Teacher's Preparatory Guide

Lesson 1: Transistor Mania

Purpose: This activity is designed to help the students understand the significance of transistors in their lives. Students will learn how current research on nanoscale transistors is making their favorite electronic devices (i.e., cell phones, gaming devices, computers, etc.) faster and more powerful. Students will model a transistor in order to understand the relationship between voltage and electron flow.

Level and Subject: Middle or high school; Physical science or physics

Time required: (1) 50-minute class period

Teacher Background: Transistors may be a very new concept to students. Present the history of transistors and the basic science controlling the device before this lab. The background information below explains the very basic science behind transistors. The resource section below provides links to useful information and videos on transistors and computers.

There are many types of transistors (BJTs, MOSFETs, JFETs, etc.). The transistor built in this lesson best models a Field Effect Transistor (FET). Please note that the model does not completely represent a real FET—there are some differences. After presenting the science behind transistors, have your students explain how the model differs from a real FET. (See the *Enhancing Understanding* section).

FETs consist of 3 parts: a *source*, a *drain*, and a *gate* (see images below). These parts are on top of a semiconductor (like doped silicon). Electrons are "hanging out" in all parts of the transistor. But, when you hook up a battery with the negative end to the source and the positive end to the drain, a potential for the electrons to move from the source to the drain is created. This potential is called *voltage.*

Unfortunately, the only way from the source to the drain would be through the semiconductor they are sitting on top of. The semiconductor does not allow electrons to move very easily (as it has high resistance). The electron would bump into too many things in the semiconductor before it could ever reach the drain.

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Figure 1. Transistor with voltage across the source and the drain. The electrons at the source want to go to the drain, but cannot cross the semiconductor. (There is no voltage at the gate, so no conductive region is present, and therefore there is no electron flow from source to drain.)

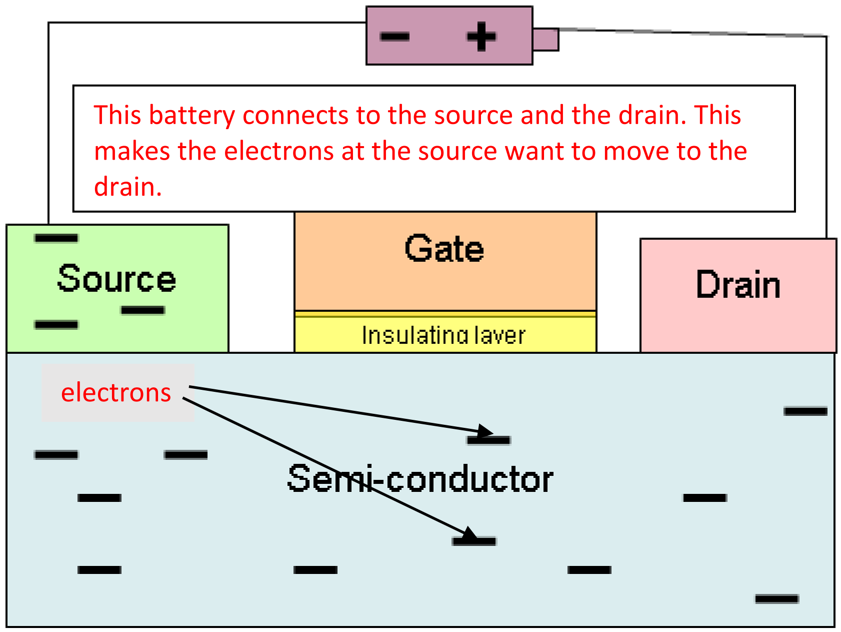

Figure 1

This is where a gate helps. If a positive voltage is applied to the gate, the electrons in the semiconductor are attracted to it. The electrons move towards the gate. These electrons cannot reach the gate; there is an insulating layer between the gate and semiconductor. So these electrons “hang out” as close to the gate as they can get.

This makes a conductive region at the top of the semiconductor. Now, electrons can move from the source to the drain (Figure 2). Remember, there must also be a voltage between the source and drain in order to have the potential for electrons to move in the first place.

