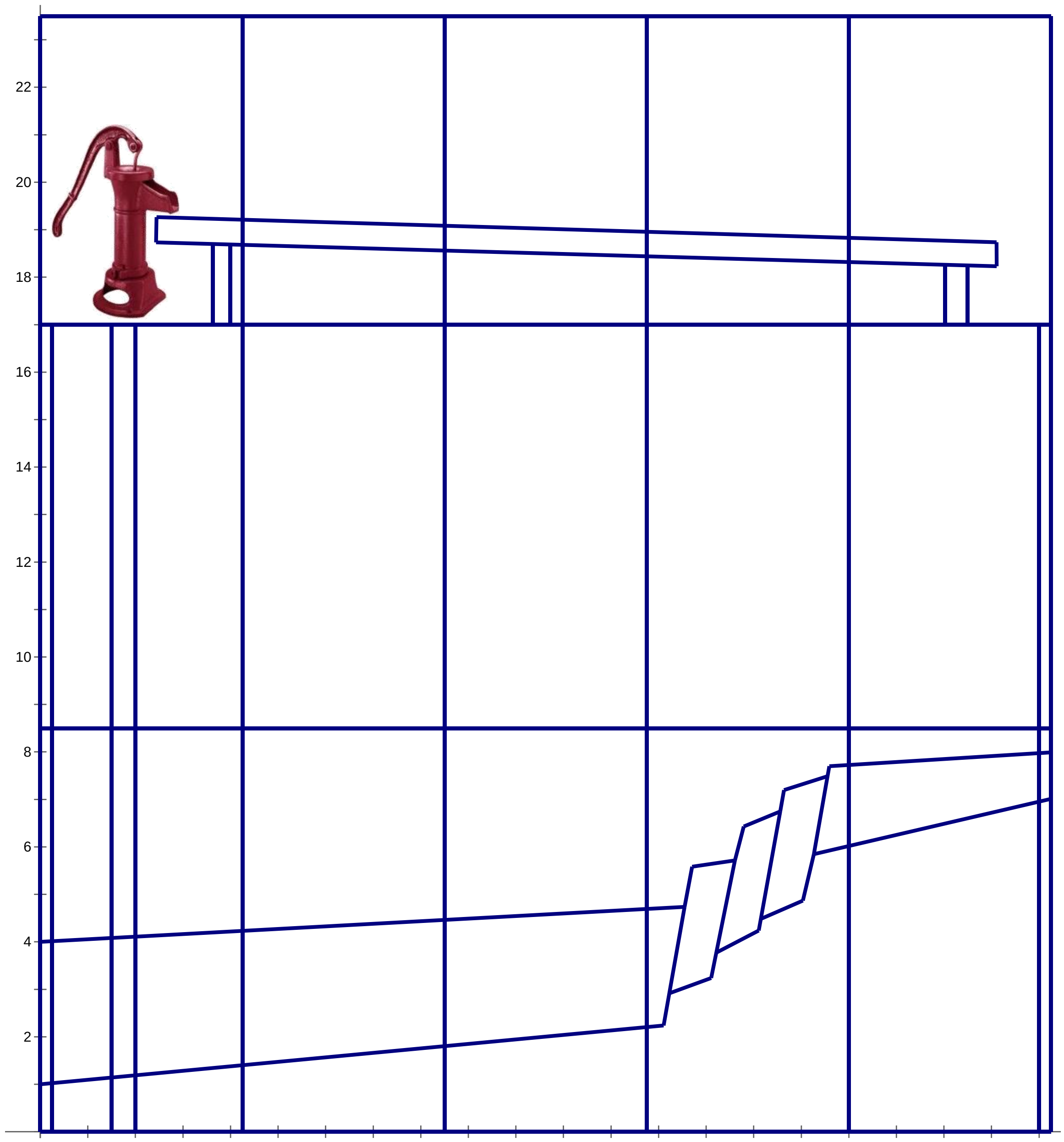
Along with our research in 3D prints, we are developing lessons on porosity and permeability of rocks. Calculating the porosity and permeability traditionally requires very expensive and time consuming equipment. Often the original sample is altered through the process of taking these measurements making it difficult to bring back to its initial state. Using enlarged 3D prints of rocks, students can now conduct porosity and permeability labs to calculate these measurements and learn in a hands-on way the meaning of porosity and permeability. The enlargement of the pores is the biggest help. We would like to share these lesson plans with the Thinkery for your use in your camps, special programs, or in your Kitchen Lab.

