Magnetic Mad Libs

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Subject: Physics

Grade Level: 6-9

Standards: *Next Generation Science Standards (www.nextgenscience.org)*

MS-PS2-5. Conduct an investigation and evaluate the experimental design to provide evidence that fields exist between objects exerting forces on each other even though the objects are not in contact.

Schedule: 60 minutes

CCMR Lending Library Connected Activities:
Electromagnets

Objectives:	Vocabulary:
• Learn how hard drives work • Review basic principles of magnetism • Understand how digital electronics store information in binary	Binary Bit Byte Platen Read Head Nanotechnology
Students Will: • Explore magnets and derive some of their properties • Translate messages to and from binary • Learn what nanotechnology is and see a hands-on example • Simulate hard drives by sending one another messages encoded in magnets, and in doing so, complete "mad libs" • Complete a work sheet to reinforce learning	**Materials:** **For Class:** __ Hard Drive __ Electromagnet __ Compass __ Alphabet Code **For Each Group (2-3 Students):** __ Ring Magnet Stand __ 6 Ring Magnets __ Reader Magnet __ Felt Pocket Board
Safety	This activity contains a battery hooked up to a low-resistance wire. Care should be taken not to leave the battery connected, or it can become very hot.

Science Content for the Teacher:

Introduction

Students are constantly using hard drives, but few understand how they work. How does a song from iTunes get stored on the computer? By trying to answer the question, "how do hard drives work?", kids will not only learn more about the world around them, but they will see a concrete example of some abstract math (binary) and science (magnetism) concepts that might otherwise seem academic and pointless. Additionally, hard drives are a great example of nanotechnology, which is an emerging area of technology that will be increasingly important in tomorrow's society.

So how *does* a song from iTunes get stored on the computer? The answer is that the song is stored in a code called binary in tiny magnets. We'll break that down into several parts. First, we'll talk about storing information in binary. Second, we'll talk about how magnets can represent binary information. Third, we'll talk about reading and writing information in a hard drive. Finally, we'll talk about scale, how small the magnets in a hard drive are, and how many of them one needs to store an iTunes song.

Binary

All information in computers is stored in binary, which means that it is stored as a series of 0s and 1s. For example, to store a text file, each letter is assigned to a particular combination of 0s and 1s. The letter 'z', for example, is usually stored in computers as 01111010. Then whole messages can be stored as long strings of 0s and 1s. When we translate information into binary, each "0" or "1" is called a "bit". For example, we might say that the code for 'z' written above, 01111010 has eight bits. The first, sixth, and eighth bits are 0, while the others are 1. In digital electronics, all information is always stored in binary, and pretty much anything can be stored in this way.

For example, one could imagine that songs could be translated by assigning each note to a particular string of 0s and 1s. It turns out that this *isn't* how songs are translated to binary. The actual methodology, which has to distinguish between the difference between middle C played on a guitar as opposed to middle C sung by Justin Bieber, involves digitizing sound waves in a rather complicated way. But that's beyond the scope of this lesson.

Representing information in magnets

Hard drives are collections of billions of tiny magnets. Each magnet is one bit. As your students know, magnets have two poles, north and south. If the north pole is pointing up, that represents "1"; if the south pole points up, that represents "0". The particular shape of the magnets in the hard drive prevent them from pointing in any other direction. That's it—all information on a hard drive is magnets pointing up or pointing down. Magnets are a particularly good way of storing information, because they continue pointing in whatever direction they're pointing in even when you unplug your computer. (Imagine your refrigerator magnets—they're not plugged in, but they continue to work.)

Reading and writing magnets

Hard drives have two main functions: they need to *read* out stored data, and they need to be able to *write* new data. Reading is what the drive does when I want to listen to a song from my iTunes library. Writing is what I do when I download and save a new song, so that I can get to it later.

When you take a hard drive apart, you see something like the diagram shown in figure 1. If you could zoom in on the section shown by the white dotted line, you would see something that looks like the geometry shown in figure 2. The shiny metal disk is where the magnets are. This is called the platen. You can't see where one magnet starts and the next ends—the magnets are too small.

Figure 1: A photo of a hard drive. The white dotted box shows the read head sitting on top of the platen, as will be shown schematically in figure 2.