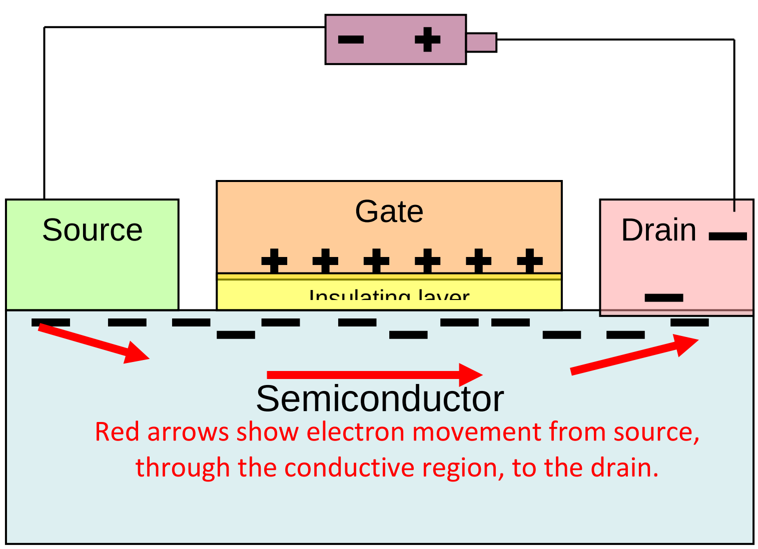

Figure 2. Transistor with voltage between source and drain. There is voltage at the gate, so a conductive region is present, so electrons flow from source to drain.

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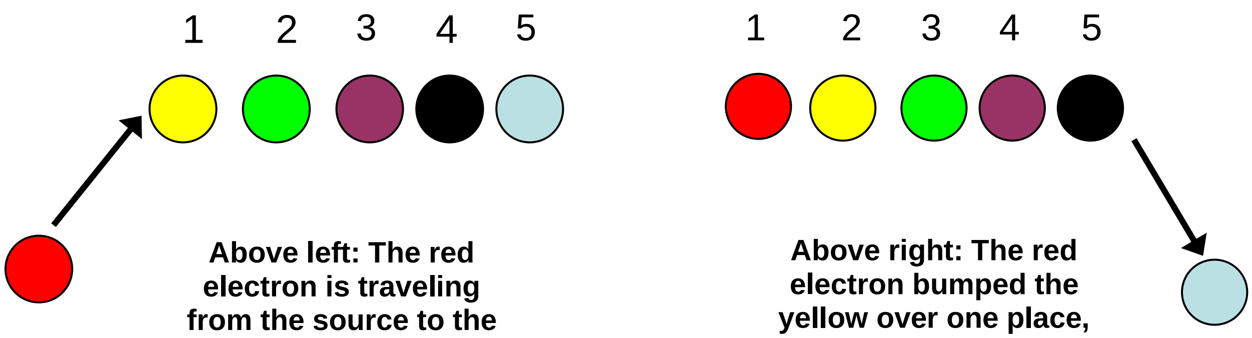
How the electrons actually move is by “bumping” one another into the next position. Imagine that the electrons are students sitting in chairs next to each other in a line. If a new electron/student arrives (shown as a red dot Figure 3 below), say from the “source” of the transistor, (s)he can ask the first sitting student (yellow dot) in the line to leave and then sit in the next (2nd) chair. The newly displaced student (green dot) can then ask the student in the next chair (3rd) to move and take that chair, and so on. If each student moves over one seat, the student that was at the end of the line will end up without a chair to sit in and can move to the “drain.” You can try this activity with your students to help them understand the concept of electricity!



Above left: The red electron is traveling from the source to the conductive region in the semiconductor.

Above right: The red electron bumped the yellow over one place, which moved the green over, and so on, until the blue is “bumped” out to the drain.

Figure 3

In order to process and deliver lots of information as with streaming video, Internet gaming, and cell phone applications engineers are making transistors smaller and faster. These transistors are now so small that “[m]ore than 2 million 45 nm (nanometer) transistors could fit on the period at the end of this sentence” or “more than 100 million 22nm tri-gate transistors could fit onto the head of a pin (1.5mm in diameter).[1] These nanoelectronics allow for faster, smaller and more portable systems (think about your smart phone) and they can manage and store large amounts of data/information (think about the increasing storage capacity of USB drives and computers).