We hope you find our ideas important concepts to share with the public. In the next pages you will find images of our designs to assist you with our visions for the Thinkery. Our contact information is shared below in the event you would like to further discuss these ideas.

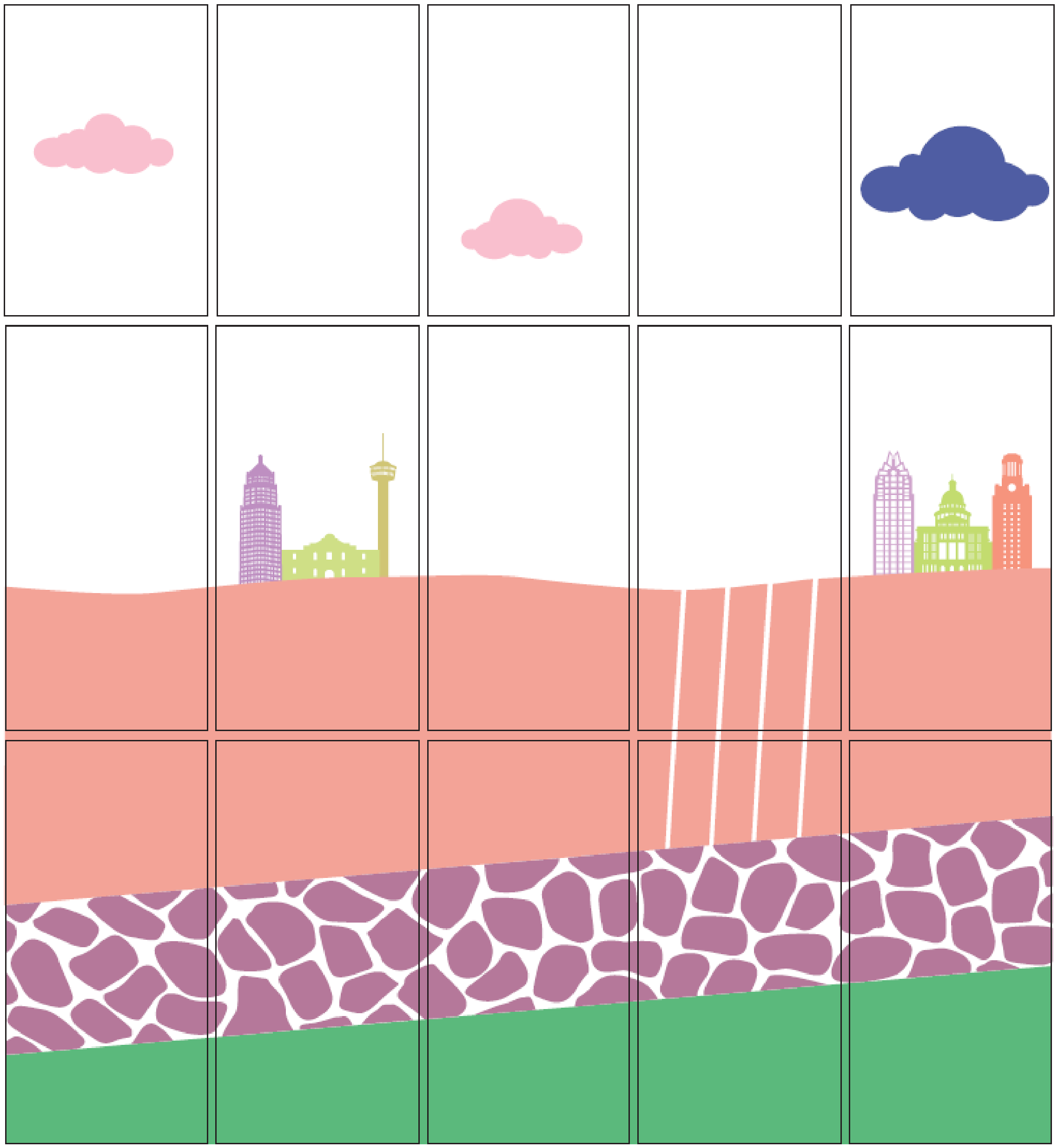
Interior Windows in the Currents Exhibit to be used at the Thinkery.
Hand water pump will be place at the right corner of image and the water trough will run along the window.

