Tutorial reading 1 (only part 1 is required, part 2 is an optional append... Due August 23, 2026 at 8:00 PM EDT 0-3 points	Tutorial reading 2 Due August 25, 2026 at 10:00 PM EDT 0-3 points	Watch the first 2 minutes of this video to prepare us for... Due August 27, 2026 at 1:00 PM EDT 0-3 points
3 ✓	2 ✓	1 ✓
2 ✓		
3 ✓		
1 ✓	0 ✓	0 ✓
3 ✓	3 ✓	0 ✓
3 ✓	3 ✓	
2 ✓	3 ✓	
2 ✓	3 ✓	1 ✓
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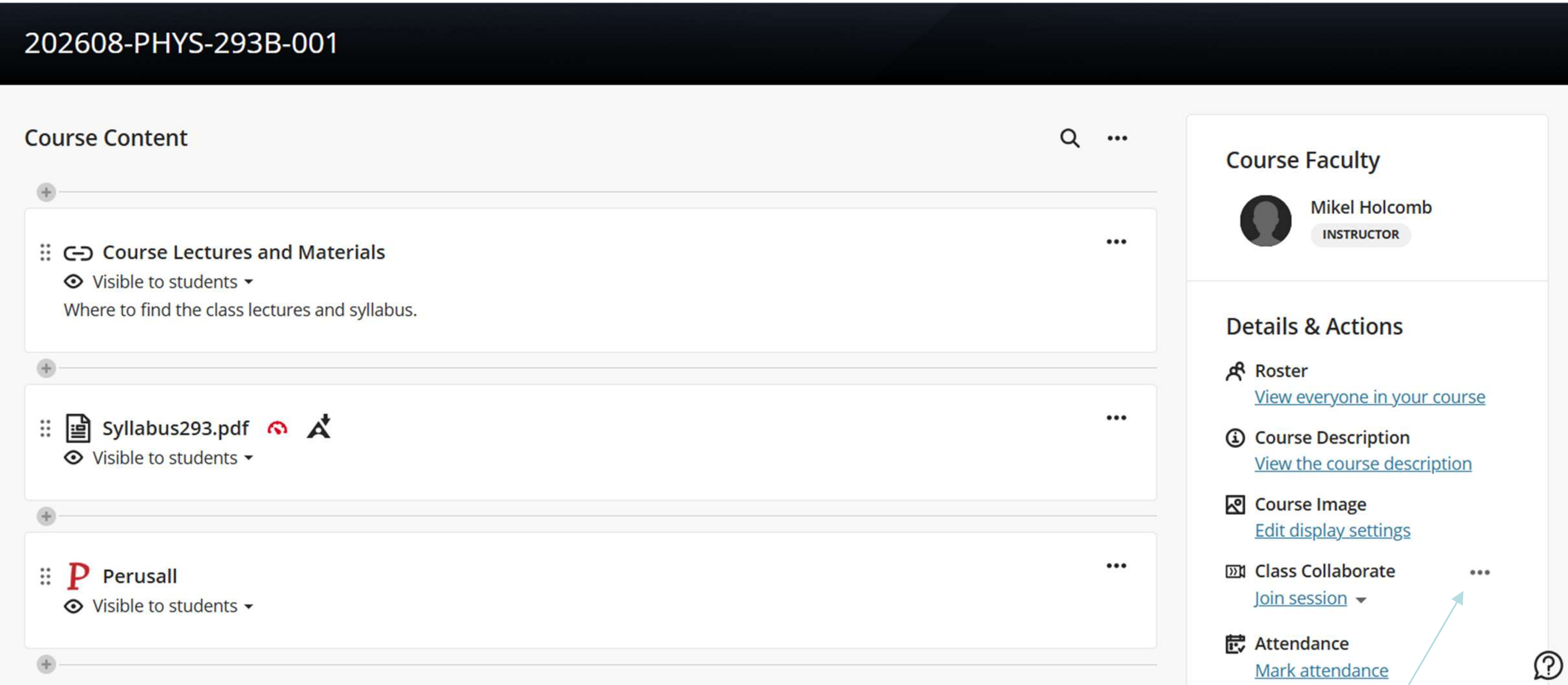
3 ✓	3 ✓	1 ✓
3 ✓	2 ✓	
3 ✓	2 ✓	
2.5	2.2	0.6

Where to find the recording



Right click and then click on "View Recordings"

Define Topic ↔ Gather Sources ↔ Experiment ↔ Analyze ↔ Communicate

Any Questions?

Instructions for safety assignment:
Email me when you email Miranda as in instructions:
Safety Training | Department of Physics and Astronomy | West Virginia University

It's not short so get a start when you can!

Perusall

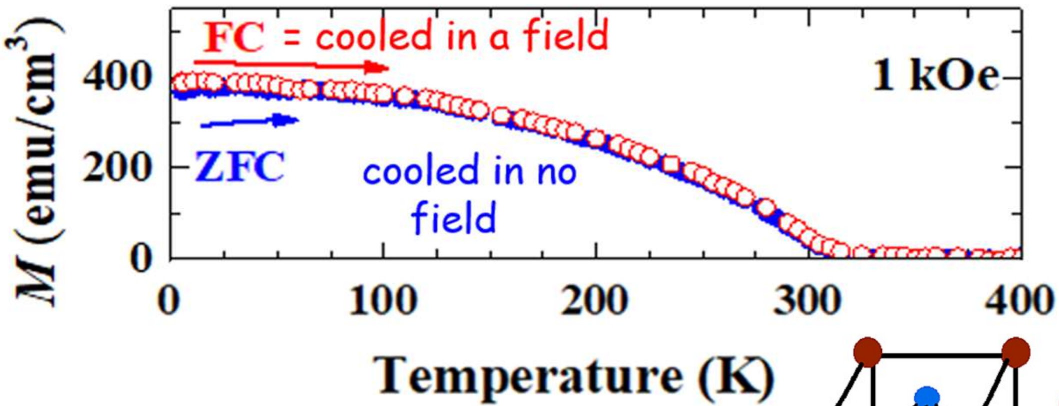
Date	293 Topic	Homework (with goals color)
18-Aug	Pre-Surveys; What is this Class About?	Partner/Scheduling Info
[illegible]Aug	Di[illegible]gnetism	[illegible]eading[illegible]
[illegible]Aug	Ho[illegible]	[illegible]eading 2 [illegible]
27-Aug	MOKE versus Other Magnetometry	Watch Video on Perusall
1-Sep	Project Planning: What Kinds of Magnetic Measurements	Syllabus Read/Agree
3-Sep	Finding Published Papers Relevant to Your Project	Bring a Related Paper to Class
8-Sep	Reading and Evaluating Papers	
10-Sep	Best Practices with Lab Notebooks	University Safety Requirement
15-Sep	MOKE Hands-On Demonstration	
17-Sep	VSM Hands-On Demonstration	Important Papers. Why? (2-5)
22-Sep	How to Give Peer Feedback and Group Project Planning	
24-Sep	Planning Group Oral Reports and Peer Grading	Mini Reports (in class)
29-Sep	Group Project Planning and Refinement	Quality Reading on Perusall
1-Oct	Assessing the Quality of Materials	Project Proposal
6-Oct	Best Practices with Graphing	Good/Bad Graphs
8-Oct	Fall Break (No Class)	
13-Oct	Introduction to Excel: Spreadsheets, Graphing and Fitting	
15-Oct	Understanding and Processing Your Data	Lab Notebook Check-In
20-Oct	Building a Story with Your Data When It Isn't Obvious	
22-Oct	Check-In and How Are Materials Grown	
27-Oct	How to Give a Good Talk	
29-Oct	Peer Evaluation of Lab Notebooks (Bring Notebooks)	
3-Nov	Election Day (Vote If You Can)	
5-Nov	Project Speed Dating: Share Your Project with Others	Graphs of Your Data
10-Nov	Time for groups to Discuss Presentation/Data Planning	
12-Nov	Eight Minute Group Presentations	Presentations
17-Nov	Eight Minute Group Presentations	Presentations
19-Nov	How to Write a Good Abstract	
1-Dec	Ask Your Final Questions of Instructor, Partners or Class	
3-Dec	Discussion of Research and Scholarship Opportunities	Abstract & Notebook