Source:

1. Intel. “Fun Facts: Exactly How Small (And Powerful) is 45 Nanometers?” and Fun Facts Exactly how small (and cool) is22 Nanometers?
   https://www.intel.com/content/dam/www/public/us/en/documents/corporate-information/history-moores-law-fun-facts-factsheet.pdf
   http://www.intel.com/pressroom/kits/45nm/Intel45nmFunFacts_FINAL.pdf

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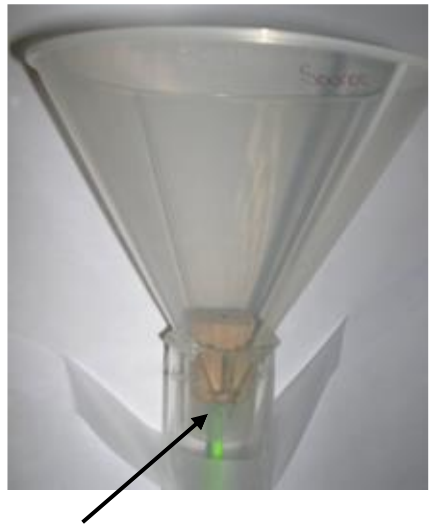
Materials per class:

- electric drill and bit
- sandpaper
- scissors



Cork in stem of funnel

Figure 4

Materials for each group of 4 students:

- funnel (~1 in. diameter stem)
- cork (able to fit snugly in the stem of the funnel)
- cork borer
- plastic or PVC pipe, clear (~1.5 in. diameter, 1 ft. long)
- bendy straw
- wooden skewer
- balloon, cut into 1 square inch pieces
- clear scotch tape
- hot glue gun
- glue sticks
- paper plate
- scissors
- clear plastic beaker, 200 mL
- 70 mL of sugar sprinkles (i.e. toppings for cupcakes)
- stopwatch
- butcher paper (~3 ft. long, standard width)
- markers
- small paper plate
- student worksheet
- protractor (provided in appendix)

Safety Information: The hot glue gun gets VERY hot. If you do not trust students to be responsible with this tool, have groups bring you their models and complete this step for them. Although the sprinkles are edible, discourage students from eating them so that they can be reused for multiple classes.

Advance Preparation: Materials may be found at grocery, craft, hardware, and school supply stores. **Note:** Make sure the size of the corks is such that they fit snugly in the necks of the funnels.

1. Prepare the clear pipe

a. *Important!* Make sure your clear tube is longer than the straws the students will be using. About 1 foot of tube is sufficient.

b. There are two parts to a bendy straw. Measure the length of the long part (for most straws this is 6 inches). Subtract 1 inch from that measurement and write down this number. For a 6-inch straw, the final number would be 5 inches.

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c. On the clear tube, measure from the top down to the final number you calculated in step b. (In this example, 5 inches) and mark with a pencil.
d. Use an electric drill and1/2" bit to drill a hole at the mark made in step c. The final hole should be about ½ inch in diameter. Sand the rough edges. Make one pipe per student group and one pipe to use as a demonstration.

Figure 5

2. Cut the balloon pieces
   One balloon should yield about 3 pieces. Buy the amount of balloons according to the number of student groups you will have in the lab. Cut 1 square inch of balloon for each group.
3. Make an example model to demonstrate each step in the procedure.

   What does the final model look like?
   Please note that the bamboo skewer is at the "Resting" position (right). The real symbol for a transistor that this models is written in red to the right of the model. Notice that the ***source*** of electrons is represented by the funnel. The ***gate*** is represented by the lever. The ***voltage*** is represented by the angle (resting angle = no voltage, larger angles represent larger voltages). The ***drain*** is represented by a cup taped to the bottom.