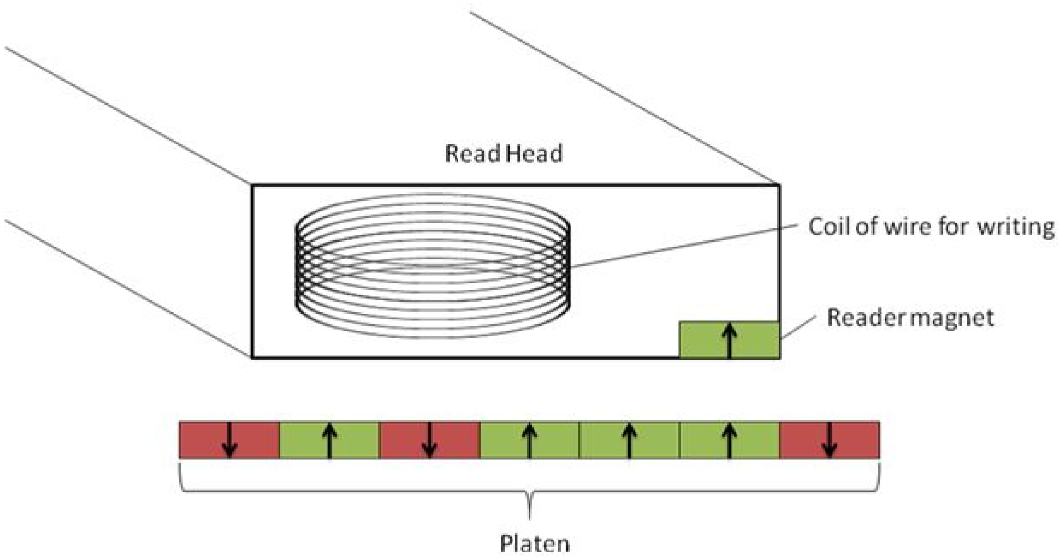

Figure 2: A schematic of a hard drive head

To read data, the reader head passes over the platen. The reader magnet tends to align with whatever magnet is directly underneath it. (Why? The north pole on top of the underlying magnet attracts the south pole on the bottom of the reader magnet.)

To write data, the magnets on the platen have to be flipped. This is achieved by using the connection between electrical current and magnetism. If they've ever seen or played with an electromagnet, your students may know that current flowing in a loop can induce a magnetic force along the perpendicular axis. This is how the hard drive flips the magnets on the platen. Inside the read head there is a coil of wire. As in an electromagnet, passing an electrical current through the wire creates a strong magnetic field, which is just another way of saying that it creates a magnetic force in one direction. Depending on which direction the current flows through the wire coil, the magnet on the platen underneath either wants to flip up or flip down.

Very Small and Very Large Numbers: Nanotechnology and Gigabytes

The magnets in a hard drive are too small to see. Just how small are they? And how many are on the platen of a hard drive? In today's hard drives, the magnets are on the order of 50 nanometers wide, and only a few nanometers thick. A nanometer is 10^{-9} meters. Another way of thinking about this is that one million nanometers will fit into space between millimeter marks on a ruler. Because the magnets are small enough that they can be measured in nanometers, hard drives are an example of "nanotechnology"—the practice of making very small objects do useful things.

So how many of these tiny magnets fit onto the platen? In fact, we're used to talking about the size of hard drives, although we don't normally think about the fact that these sizes are actually counts of the number of magnets on the platen. When you go to Best Buy today, you might buy a hard drive with 200 gigabytes, or even 1 terabyte or storage. What does that mean? Byte is a word that means 8 bits. "Giga-" means 10^9, or a billion. "Tera-" means 10^{12} or a trillion. So a drive with a terabyte of storage means that it has 8 trillion magnets.

Preparation:

1. Photocopy print activity sheets.
2. Pass out magnet stacks (5 circular magnets on a pole and one red/blue reader) to each group. Allow students a few minutes to play with these magnetic stacks in an unstructured way before beginning the lesson.
3. Ensure electromagnet is ready for demonstration (battery has power, wiring is okay).

Classroom Procedure:

Introduction

- Motivate the lesson. Explain that we're going to learn about hard drives. Make sure students know what a hard drive is and what it does, that it stores, reads, and writes information.
- Let the students know what they can expect from the lesson. The sections are as follows:
    - *What is a hard drive? How does it work?*
    - *Thinking about magnetic properties with the ring magnets*
    - *Introduce the idea of binary*
    - *How many bits do we need? How small must they be?*
    - *Electromagnets and hard drive writing*
    - *Mad Libs*

Thinking about magnetic properties with the ring magnets

- How do you take two magnets that stick together and get them to repel? Ans: flip one of the magnets upside down. Why does this work? Ans: magnets create forces that work at a distance. They have two poles, opposites attract and likes repel. Flipping one of the magnets changes the two nearest sides from N-S to N-N (or perhaps S-S).
- How can we prove that the opposite poles attract while similar poles repel? Ans: stick two magnets together. Now put them on the table with the two sticking sides up. Bring over a third magnet. It behaves differently with the two magnets, showing that the two attracting sides have opposite polarity.
- What are the forces at work in levitating the magnets? Ans: Gravity pushes the magnet down, and magnetic forces push the magnet up.