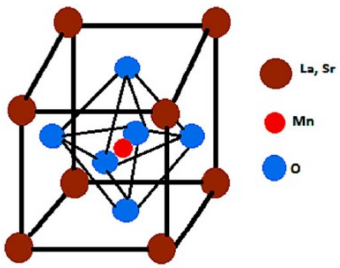
Safety Training (Last priority but needs done eventually)

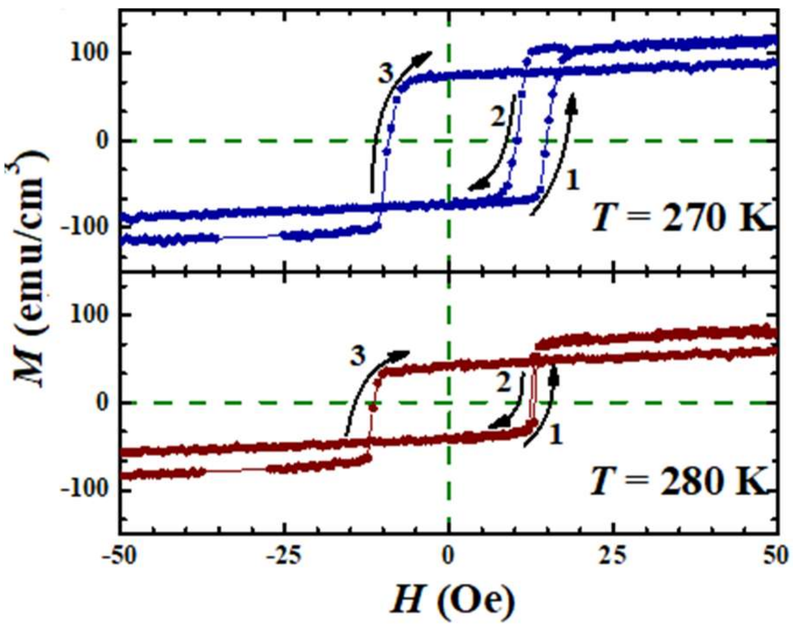
- EHS Hazardous Waste Training is required annually for access and use of labs.
- Follow the directions at: https://physics.wvu.edu/graduate-students/handbook/safety-training

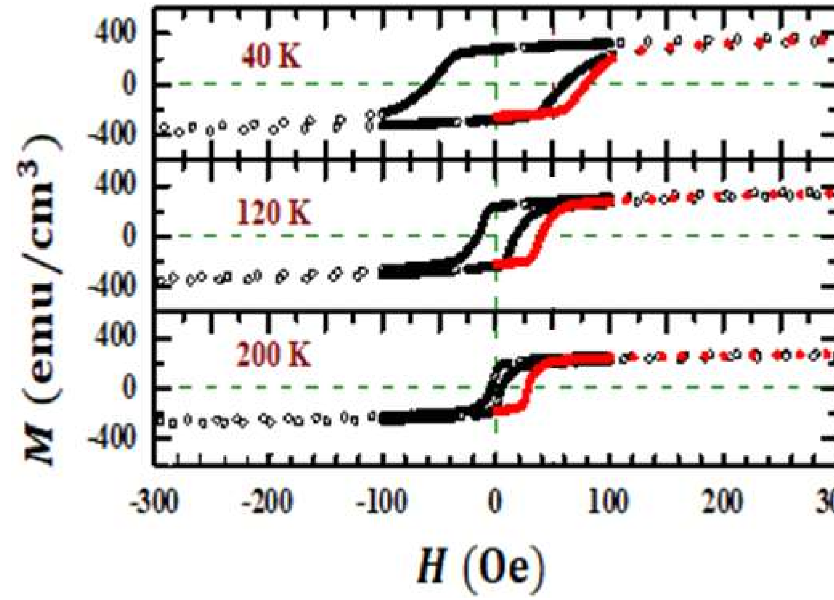
1. Go through all of the required content.
2. Complete the quiz with a minimum 80% grade. Completion form will then appear at the end of module.
3. You must complete the Required Personal Information form after you pass the training! No exceptions.
4. Email Miranda Heitz (miranda.heitz@mail.wvu.edu) to notify her that you have successfully completed your training. Copy (CC) me on that email to Miranda.