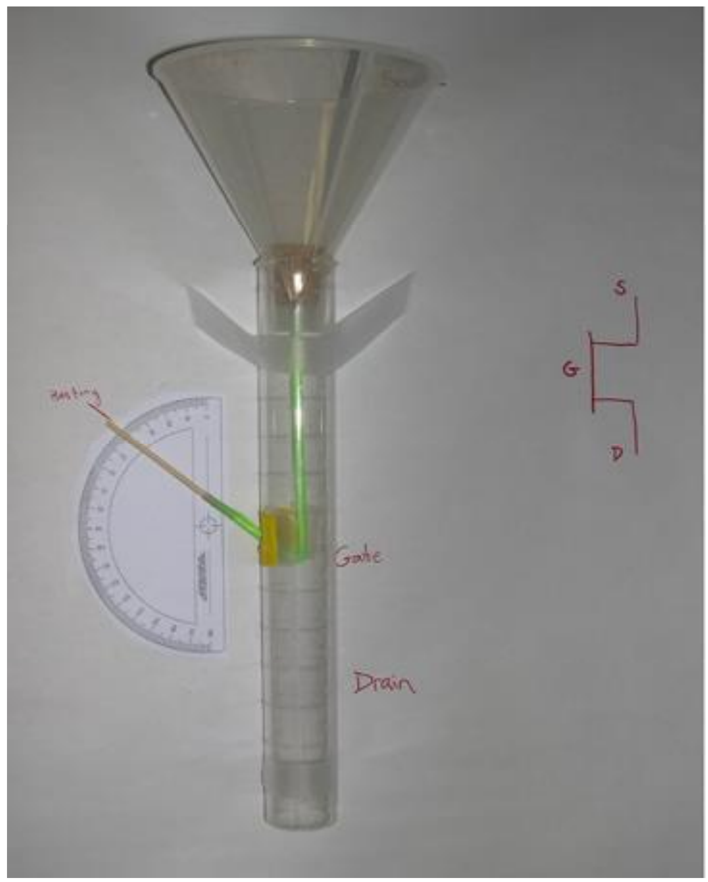

Figure 6

4. Plug in the hot glue guns
   Plug in the hot glue guns at the start of class to allow them time to warm up. Make sure the glue guns stay on the paper plates at all times to catch any glue drips.

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Resources: Background information and inspiration for this lab are from the websites below. It is suggested that the teacher explore several available YouTube videos on the topics covered in this lesson.

- How Semiconductors Work - http://computer.howstuffworks.com/diode.htm (This link also explains doping.)
- Transistorized! History of Transistors - http://www.pbs.org/transistor/album1/
- Inventing the Transistor - https://www.computerhistory.org/revolution/digital-logic/12/273
- Timeline of Computer History - https://www.computerhistory.org/timeline/computers/
- History of Computers - https://homepage.cs.uri.edu/faculty/wolfe/book/Readings/Reading03.htm
- Computers - https://en.wikipedia.org/wiki/Computer
- Modern Marvels: How the First Computer Changed the World (S2, E11) - https://www.youtube.com/watch?v=OSQld7xVMn0. This is a full 45 minute episode which you could view in class or assign as homework.
- History of Computers – How were Computers Invented Short Documentary Video - https://www.youtube.com/watch?v=Aqg6LxGCz44&t=41s
- Learn Engineering, Transistors, How do they work? https://www.youtube.com/watch?v=7ukDKVHnac4
- Science ABC, How transistors work https://www.youtube.com/watch?v=0CvdruTMH1c
- How Transistors Work - A Quick and Basic Explanation https://www.youtube.com/watch?v=0CvdruTMH1c
- Transistors - The Invention That Changed The World https://www.youtube.com/watch?v=OwS9aTE2Go4
- Diodes Explained - The basics how diodes work working principle pn junction https://www.youtube.com/watch?v=Fwj_d3uO5g8
- Build Electronic Circuits: How Transistors Work – A Simple Explanation https://www.build-electronic-circuits.com/how-transistors-work/
- Nanoelectronics – Nanotechnology in Electronics - https://www.nanowerk.com/nanoelectronics.php
- https://www.intel.com/content/dam/www/public/us/en/documents/corporate-information/history-moores-law-fun-facts-factsheet.pdf
http://www.intel.com/pressroom/kits/45nm/Intel45nmFunFacts_FINAL.pdf

Teaching Strategies: This lab works best in groups of 4 students each. Review the possible videos for use in class or as a homework assignment. Review by the students is crucial in their understanding of how transistors work. A suggested *Instructional Procedure* is provided below.

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Suggested Instructional Procedure: Lesson 1