- Why does the magnet sit at the height it's at? Why not higher? Why not lower? Ans: gravity is constant at all heights, but magnetic forces decrease with distance. The magnet sits at the point where the forces are equal.
- *Extension: draw graph of force versus distance: the magnetic force falls off as 1/r^3, theoretically, and the gravity is constant. Explain that equilibrium is where the forces balance/lines meet.*

Introduce the idea of binary

- Define the word bit.
- Referring to the 5-bit binary code for A-Z that you wrote on the board, have the students write their names in binary. Have the students change their name with a neighbor and have their neighbor decode the name to make sure that everyone did it correctly.
- Talk about how any kind of information can be stored in binary.

Hard drives: reading

- Explain that hard drives store information in magnets. Explain that north side up is 1 and north side down is 0. (Or vice versa—the polarity doesn't matter.)
- Put one of the ring magnets on the peg board. Demonstrate how that magnet can be pointed up or down by taking it off the peg board, flipping it 180 degrees, and putting it back on.
- But how does one tell the difference between 0 and 1? Not by looking. Ans: Have to bring a second magnet over top and use the magnetic force. Demonstrate this on the peg board with one of the marked "reader" magnets. Establish the convention that whichever number is up when the reader magnet attracts is the state of the bit.
- Open up the hard drive. Show the different parts, the read head, the platen with the magnets on it, the motor that controls the arm (called the actuator), the port that connects the drive with the rest of the computer.
- Explain how the reader magnet moves over top of the platen, and flips to align with the magnet underneath.
- Point out explicitly that this is how hard drives read information, but we haven't covered writing yet.

How many bits do we need? How small must they be?

- Ask: how big is a song? Ans: 5 megabytes, more or less.
- Ask: what's a byte? Ans: 8 bits. Ask: so what's a *mega*-byte? 8 million bits. Point out that this is 8 million separate magnets.
- Explain that the drive in front of you is about 14 years old, so it has very few bits by modern standards. The drive's capacity is 3000 MB (or 3 *Giga*-bytes) on 3 levels. So there's roughly 8 billion magnets on each level.
- Ask if anyone knows how large most modern drives are. Explain the prefix Tera-.
- Ask the kids to consider how large each magnet is on this drive if there are 8 billion magnets on each platen. It turns out that each magnet is roughly 1 square micron. *(As an extension, the kids can figure this out themselves: radius of the platen is 5cm. Area is pi*r^2, which is approx 79 cm^2. Divide that area by the number of magnets, $8x10^9$.)* Define a micron. Explain that now, 14 years later, magnets are probably about 400 times smaller, on the order of 50 nanometers. (Define "nanometer".) This makes sense, because hard drives today can hold about 400 times more data (1.2 terrabytes).
- What is "nanoscience"? ans: study of things that have sizes in the range of nanometers. Like magnets in hard drives! Hard drives are "nanotechnology".
- *Extension: if desired, it's easy to extend this section into a longer discussion of orders of magnitude and to practice doing math problems with scientific notation. See Extension Activities below.*

Electromagnets and hard drive writing

- Show the various parts of the nail-and-battery electromagnet. This device is just a length of wire wrapped around a nail. When the switch is is just a length of wire wrapped around a nail. When the switch is connected in one direction, current flows through the loop in one direction. If the switch is connected in the other direction, current flows through the loop in the opposite direction. The nail is a magnet, made of iron.
- Assert that current in loops creates magnetic forces, just like refrigerator magnets.

- Let a student briefly connect the switch in one direction and then disconnect it. Have them check the direction of the magnet [the nail] with the compass. **Safety note: don't forget to disconnect the switch soon after connecting it, or the battery will get hot quickly.**
- Have the student connect the switch in the opposite direction and then disconnect it. Note that the magnet's direction has been switched. Point out that we have just switched a magnet with a current. This is the key idea of writing a magnetic bit.
- The field remains after you cut power—this is also a key point.
- Show how writing works in the hard drive by pointing out the loop of wire in the schematic of the read head on the board.