Exterior Windows in the Our Backyard Exhibit to be use at the Thinkery.
The water pump will be on the left side of these windows. Rain will fall over the bottom two rows of windows from the water trough. Our art work will fill all 15 window panes.

Sketch of the Mechanics of the Water Well and Edwards Aquifer System.
Units are in feet.



Artist Rendition of Visual Display on Windows that will Overlay the Mechanics
Art by Kaitlin E. Kyle



Bibliography

Almquist, Heather, et al. "An Integrated Field-Based Approach to Building Teachers' Geoscience Skills." *Journal of Geoscience Education* 59.1 (2011): 31-40. Print.

"The AW3D V.5.5 Printer." *3D Printer Products: Fully Assembled 3D Printers and Kits*. Airwolf 3D Printers, 2013. Web. 26 July 2014. <http://airwolf3d.staging22.gigasavvy.net/wp-content/uploads/2012/05/3d-printer-v.5.5-airwolf3d1.jpg>.

Bagnato, Robert A. "Collaboration in the Mathematical Community." *Mathematics Teacher* 67.8 (1974): 682-86. Print.

Barab, Sasha A., and Thomas Duffy. "From Practice Fields to Communities of Practice." *Theoretical Foundations of Learning Environments*. Ed. David Jonassen and Susan Land. 2nd ed. New York: Routledge, 2012. 29-65. Print.

Barnatt, Christopher. *3D Printing: The Next Industrial Revolution*. N.p.: ExplainingTheFuture.com, 2013. Print.

Bear, Jacob. *Dynamics of Fluids in Porous Media*. Unabr., Corrected ed. New York: Dover, 1988. Print.

Benson, Robert G. "The Campus Mine: An Adaptable Instruction Approach Using Simulated Underground Geology in a Campus Building to Improve Geospatial Reasoning before Fieldwork." *Journal of Geoscience Education* 58.5 (2010): 253-61. Print.

Bielaczyc, Katerine, and Allan Collins. "Learning Communities in Classrooms: A Reconceptualization of Educational Practice." *Instructional-Design Theories and Models*. Ed. Charles M. Reigeluth. Vol. II. Mahwah: Lawrence Erlbaum, 1999. 269-92. Print.

Black, John B., et al. "Embodied Cognition and Learning Environment Design." *Theoretical Foundations of Learning Environments*. Ed. David Jonassen and Susan Land. 2nd ed. New York: Routledge, 2012. 198-223. Print.

Bratton, John. Oil is a fossil fuel that is formed from plankton that is deposited in the sediments of oceans and lakes, and then buried deeply in the earth. *Gulf of Mexico Deep Sea Habitats: September 25, 2003 Mission Log*. National Oceanic and Atmospheric Administration, 24 Aug. 2010. Web. 14 July 2014. <http://oceanexplorer.noaa.gov/explorations/03mex/logs/sept25/sept25.html>.

Carberry, Adam R., and Ann F. McKenna. "Exploring Student Conceptions of Modeling and Modeling Uses in Engineering Design." *Journal of Engineering Education* 103.1 (2014): 77-91. Print.

Chan Hilton, Amy B., and Roseanna M. Neupauer, eds. *H2OH!* Reston: American Society of Civil Engineers, 2013. Digital file.

Chapter 111. Texas Essential Knowledge and Skills for Mathematics, Subchapter B. Middle School. Texas Education Agency, 1 Aug. 2006. Web. 29 July 2014. <http://ritter.tea.state.tx.us/rules/tac/chapter111/ch111b.html>.

"Circle Packing." *Circle Packing*. Wolfram Math World, 2014. Web. 2 Aug. 2014. <http://mathworld.wolfram.com/CirclePacking.html>.

Clark, Scott K., et al. "A Novel Approach to Teaching and Understanding Transformations of Matter in Dynamic Earth Systems." *Journal of Geoscience Education* 57.4 (2009): 233-41. Print.

Colaianne, Blake A., and Matthew G. Powell. "Developing Transferrable Geospatial Skills in a Liberal Arts Context." *Journal of Geoscience Education* 59.2 (2011): 93-97. Print.

Common Core State Standards for Mathematics. Common Core State Standards Initiative, 2014. Web. 31 July 2014. <http://www.corestandards.org/wp-content/uploads/Math_Standards.pdf>.