Time	Instruction	Reasoning
5 min	Guide a discussion based on this question: "How does your computer work?" Write ideas on the board.	Students most likely take their everyday electronics for granted. This will encourage students to think about these conveniences from a new perspective.
10–15 min	Use the previous discussion to transition viewing a video or reading on the History of Transistors and Computers. Discuss the properties of electrons and define electricity. (See *Guided Dialog* section below.) Include diagrams and explanations of FETs. Have students draw the basic schematics on their worksheets to reference during the lab.	This portion of the lesson will provide the students with the background knowledge of electricity and transistors necessary to achieve a complete understanding of the transistor models they will make. The diagrams of FETs that are used by engineers are very simple to understand and provide students with a real-world application of the lab.
10 min	Divide the class into groups of 4 students. Distribute materials and begin construction of the model transistors. You may wish to guide the construction of this model as a class step-by-step, or allow each group to construct on their own by following the procedure on their worksheets.	These models are tangible analogies of transistors, but there are limitations. During construction, encourage students to compare and contrast the properties of their model versus a real transistor.
10–15 min	Once the models are fully constructed, pass out the sprinkles, beakers, butcher paper, markers, stopwatches, and tape. Students will follow the procedures on their worksheets to gather data on the variations in the output of "electrons" due to different lever angles.	While students are completing this quantitative investigation, remind them of the similarities between the model and real transistors. If you vary the voltage at the gate of a real FET, you will get a different output of electric current at the drain.
5 min	Have students share their results in graph form with the class as a whole. Encourage a discussion by asking: "Are there any patterns?" "What can we conclude from the results?" Clean-up the work areas and store models in the classroom.	This will provide the students with a chance to communicate their ideas with the group and to synthesize the knowledge they gained from the beginning of the lesson with the concepts explored during the lab.

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Guided Dialog: After the *History of Transistors*, but before beginning the lab, review the meaning of the terms below. Write student responses on the board for reference during the lab.

Electricity *The movement of free electrons within a substance.*
Transistor *A 3-part device that controls the movement of free electrons within a substance by applying or removing voltage.*
Source *The part of a transistor that is the source of the electrons.*
Gate *The part of a transistor that controls the flow of electrons from the source to the drain.*
Drain *The part of a transistor that collects all of the electrons and can connect to other transistors to continue the circuit.*

Ask students questions to provoke thought and review what they already know. For example:

1. How are transistors used? *Transistors can be used as switches or amplifiers that transfer electrical current that in turn produces the computing/memory capabilities of your favorite electronics (cell phones, computers, etc.).*
2. How can transistors be used to send signals? *Transistors that are connected in parallel in a circuit can send complicated signals.*
3. What factors/variables are important to keep in mind while building a model of a transistor? *Students may come up with things like the diameter of the hole in the source cup, the length of the lever, etc.*

Cleanup: Have a broom and dustpan ready for sprinkle spills. Students should label their models and store their transistor models in the classroom to use as examples during the subsequent inquiry lesson. You may wish to tape each group's model to the wall for future use. If not enough wall space is available, boxed storage works, too. Any leftover materials can be collected and stored for use with another class.

Going Further: Students who have a good grasp of the content of the lab can be further challenged with these questions:

1. Why did we use sprinkles to represent free electrons in this lab? Think of another substance that would be a good representative of free electrons and explain why? *Free electrons are able to move around, which results in electricity, so the sprinkles are good representatives of these electrons because they flow easily. Another substance that could represent free electrons might be water because it also can flow smoothly from one place to another.*
2. List two aspects of the model transistor that do not correlate with a real electrical transistor? Explain.
   a. *The model transistor cannot reset itself. Once the sprinkles have emptied into the drain (beaker), you have to manually refill the source (funnel). In a real transistor, the free electrons are always present.*
   b. *In a real transistor, voltage controls the gate, which affects the flow of electrons from the source to the drain. In the model transistor, human power (pushing the gate lever) is what controls the flow of "electrons."*

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3. Why is it important to know how different voltages applied to the gate will affect the output at the drain? *In order to make many different messages, transistors in electronic devices need to send and receive different amounts of electricity. This allows the computer chip to complete so many different tasks.*

Assessment:

Formative Assessment Opportunities

1. The guided discussion at the beginning of the lesson prompts students to think about the question "How does your computer work?" The teacher monitors student responses during the discussion to gauge their prior knowledge and direct the focus of the videos or readings on transistors. This will help to fill in the gaps in their understanding.
2. During the construction of the model and the data gathering portion of the lab, the teacher can monitor student progress and the problems that they encounter. This information can help the teacher formulate questions for the closing discussion that will guide students to grasp the concepts on their own.

Summative Assessment Opportunities

The students will each turn in their completed worksheets at the end of the lab. This provides the teacher with several opportunities for assessing what the students were able to gain from the lab. Points can be given for the following categories:

1. The students' abilities to perform scientific skills, such as making hypotheses, collecting, organizing, and graphing data.
2. The students' overall understanding of the model transistor and how it relates to the real thing can be assessed by analyzing their responses to *Enhancing Understanding* questions, which require the students to apply what they learned to a new situation.
3. The final discussion at the closure of the lab asks students to look for patterns amongst the data from all the groups, and the responses during this discussion will provide the teacher with insight into the students' understanding of the big picture.