Mad Libs

- Review reading and writing hard drive bits. Show how we will simulate these things with our pegboards, but point out the differences. (Reading is quite similar, but we write by picking the magnet up and flipping it, whereas on the hard disk the magnet doesn't move, the electromagnet switches it in place. Also, scale is very different.)
- Establish a convention: the reader magnet is always the red side down. If it attracts to the other magnet, that is a 1. If it repels, that is a 0.
- Have the students pair up and distribute a board and 6 magnets (including one marked, "reader" magnet) to each student. Pick a practice word, and have everyone make that word on their board, and then switch boards with their partners for decoding. Make sure everyone has the hang of the activity.
- Begin the activity in earnest. Each student should:
    - Step 1: Choose words they want to send and translate those words into binary with the dictionary
    - Step 2: Make the first word on their board and pass to their partner
    - Step 3: Decode their partner's word, and fill that word into their own madlib.
    - Step 4: Repeat steps 2 and 3 until all words have been communicated.
    - *Extension: if some students finish early, consider challenging them with question 1a from the Extension Activties section below.*

Worksheet and learning review

Give the students the worksheet to fill in. When they are finished, go over the answers as a group. Here are some examples of good answers:

- ans 1: Stores as ones and zeros. A bit is a one or a zero.
- ans 2: A magnet
- ans 3: The direction the magnet points
- ans 4: Read and write
- ans 5: A reader magnet passes over the storage magnets on the platen, and it feels a force from the storage magnets, which the computer detects.
- ans 6: A coil of wire passes over the storage magnet on the platen and a pulse of current through that wire switches the magnet on the platen.

Extension Activities:

High school teachers might find that the lesson above does not go into enough depth for their students. The information in the "supplementary information below" should give the extra depth they need. Communicating that information through lecture and discussion is one possible extension activity. Teachers might start the discussion of different kinds of memory with the following math problems:

1) In this problem, we want to know how long it should take to write a song to a hard drive.
   a) Suppose that a song is 5 MB, and that the bit size is 50 nm. How long are the magnets needed to save that song, laid out end to end?
   b) Modern hard drives spin at around 7200 rpm. How fast is a bit on the middle of the platen travelling? Assume that the drive is about 10 cm in diameter.
   c) So how long does it take to write a song?

   Answers: the read head needs to cover 5*8*10^6*50nm=**2m**, and it's travelling at a speed of 7200 rpm * 2*pi*2.5 cm=**19 m/s**. So time = distance/speed=about **0.1s**. Note: That's pretty fast, not too bad. This shows that when writing serially, hard drives are pretty quick.

2) How long does it take a hard drive to get from one side of the platen to the other, given a spin speed of 7200 rpm? Given that most computer processors today run at about 2GHz, how many processor cycles will have

completed by the time the hard drive gets from one bit to another on the opposite side of the disk? (Answer in supplementary info below.) This shows why hard disks aren't used for RAM.

Supplemental Information:

Different kinds of memory

To put this lesson in context, it is important to realize that computers today have different kinds of memory. Hard drives are great because they store information without power. As such, they excel at storing large amounts of data for long periods of time. They're also not bad at reading bits "serially"—one after another in order, as when you watch a movie. However, they're very bad for "random access memory". For an operating system to work, it needs to draw instructions from diverse places on disk, and in order to get from one random bit to the next, the disc has to spin and the arm has to move. Although both of these actions happen quickly by human standards, by computer standards, they are very, very slow. (Modern hard drives move at 7200 revolutions per minute, or about 80 mph on the outside edge. Still, if the two bits the computer needs are on opposite sides of the platen, it will take about 5 milliseconds to make the move. An average processor, however, runs at 2 GHz, which means it reads and writes bits every 0.5 nanoseconds. That means that the hard drive is 10 million times too slow to keep up with the processor.)

So processors have their own memory called RAM (for "random access memory"), that is much faster than hard drives at retrieving and storing information. Unlike hard drives, RAM has nothing to do with magnets. A bit of RAM is a small capacitor. In other words, each bit of a RAM is a small bit of metal. If that bit of metal is negatively charged, if it has extra electrons, then that's the "1" state, but if it's neutral, then that's the "0" state. The trouble with RAM is that those extra electrons leak off very quickly. They have to be refreshed very frequently—millions of times per second. That's where a lot of the power goes in modern computers.