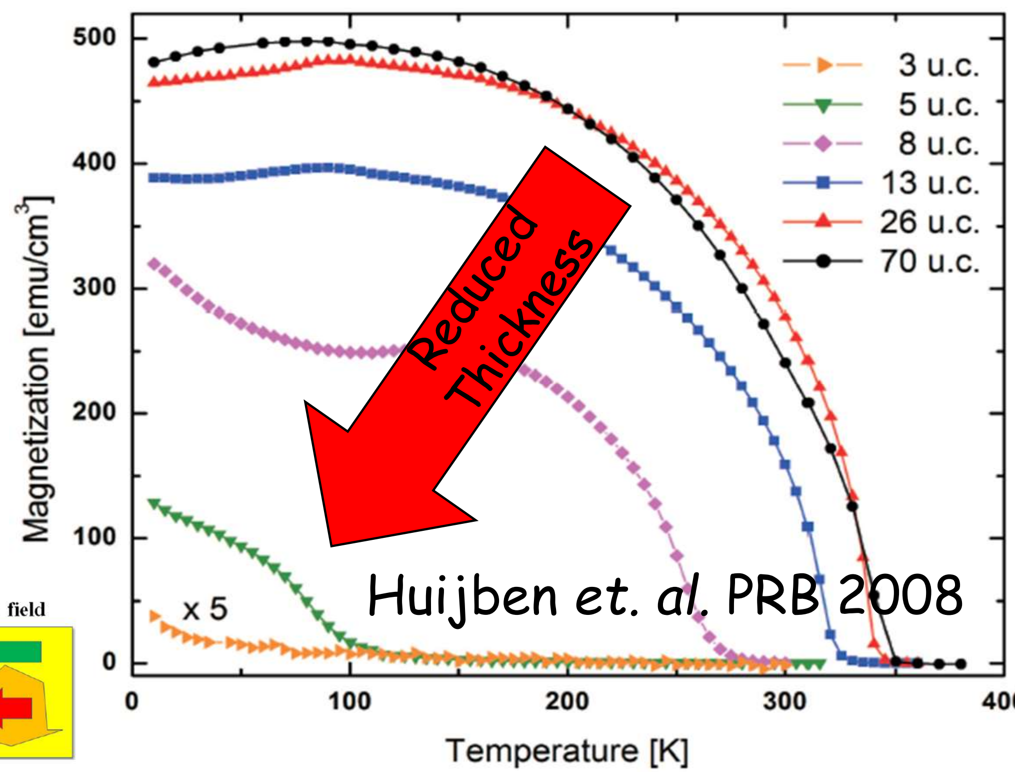
Last Time: $La_{0.7}Sr_{0.3}MnO_3$



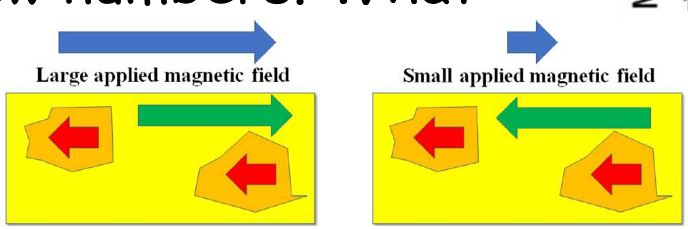




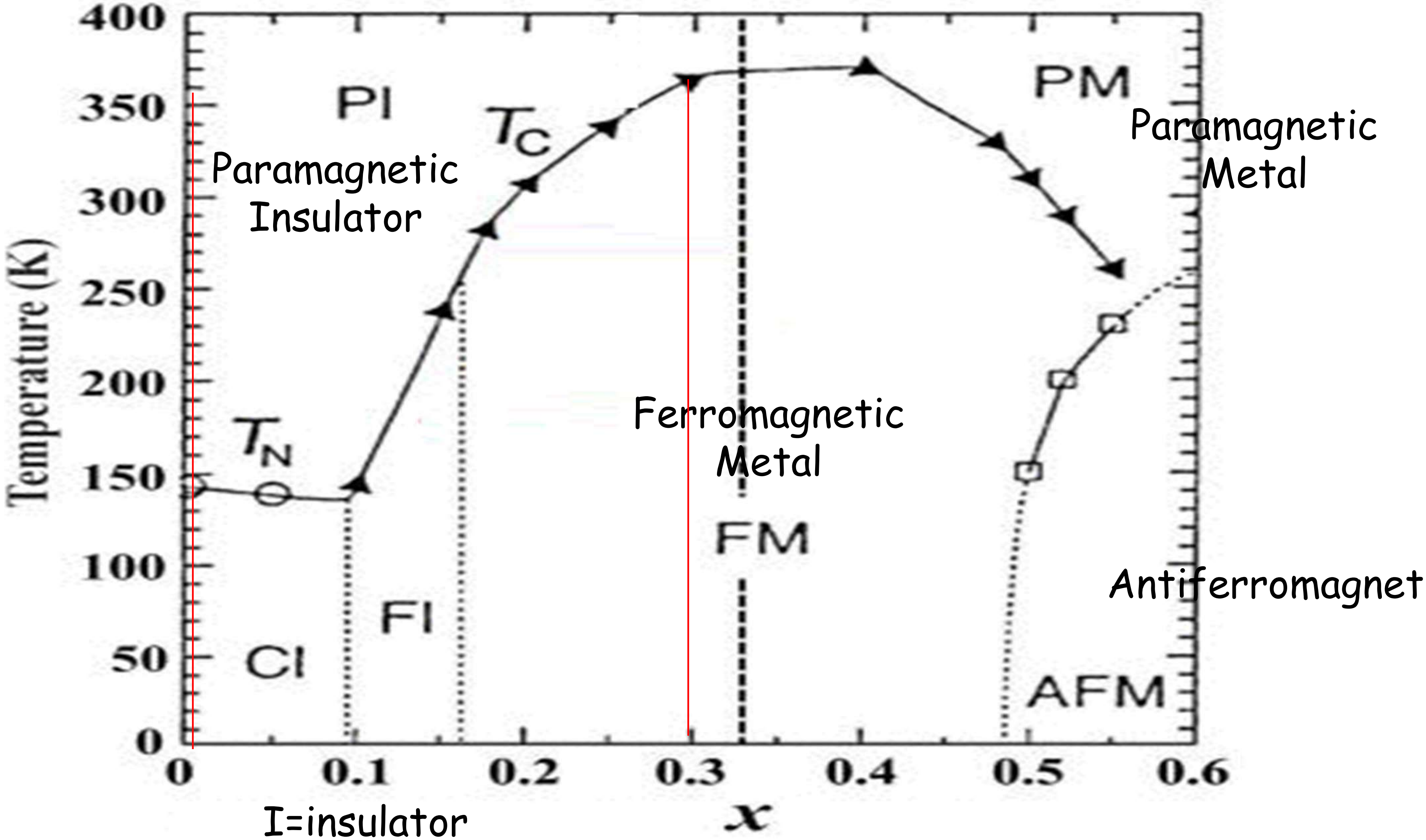




I've added a few numbers. What do they mean?



$La_{1-x}Sr_xMnO_3$ phase diagram

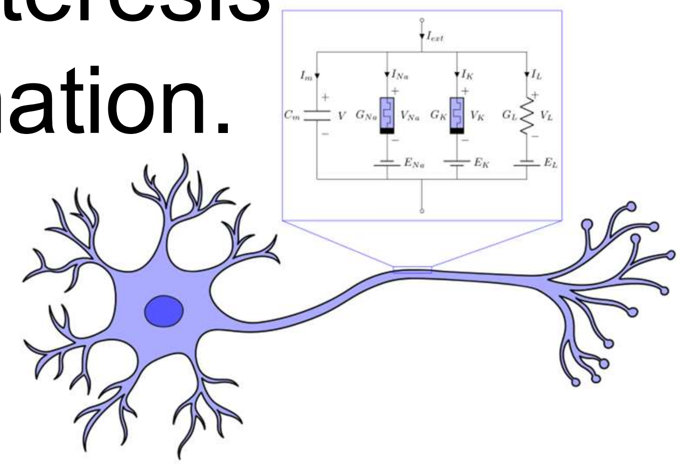


C=Canted (Magnetic): The magnetic moments (spins) of the manganese ions are not fully aligned in a single direction like a standard ferromagnet. Instead, they tilt or "cant" relative to one another, often leading to a weak ferromagnetic or complex antiferromagnetic-like ordering.