National Science Education Standards (Grades 5–8)

Content Standard A: Science as Inquiry

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

Content Standard F: Science in Personal and Social Perspectives

- Science and technology in society

Content Standard G: History and Nature of Science

- History of science

National Science Education Standards (Grades 9–12)

Content Standard A: Science as Inquiry

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

Content Standard F: Science in Personal and Social Perspectives

- Science and technology in local, national, and global challenges

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Content Standard G: History and Nature of Science

- Historical perspectives

Next Generation Science Standards:
Middle School:

- Science and Engineering Practices
  - Developing and using models
  - Obtaining, evaluating, and communicating information
  - Analyzing and interpreting data
- Influence of science, engineering, and technology on society and the natural world
- MS-PS Structure and properties of matter

High School:

- Science and Engineering Practices
  - Developing and using models
  - Obtaining, evaluating, and communicating information
  - Analyzing and interpreting data
- Influence of science, engineering, and technology on society and the natural world
- HS-PS Structure and properties of matter

Student Worksheet

(with answers in red)

Transistor Mania

Safety
Hot glue guns can burn. Scissors can cut. Use them with care.

Introduction: Do you know what a transistor is? Transistors are what allow you to talk to friends on cell phones and search online for myriads of information. Videos games have become more detailed and faster because of advances in micro and nano-electronics. They are the building blocks of modern electronics. They must be incredibly complicated devices that are made in sophisticated laboratories with expensive tools, right? Let's find out!

As a class you may watch one or two videos on the history of transistors. Alternatively, your teacher may assign you to view these as homework. Following the viewing of the videos, there will be a class discussion about what your learned from each.

1. What was the size of the first vacuum tube computer? *2 classrooms*__

2. How many transistors does Intel state could fit on the head of a pin? *100 million* (22nm)

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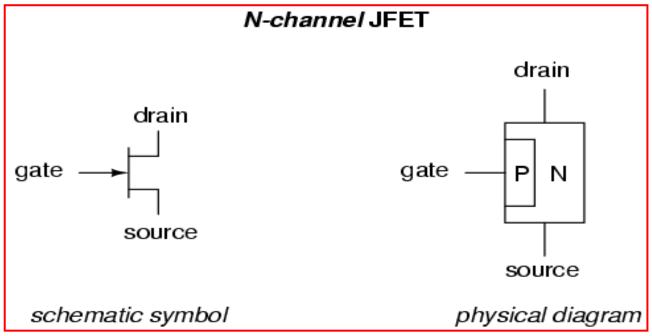
3. Draw the schematic diagram of a Field Effect Transistor (FET).



4. List any questions you would like answered concerning transistors and they work on a computer chip.

Materials:

- funnel
- cork
- cork borer
- clear plastic tube
- bendy straw
- wooden skewer
- balloon piece, cut into 1 square inch
- clear tape
- hot glue gun
- glue stick
- paper plate
- scissors
- clear plastic beaker, 200 mL
- 70 mL of sprinkles
- stopwatch
- butcher paper, 3 feet
- markers
- protractor

Question:

Does the amount of power applied to the gate of a model transistor affect the output at the drain? Make a prediction:

Example prediction: I think that if more power is applied to the gate, the electrons will fill the drain faster because they will have more space to move.

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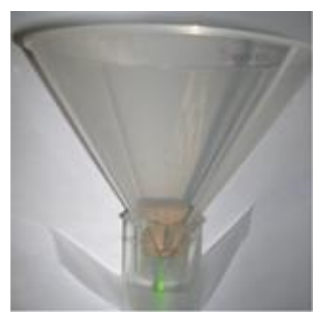
Procedure: Making a Model Transistor

1. Put a line of hot glue along the top of the clear tube. Quickly insert the plastic funnel into the glued end of the tube. Make sure that the funnel is straight up and down. Set this aside standing up for the glue to dry.

2. Insert the skewer into the long part of the straw. Tightly tape the straw to the skewer.
3. Measure 2 cm from the end of the straw (where the skewer sticks out) and make a mark. Cut the skewer at the mark. Save the rest of the skewer for the next step.
4. Insert the wooden skewer (the part that was just cut off) into the short part of the straw. Tightly tape the straw to the skewer.
5. Measure 6 cm from the end of the straw (where the skewer sticks out) and make a mark. Cut the skewer at the mark.