If you ever shop for a computer, you'll notice that the specs for the computer specify these two different kinds of memory—the RAM, often around 4 GB, and the hard drive, often around 500 GB. Both kinds of memory store information, but in different ways and for different purposes. RAM is very fast, but it consumes a lot of power, and it's more expensive. Hard drives are slower, but they are cheap, and they can store lots of information without power.

Students may ask how solid state drives work, as many devices today, such as the Macbook Air, are driven by solid state drives. Most solid state drives have flash memory. Flash is also a kind of capacitor, similar to RAM. However, in flash memory, the bit of charge that indicates “0” or “1” is stored on top of a thick insulator that keeps it from leaking away. The problem is that it’s difficult to write flash: it requires a lot of voltage to push the charge through the large barrier and get it to the metal on top. This means that flash can only be written in certain ways—you have to write many bits at once. Worse, these large voltages cause the insulator to break down over time, which is why flash wears out. Flash is getting better by the year, though, as materials scientists find better ways of making it.

Giant Magnetoresistance

The discussion above of how hard drives read out information is incomplete. It’s true that a reader magnet in the read head passes over the magnets in the platen and partially aligns with the magnet over which it is passing. But then what? Computers are electric devices. They operate with voltages, currents, and resistances. How does the change of the orientation of the reader magnet get translated into a change in an electric signal—a voltage, current, or resistance? The answer is an effect called “Giant Magnetoresistance”, and the discovery of this effect was the subject of the 2007 Nobel Prize in physics.

As show in Figure 3, the read head actually has two magnets in it. The smaller magnet, which we previously called the “reader magnet”, is also called the free layer, and it is positioned next to a larger magnet, the “fixed layer”. The giant magnetoresistance effect says that when current is passed through the two magnets, and the magnets point the same direction, the resistance is low. When the magnets point in opposite directions, the resistance is high. That is how the direction of the reader magnet, aka the free layer, is converted into an electrical signal.

The mechanism behind this effect has to do with the spins of the electrons in the current. Recall that electrical current is just flowing electrons, and that electrons have a fundamental property called spin. (Unbalanced spins are responsible for ferromagnetism, incidentally.) As shown in Figure 4, when electrical current passes through the fixed layer, the electrons’ spins align with the magnetic direction of that layer. In other words, the current becomes “spin polarized”. The spin polarized current pass through the barrier and tries to enter the free layer. If the free layer is pointed in the same direction as the spins of the electrons, the electrons find that they can enter easily—they experience little resistance. But if the free layer is pointed in the opposite direction as the spins of the incoming electrons, they pass with difficulty—the circuit has high resistance. In this way, we have successfully converted the orientation of a magnet into a difference in resistance. This difference can be significant: the resistance may double. This idea is significant because it is a fairly recent discovery, the key to significant improvements in hard drive technology, and an example of both spintronics and nanotechnology.