"Conference on Models Held at the 42nd Annual Meeting, S.P.E.E., Cornell University, June 19, 1934." *Journal of Engineering Education* 25.June (1935): 692-706. Print.

Cuoco, Al, E. Paul Goldenberg, and June Mark. "Organizing a curriculum around Mathematical Habits of Mind." *Mathematics Teacher* 103.9 (2010): 682+. Print.

DiCarlo, David. *PGE Department of the University of Texas at Austin CT Scanner*. 9 May 2014. Photograph.

Download Lesson Plans. Energy 4 Me, 2014. Web. 5 Aug. 2014. <http://www.energy4me.org/classroom-resources/download-lesson-plans/>.

Drennan, Gillian R., and Mary Y. Evans. "Introductory Geological Mapwork—An Active Learning Classroom." *Journal of Geoscience Education* 59.2 (2011): 56-62. Print.

Durelli, A. J. "Visualization of Fundamental Principles in Elasticity Using Rubber Models." *Journal of Engineering Education* 40.May (1950): 525-31. Print.

Eger, John M. "Future Leaders Need Art-Infused Education." *San Diego Business Journal* 31.10 (2010): 39. Print.

Engineer Your World, 2013-2014 Scaffolded Course Framework. UTeach*Engineering*, University of Texas at Austin, 2013. Web. 31 July 2014. <http://engineeryourworld.org/AboutCourse/2013-14%20Engineer%20Your%20World%20Scaffolded%20Framework.pdf>.

Fiji is Just Image J. Fiji, 1 Aug. 2014. Web. 5 Aug. 2014. <http://fiji.sc/Fiji>.

Flannery, Brian P., et al. "Three-Dimensional X-Ray Microtomography." *Science* 237.4821 (1987): 1439-44. Print.

Fraser, D. M., et al. "Enhancing the Learning of Fluid Mechanics Using Computer Simulations." *Journal of Engineering Education* 96.4 (2007): 381-38. Print.

Gilkey, H. J. "Various Types of Loaded Models and Some Problems to Which Their Use is Adapted." *Journal of Engineering Education* 25.June (1935): 702-06. Print.

Gwiazdowski, A. P. "Model Factory in the Engineering College." *Journal of Engineering Education* 20.June (1930): 948-60. Print.

Hartenberg, Richard Scheunemann. "Demonstration Models, Their Use and Construction." *Journal of Engineering Education* 40.April (1950): 430-34. Print.

Herbert, Neal. "Chocolate Drops (Maze District)." *Park Scenes - Canyonlands National Park*. National Park Service, 5 July 2014. Web. 17 July 2014. <http://www.nps.gov/media/photo/gallery.htm?id=5AB4426C-155D-451F-670E2F4BB408AFDD>.

"History of Energy Consumption in the United States (1776-2012)." *Today in Energy*. U.S. Energy Information Administration, 3 July 2013. Web. 21 July 2014. <http://www.eia.gov/todayinenergy/detail.cfm?id=11951&src=Total-b3>.

Hoisch, Thomas D., et al. "Application of Tablet PCs to Lecture Demonstrations on Optical Mineralogy." *Journal of Geoscience Education* 58.4 (2010): 221-31. Print.

Horowitz, Seth S., and Peter H. Schultz. "Printing Space: Using 3D Printing of Digital Terrain Models in Geosciences Education and Research." *Journal of Geoscience Education* 62.1 (2014): 138-45. Print.

Hubbert, M. King. "Nuclear Energy and the Fossil Fuels." Spring Meeting of the Southern District, Division of Production, American Petroleum Institute. Plaza Hotel, San Antonio, Texas. 7 Mar. 1956. Lecture.

Hundhausen, Christopher, et al. "The Design and Experimental Evaluation of a Scaffolded Software Environment to Improve Engineering Students' Disciplinary Problem-Solving Skills." *Journal of Engineering Education* 100.3 (2011): 574-603. Print.

Jonassen, David, and Susan Land, eds. *Theoretical Foundations of Learning Environments*. 2nd ed. New York: Routledge, 2012. Print.

Jonassen, David H., and Matthew A. Easter. "Conceptual Change and Student-Centered Learning Environments." *Theoretical Foundations of Learning Environments*. Ed. David H. Jonassen and Susan Land. 2nd ed. New York: Routledge, 2012. 95-141. Print.