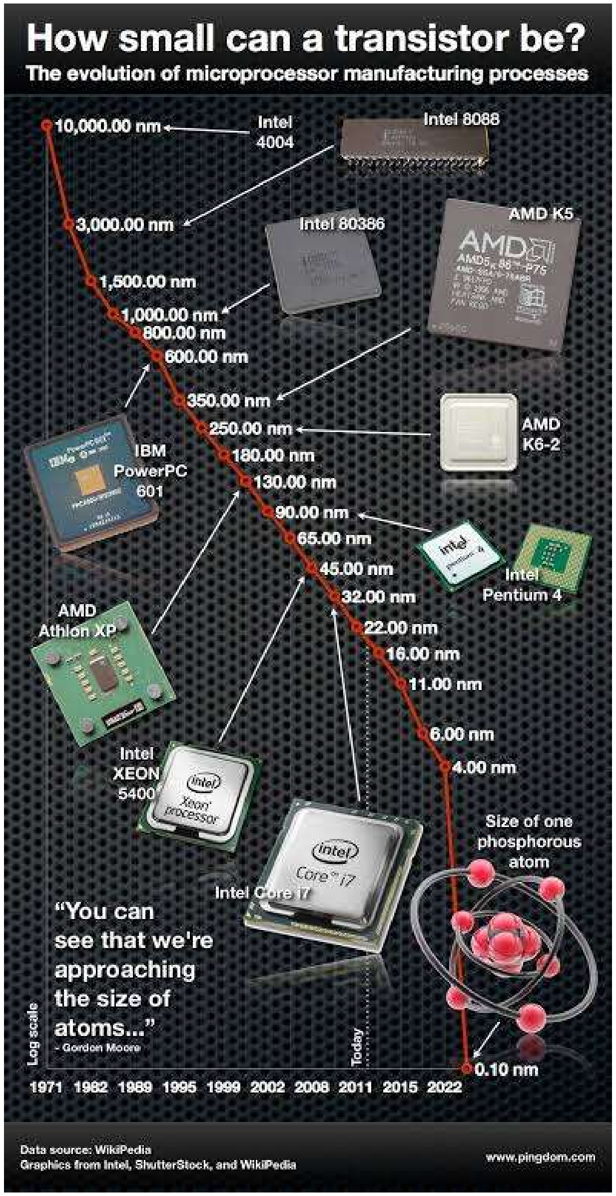
Possible Applications

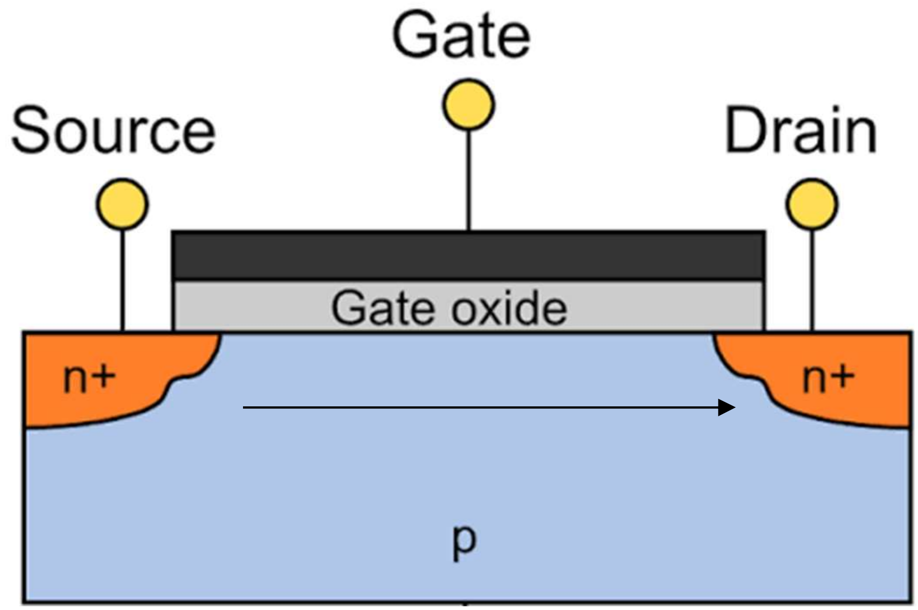
Flipping at low field could be interesting for:

- **Magnetic sensors** – detecting when a field crosses through zero.
- **Magnetic logic or memory devices** – where sharp switching thresholds are useful.
- **Magnetic ratchets or neuromorphic circuits** – where unusual hysteresis responses can encode information.



Why might this be useful for computing?



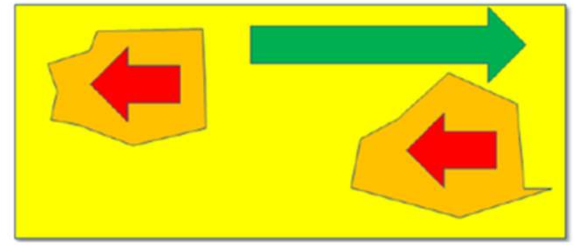


Transistor

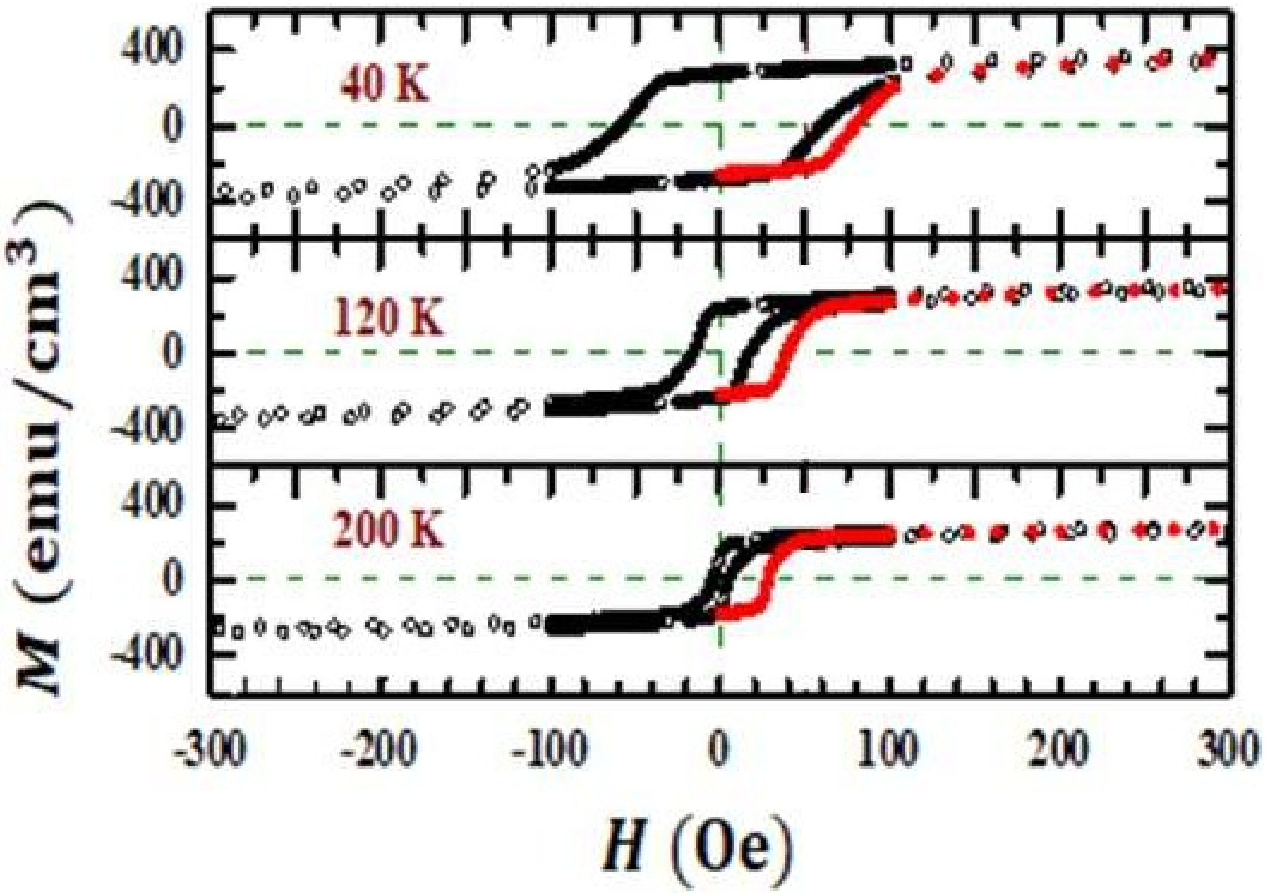
A bit is a 0 or 1 depending on whether electrons flow across this region. Thus, we need constant energy to maintain this information. This is called volatile memory.