6. Insert the long part of the straw into the hole in the side of the clear tube so that it sticks up through the funnel. The other end of the straw (with the 6 cm of skewer) should stick out of the hole on the side.



7. Make a hole (about 1 cm deep) in the small end of the cork with a cork borer. Put a small drop of hot glue into the hole of the cork and push it onto the top of the straw (with the 2 cm of skewer sticking out). The cork should fit snugly into the neck of the funnel.

8. Cut a small (about 1 cm) slit into the center of the balloon piece. Push the small part of the straw (with the 6 cm of skewer) through this slit. Tape the balloon piece to the clear tube so that it covers the hole. You now have a functional model transistor.!

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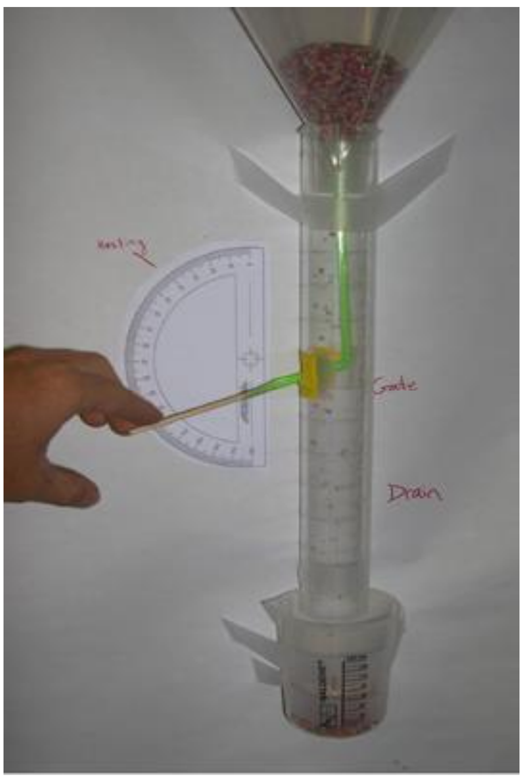
Procedure: Gathering data on the variations in the output of "electrons" due to different lever angles

Step 1:
Add sprinkles to the funnel to represent free electrons.



Step 2:
Pull the lever. Note the angle and time it takes for the sprinkles to fill the container below (left).

Record observations in a table on the butcher paper (right).

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Record Your Observations:

1. Tape the butcher paper to the wall. Tape the model upright onto the paper. Tape the angles paper next to the *gate lever* of your device. Record the resting angle of the gate lever. __*40˚*______
2. Sketch your device. Label the source, drain, and gate.

3. What do the sprinkles represent in your model? *They are the free electrons that are available to move as electricity (called carrier electrons).*
4. Using our new terminology, describe what happens when you apply voltage to (you push down) the gate of your device. *The sprinkles at the source fit through past the cork and flow to the drain.*
5. At what angle does your device first "turn on?" (i.e. electrons start to flow) *120˚*
6. Does the amount of voltage at the gate affect the speed of your device? Time the flow of electrons at different gate angles to find out! (*Hint*: To stay organized, you can fill in the table below or make your own table on the butcher paper!)

Drainage Time vs. Gate Angle

	Time (s)			
Gate Angle (˚)	**Trial 1**	**Trial 2**	**Trial 3**	**Average**
110˚	*No flow*	*No flow*	*No flow*	*No flow*
120˚	*17 s*	*16 s*	*22 s*	*18.3 s*
130˚	*5 s*	*4 s*	*3 s*	*4 s*
160˚	*1 s*	*1 s*	*2 s*	*1.3 s*

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7. What else do you notice? Record 3 intriguing observations.

   a. *Example observation: Some of the sprinkles always get stuck on the top of the cork.*