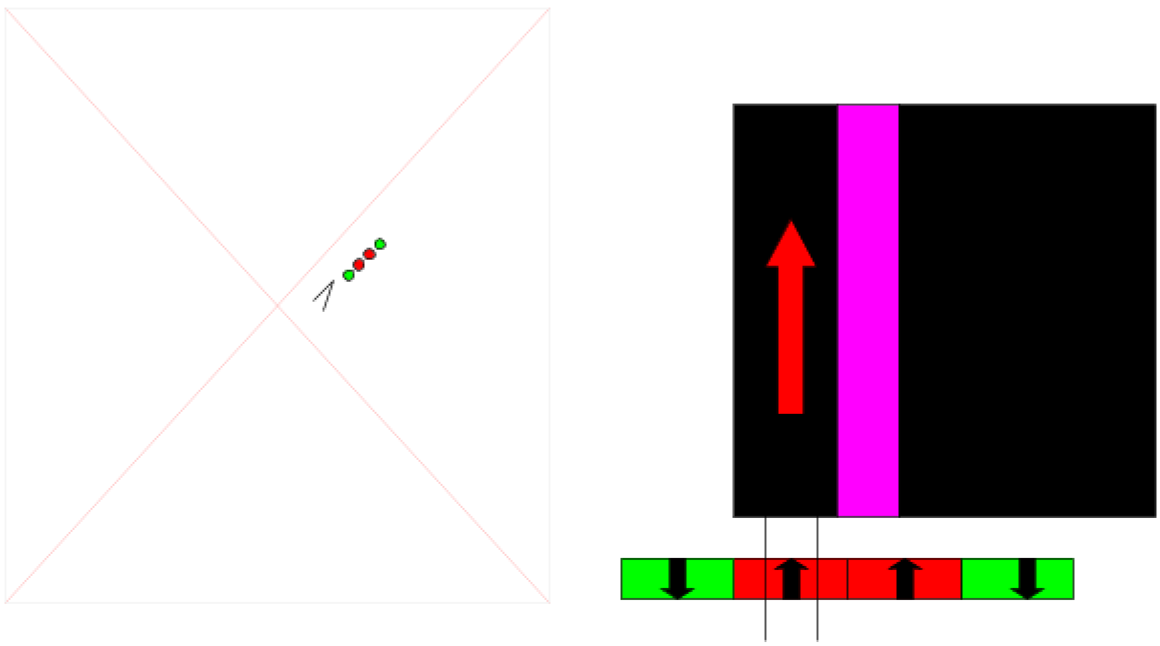

Figure 3: A more detailed look at the read head. What was previously called the "reader magnet" is now called the "free layer". It is positioned next to a larger magnet called the "fixed layer".

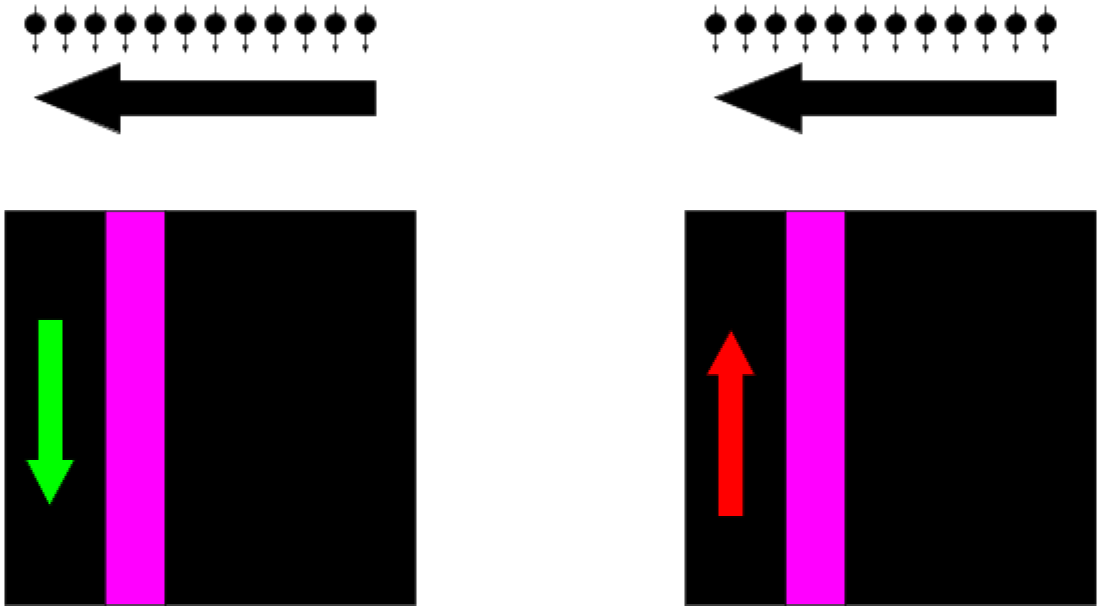

Figure 4: Schematic explanation of giant magnetoresistance, the physics behind hard drive read heads.

Assessment:

The following rubric can be used to assess students during each part of the activity. The term “expectations” here refers to the content, process and attitudinal goals for this activity. Evidence for understanding may be in the form of oral as well as written communication, both with the teacher as well as observed communication with other students. Specifics are listed in the table below.

4= exceeds expectations
3= meets expectations consistently
2= meets expectations occasionally
1= not meeting expectations

	Engage	Explore	Explain
4	Shows leadership in the discussion and an understanding of magnets, electromagnets, binary code, and hard drives.	Completes work accurately while providing an explanation for what is observed. Works well with group.	Provides and in-depth explanation of findings. Fills out actviity sheet clearly.
3	Participates in the discussion and shows an understanding of magnets, electromagnets, binary code, and hard drives.	Completes work accurately and works well with group	Provides clear explanation of findings. Fills out activity sheet clearly.
2	Contributes to the discussion, but shows little understanding of magnets, electromagnets, binary code, and hard drives.	Makes some mistakes with the activities and does not work well with group.	Provides a limited explanation of findings. Fills out some of the activity sheet.
1	Does not participate in discussion. Shows no understanding of magnets, electromagnets, binary code, and hard drives.	Does little to complete the activity	Is not clear in explanation of findings. Does not fill out activity sheett.