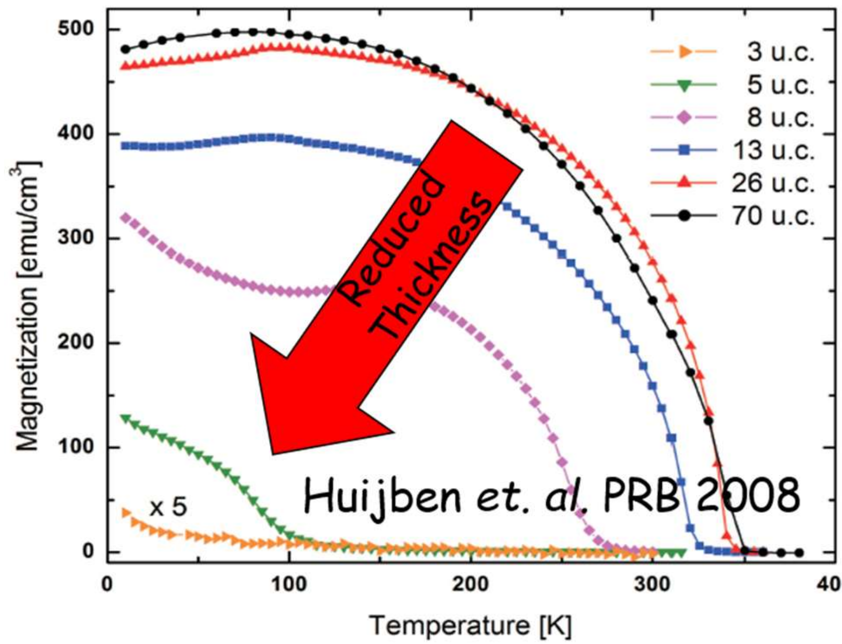
We could alternatively use a magnetic domain to nonvolatilely store this information. Past MRAM used magnetic fields to switch the magnetic direction. Energetically costly. Future ones use spin orbit torque (later).

What Problem Did We Solve?

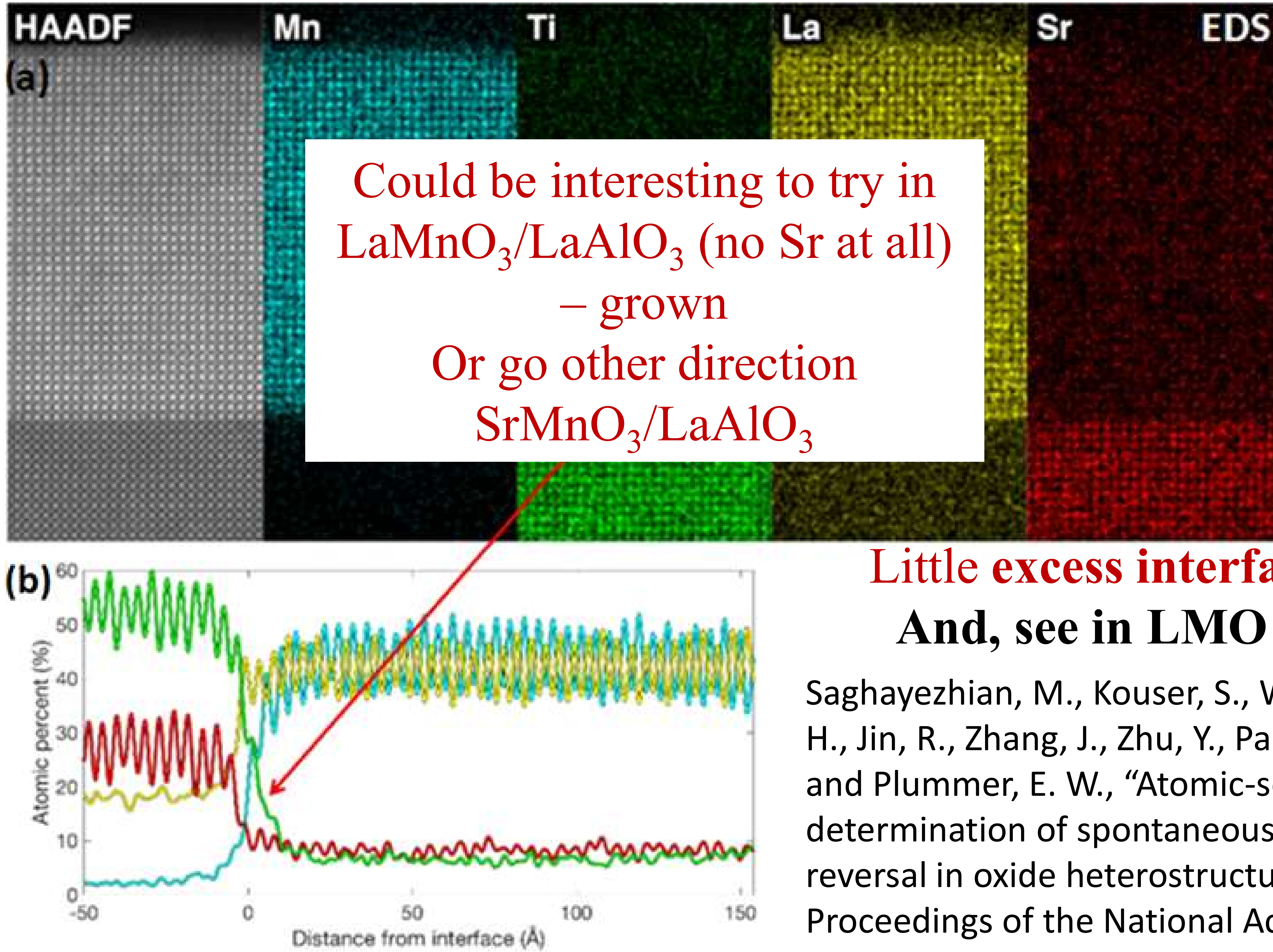


Why would it be almost fully saturated but not completely?





Another Problem: What It is Not



Could be interesting to try in $LaMnO_3/LaAlO_3$ (no Sr at all) – grown

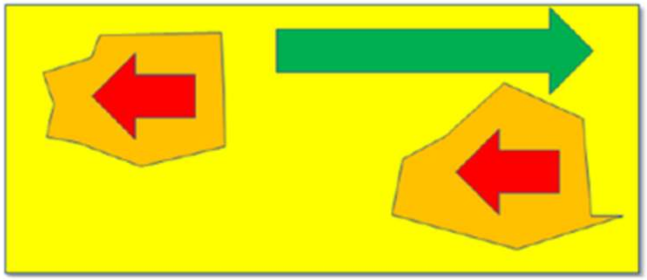
Or go other direction $SrMnO_3/LaAlO_3$

Little **excess interface Sr**

And, see in LMO too!