Jordan, Mike, and Cathy Kelloes. "SEM Photomicrographs of the Silurian Clinch Sandstone from Thorn Hill, Tennessee." *Sandstone Petrology GEOL 8180 - Clinch Sndstn SEM Views*. U of Georgia, n.d. Web. 30 June 2014. <http://www.gly.uga.edu/railsback/8180Clinch1.html>.

Kastens, Kim. "Commentary: Object and Spatial Visualization in Geosciences." *Journal of Geoscience Education* 58.2 (2010): 52-57. Print.

Kaur, Satwant. "How is 'Internet of the 3D Printed Products' Going to Affect Our Lives?" *IETE Technical Review* 29.5 (2012): 360-64. Print.

Kemler, E. N., and C. R. Freberg. "Electrical Models in the Teaching and Application of Vibration Theory." *Journal of Engineering Education* 34.November (1943): 274-81. Print.

Kendall, Lydia. "2004-2013 Ten Year Undergraduate Historical Counts for School of Engineering." 5 Aug. 2014. Raw data.

Koh, Caroline, et al. "Investigating the Effect of 3D Simulation-Based Learning on the Motivation and Performance of Engineering Students." *Journal of Engineering Education* 99.3 (2010): 237-51. Print.

Kyle, Kaitlin E. Artist rendition of the visual display on windows that will overlay the mechanics of the proposed Edwards Aquifer Thinkery exhibit. 14 July 2014. JPEG file.

Larson, Harold C. "Project Tinker Toy." *Journal of Engineering Education* 49.April (1959): 725-30. Print.

Lorensen, William E., and Harvey E. Cline. "Marching Cubes: A High Resolution 3D Surface Construction Algorithm." *ACM SIGGRAPH Computer Graphics* 21.4 (1987): 163-69. Print.

Martin, Robert L., Nicholas S. Bowden, and Chris Merrill. "3D Printing in Technology and Engineering Education." *Technology and Engineering Teacher* 73.8 (2014): 30-35. Print.

Mathematics Texas Essential Knowledge and Skills. Texas Education Agency, 19 June 2012. Web. 29 July 2014. <http://www.tea.state.tx.us/index2.aspx?id=2147499971>.

A Matter of Scales: How Much Can You Print with a Single 1kg Spool? Makerbot, 24 Feb. 2012. Web. 26 July 2014. <http://www.makerbot.com/blog/2012/02/24/a-matter-of-scales-how-much-can-you-print-with-a-single-1kg-spool/>.

MeshFix. Dice Holdings, Inc., 2014. Web. 5 Aug. 2014. <http://sourceforge.net/projects/meshfix/>.

Mesh Repairing Software on the Web. MeshRepair.org, 2012. Web. 26 July 2014. <http://www.meshrepair.org/>.

Mission & Vision. Breakthrough Austin, n.d. Web. 29 July 2014. <http://www.breakthroughaustin.org/about-us/mission-vision>.

Moore, Tamara J., et al. "Modeling in Engineering: The Role of Representational Fluency in Students' Conceptual Understanding." *Journal of Engineering Education* 102.1 (2013): 141-78. Print.

Nelson, Stephen A. "Porosity." *Groundwater*. Tulane University, 9 Apr. 2012. Web. 17 July 2014. <http://www.tulane.edu/~sanelson/eens1110/groundwater.htm>.

Open2 Team. "Sorting." *Geological Glossary*. The Open University, 2014. Web. 18 July 2014. <http://www.open.edu/openlearn/science-maths-technology/science/geology/geological-glossary>.

Orion, Nir, and Roger Trend. "Thinking and Learning in the Geosciences." Editorial. *Journal of Geoscience Education* 57.4 (2009): 222-23. Print.

Peters, Ekwere J. *Advanced Petrophysics*. Austin: Live Oak Book Company, 2012. Print.

Plummer, F. L. "Conference on Models." *Journal of Engineering Education* 25.June (1935): 692-96. Print.

Porosity/Permeability (Chap. 8). Review Earth Science, 2014. Web. 30 June 2014. <http://reviewearthscience.com/subjects/es/review/topic-spec/porosity.pdf>.

Pressman Toy Chess Set. Amazon, n.d. Web. 26 July 2014. <http://www.amazon.com/Pressman-2261XXXX-PRESSMAN-TOY-Chess/dp/B005DVV0B4/ref=sr_1_3?s=toys-and-games&ie=UTF8&qid=1406414203&sr=1-3&keywords=chess>.