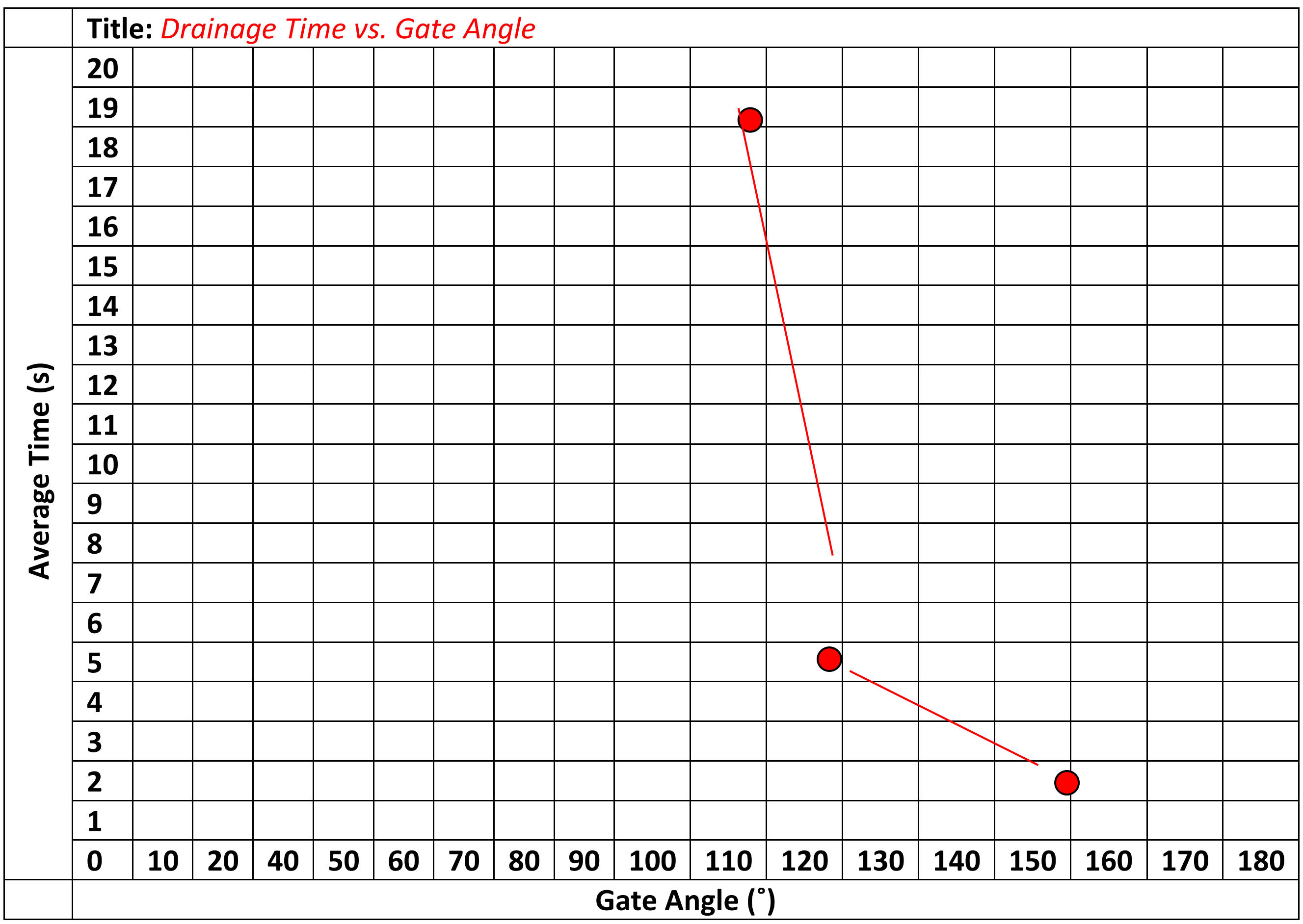
   b. *Example observation: The cork does not always completely seal the funnel neck.*

   c. *Example observation: If the straw is pushed back farther in the clear tube, there is more leverage and the sprinkles flow faster.*

Analyze the Results:

1. At what gate angle do the sprinkles flow the fastest? *160º*

2. Graph your data table.



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Draw Conclusions:

1. Use a ruler to draw a line of best fit between the points on your graph and calculate the slope *(y_1–y_2 ÷ x_1–x_2)*. *Example answer: (130 –150) ÷ (10 – 2)= –0.4 seconds/degree of angle*

2. What does the slope of your line represent? *Example answer: It represents the change of the bead flow in seconds for a 1˚ increase on the gate angle. So, for my model transistor, the time it takes to drain the sprinkles decreases 0.4 s every time I increase my gate angle by 1˚.*

3. Based on the data you collected, was your hypothesis correct? Explain why or why not using your data as evidence. *Example answer: My hypothesis was correct because as I applied more pressure to the gate, the sprinkles emptied into the drain in less time. This can be seen by the negative slope of my line graph.*

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