Saghayezhian, M., Kouser, S., Wang, Z., Guo, H., Jin, R., Zhang, J., Zhu, Y., Pantelides, S. T., and Plummer, E. W., "Atomic-scale determination of spontaneous magnetic reversal in oxide heterostructures," Proceedings of the National Academy of Sciences 116, 10309 – 10316 (2019).

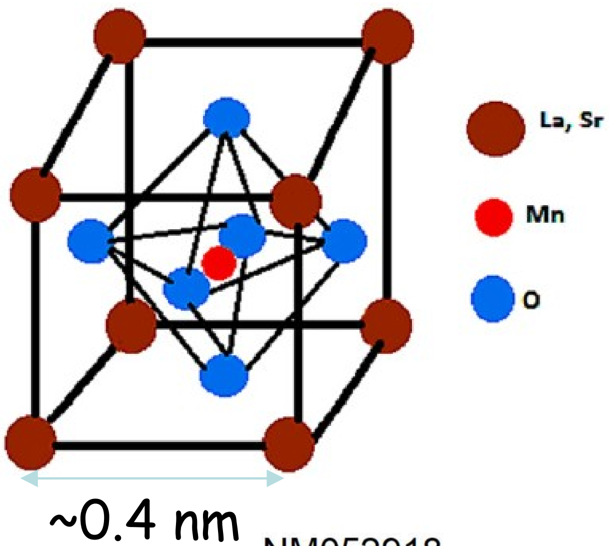
Possible Holcomb Ideas

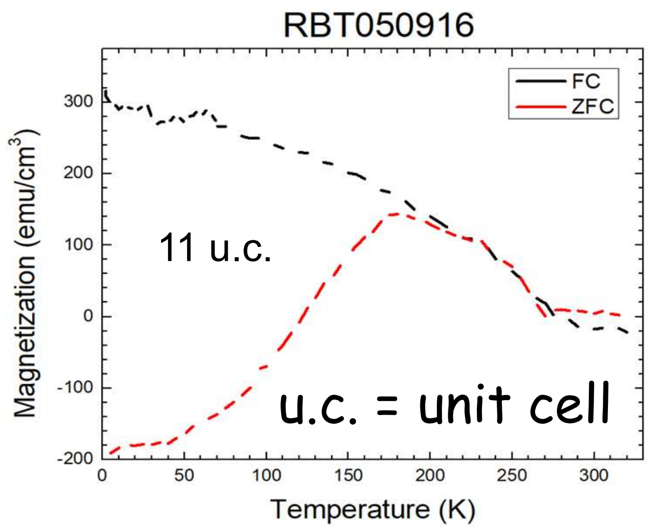


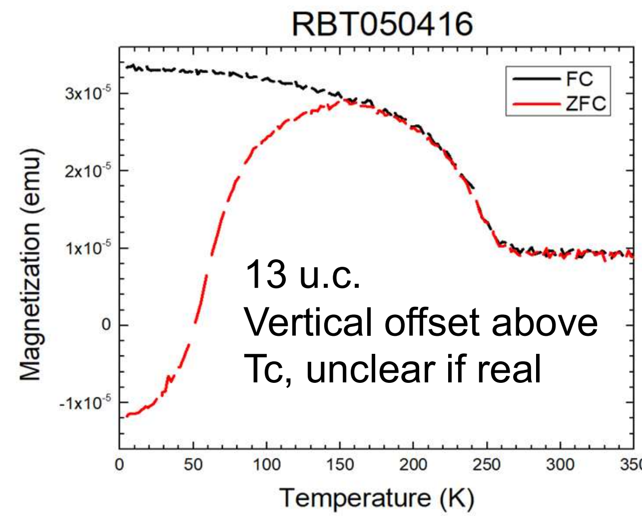
- We have some samples that we recently did beamline measurements on that need magnetic characterization.

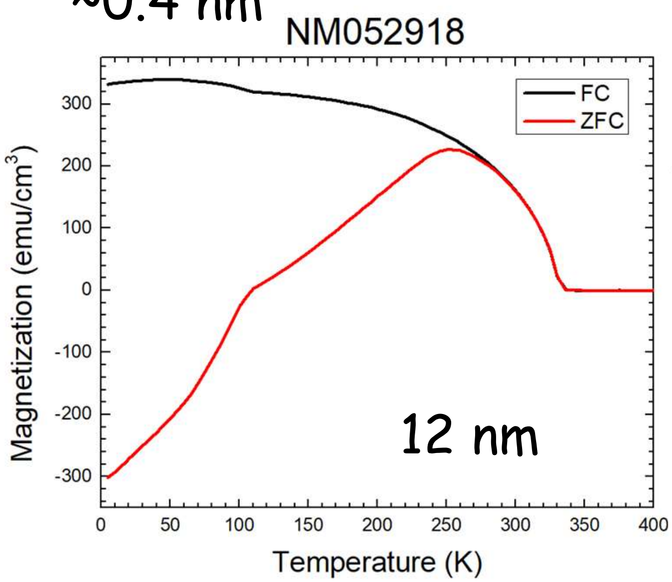
Likely to be published:

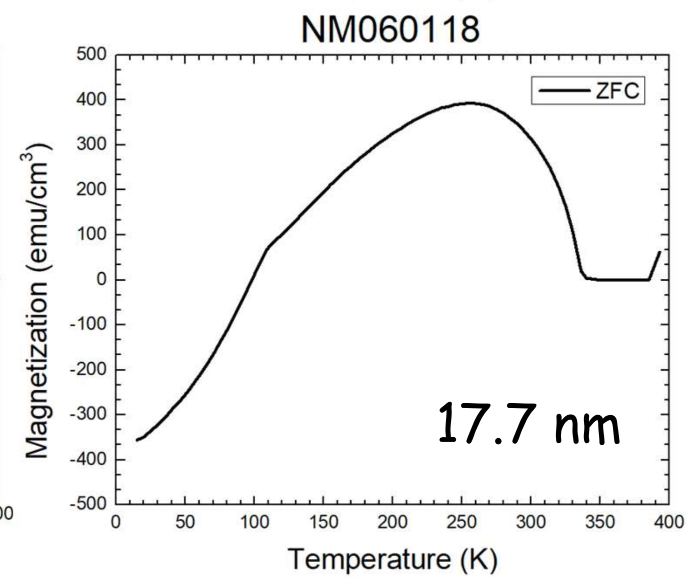
Old measurements need redone to compare with recent beamline work. May only need a few to see if similar.