Price Compare - 3D Printers. 3ders.org, 17 July 2014. Web. 26 July 2014. <http://www.3ders.org/pricecompare/3dprinters>.

Price Compare - 3D Printing Materials - Filament. 3ders.org, 17 July 2014. Web. 26 July 2014. <http://www.3ders.org/pricecompare/>.

Prodanović, Maša, et al. Imaged-based multiscale network modeling of microporosity in carbonates, Geological Society of London Journal, Special Publications, 406, first published on June 4, 2014, doi:10.1144/SP406.9

Prodanović, Maša, and S. L. Bryant. Physics-driven interface modeling for drainage and imbibition in fractures. SPE Journal 14 (3) (2009), 532--542.

Prodanović, Maša. *Barton Creek Greenbelt*. 9 May 2014. Photograph.

- - -. Core samples of sandstone and limestone. 9 5 2014. Photograph.

- - -. Segmented image of a somewhat poorly sorted unconsolidated fluvial sand pack from southern Australia. *Digital Rocks Portal*. University of Texas at Austin, 30 May 2014. Web. 5 Aug. 2014. <https://pep.tacc.utexas.edu/projects/5/>.

- - -. Cross-section of a volumetric segmented file (of unconsolidated sand, sand is in white, pore space is in black) used to create STL files for 3D printing of rock. July 2014. PNG file.

Rule, Audrey C. "Tactile Earth and Space Science Materials for Students with Visual Impairments: Contours, Craters, Asteroids, and Features of Mars." *Journal of Geoscience Education* 59.4 (2011): 205-18. Print.

Saini-Eidukat, Bernhardt, ed. "Software List." *List of Geologic Software*. Ed. NDSU Webmaster. North Dakota State University Department of Physics, Jan. 2014. Web. 30 Mar. 2014. <http://www.ndsu.nodak.edu/pubweb/~sainieid/software/software_list.shtml>.

Schwartz, Kerry L., Holly Thomas-Hilburn, and Arin Haverland. "Grounding Water: Building Conceptual Understanding through Multimodal Assessment." *Journal of Geoscience Education* 59.3 (2011): 139-50. Print.

Segerman, Henry. "3D Printing for Mathematical Visualization." *The Mathematical Intelligencer* 34.4 (2012): 56-62. Print.

Shepherd, Roy. Diagram explaining the generation and entrapment of oil and gas. *What are Fossil Fuels?* United Kingdom Geologist Equipment, 2002. Web. 24 July 2014. <http://www.discoveringfossils.co.uk/fossilfuels.htm>.

Sibley, Duncan F. "A Cognitive Framework for Reasoning with Scientific Models." *Journal of Geoscience Education* 57.57 (2009): 255-63. Print.

Szilvási-Nagy, M., and Gy. Mátyási. "Analysis of STL Files." *Mathematical and Computer Modelling* 38.7-9 (2003): 945-60. Print.

"Tentative Program for Conference on Use of Models in Technical Education and Research." *Journal of Engineering Education* 24.May (1934): 638-40. Print.

Texas Administrative Code (TAC), Title 19, Part II, Chapter 112. Texas Essential Knowledge and Skills for Science. Texas Education Agency, 24 Aug. 2010. Web. 29 July 2014. <http://ritter.tea.state.tx.us/rules/tac/chapter112/index.html>.

"Texas Drilling Statistics." *Texas Drilling Statistics*. Railroad Commission of Texas, 4 June 2014. Web. 4 Aug. 2014. <http://www.rrc.state.tx.us/media/19846/txdrillingstats.pdf>.

Titus, Sarah, and Eric Horsman. "Characterizing and Improving Spatial Visualization Skills." *Journal of Geoscience Education* 57.4 (2009): 242-54. Print.

Wildenschild, Dorthe, and Adrian P. Sheppard. "X-Ray Imaging and Analysis Techniques for Quantifying Pore-Scale Structure and Processes in Subsurface Porous Medium Systems." *Advances in Water Resources* 51.January (2013): 217-46. Print.

Wyllie, M. R. J., A. R. Gregory, and L. W. Gardner. "Elastic Wave Velocities in Heterogeneous and Porous Media." *Geophysics* 21.1 (1956): 41-70. Print.