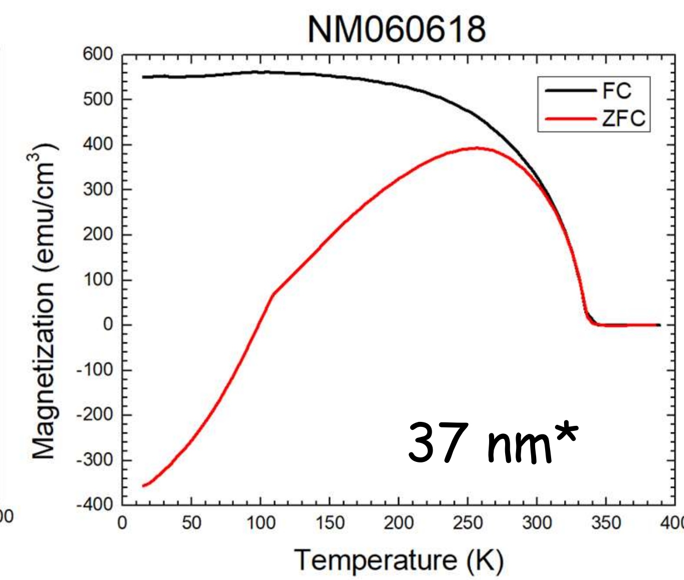




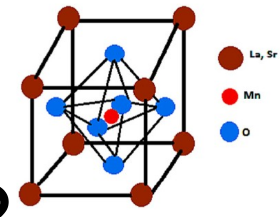




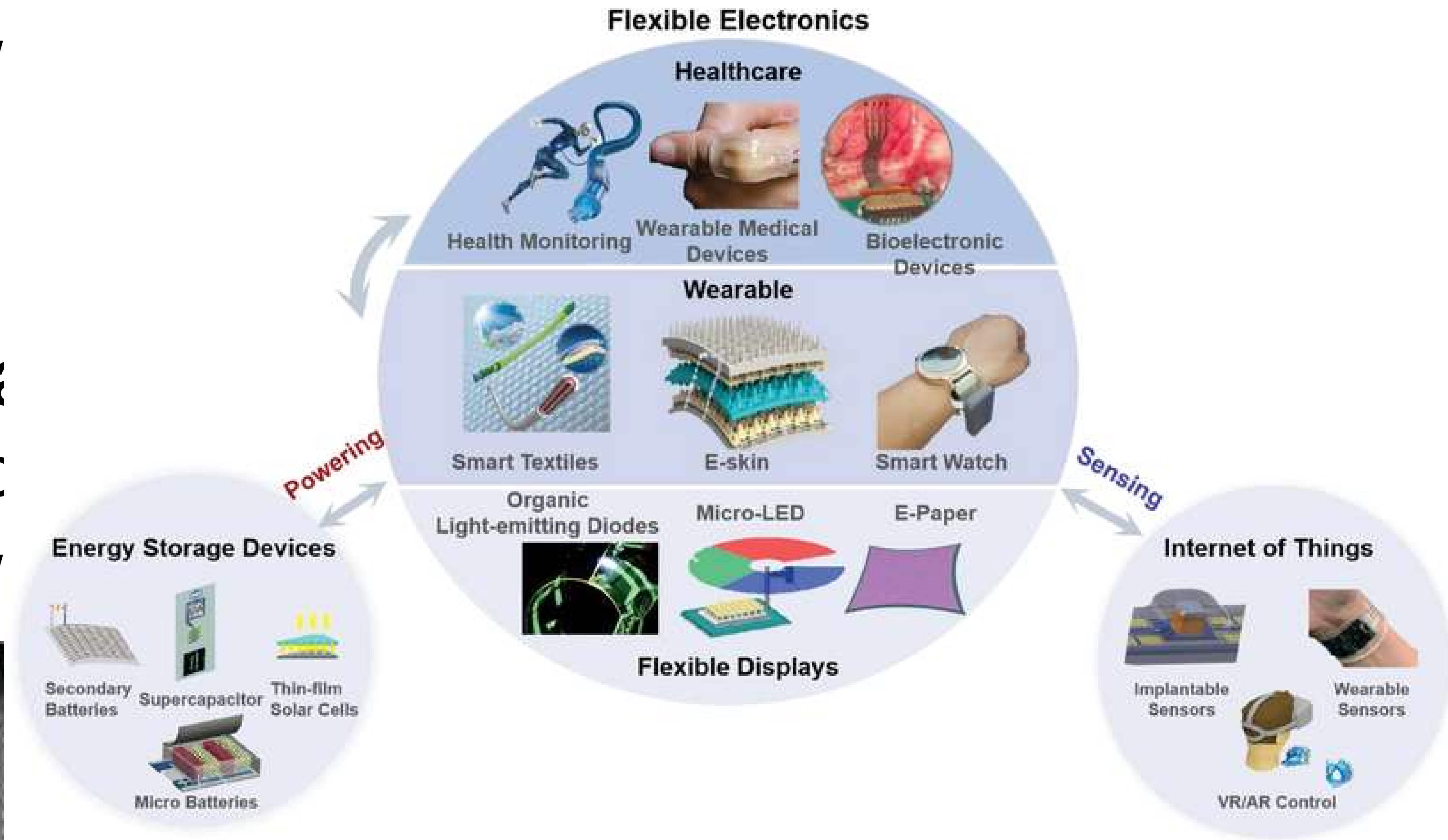


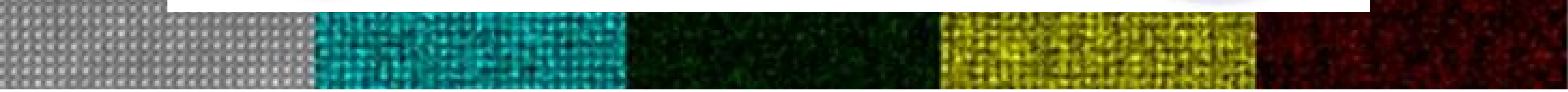


Possible Holcomb Ideas

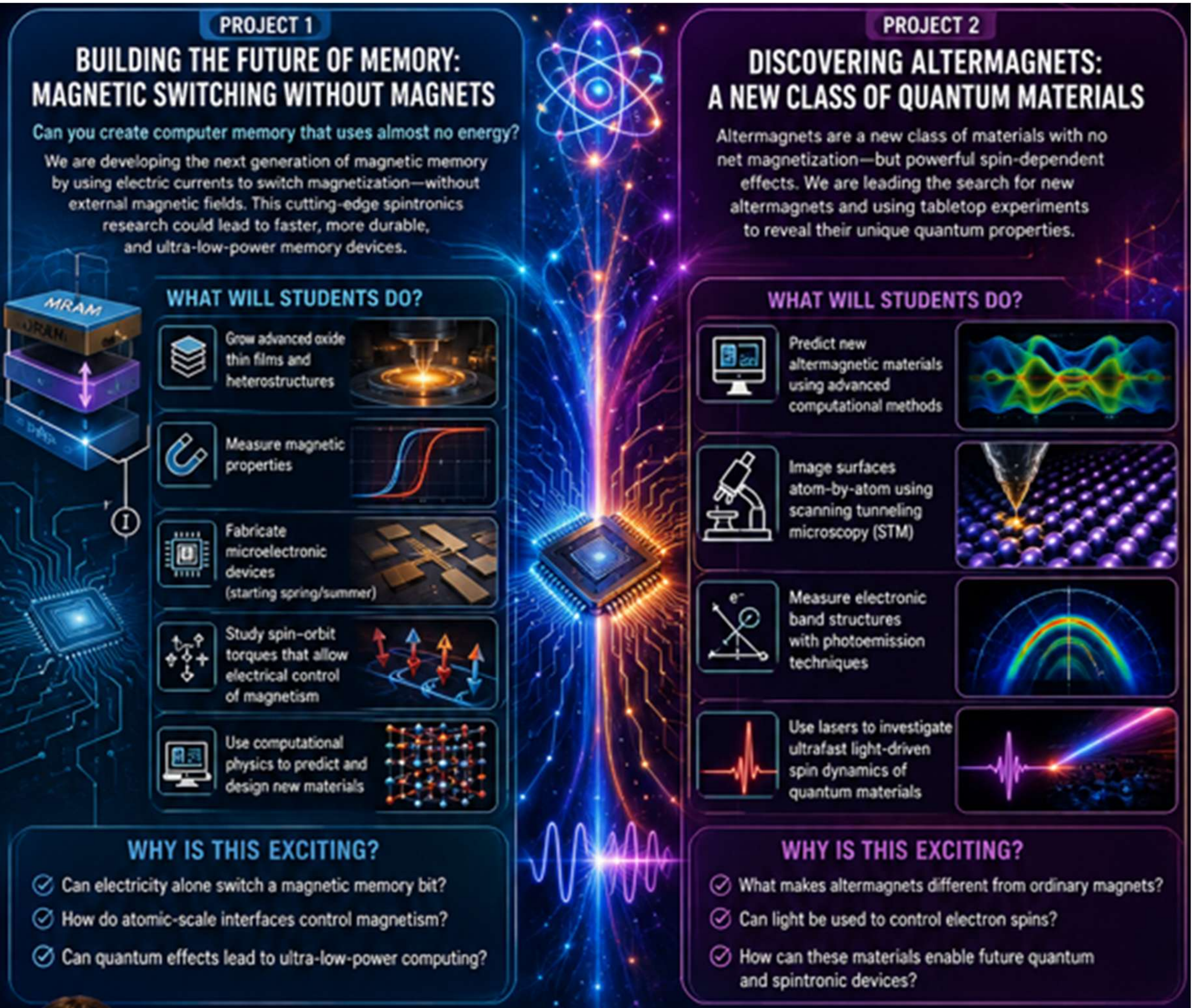


- Flexible magnetization to tune the effect?
- Maybe the effect has more to do with HOW we are measuring it? Adjust conditions.
- W … s?
  Si … een
  in …)21,
  Li… ites
  wc … s.
- W … up.





Leading $4 Million with U. Delaware



Project 3:
Quantum Dots and Quantum Memories: Controlling Spins with Light

Quantum technologies could revolutionize computing, communication, and sensing. One promising approach uses tiny semiconductor structures called **quantum dots**, often described as "artificial atoms," to trap and control individual electrons using light. In this project, researchers are exploring how the spins of electrons inside quantum dots interact with the spins of rare-earth atoms. Understanding these interactions could lead to quantum memories capable of storing information for much longer than current technologies.

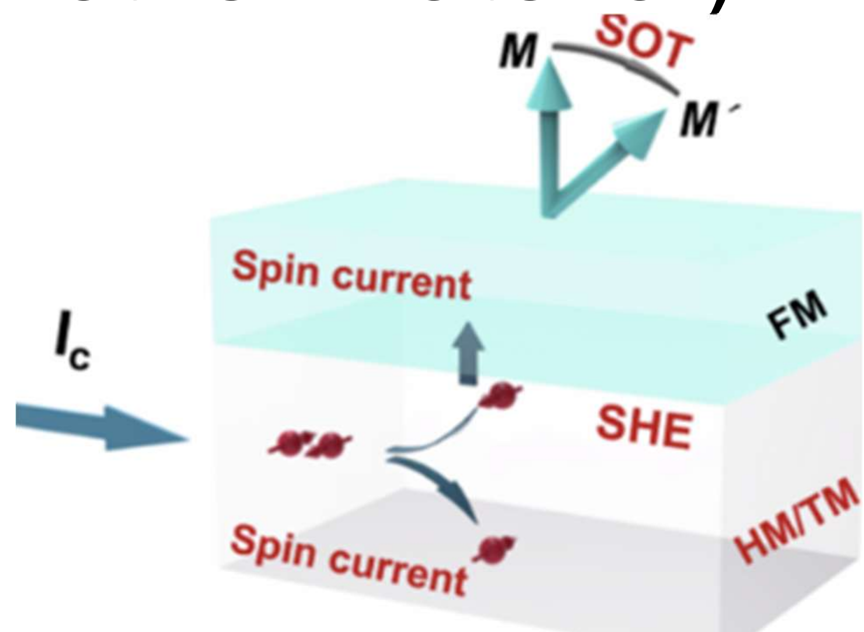
Project Leads: Holcomb Mandal/Bristow Flagg

Project 1 with U Delaware: Trying to get the LSMO to point out of plane

(Eventual goal to switch its direction by coupling with another material)

Normally, when a charge current flows through certain materials, it creates a flow of angular momentum called a spin current. This spin current can push on a neighboring magnetic layer, much like wind pushing on a weather vane. The push is called spin-orbit torque. We want to use that to switch the magnetic direction.

Current industry goal



Spin Hall effect: Strong spin-orbit coupling causes electrons with opposite spins to scatter in opposite directions.

Your background studies could involve trying to understand more about either:

What makes magnetization point in-plane or out-of-plane?

OR

What is spin-orbit torque?

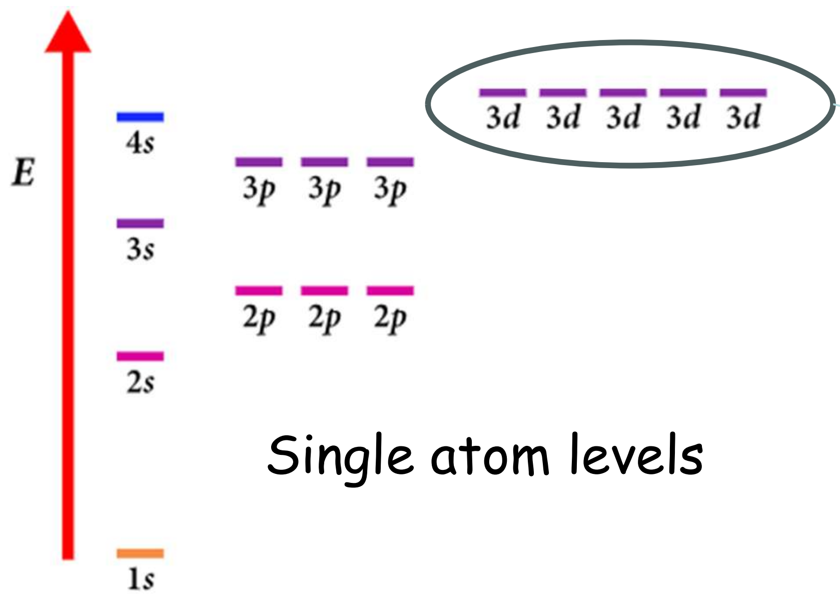
Project 2 with U Delaware: Better measuring altermagnets A brand new kind of magnetism that is hot right now!

Background: What is that?!?
Why do we care?

(Let me give you a start, but for more you'll need to talk to Prof. Subhasish Mandal, computational specialist.)

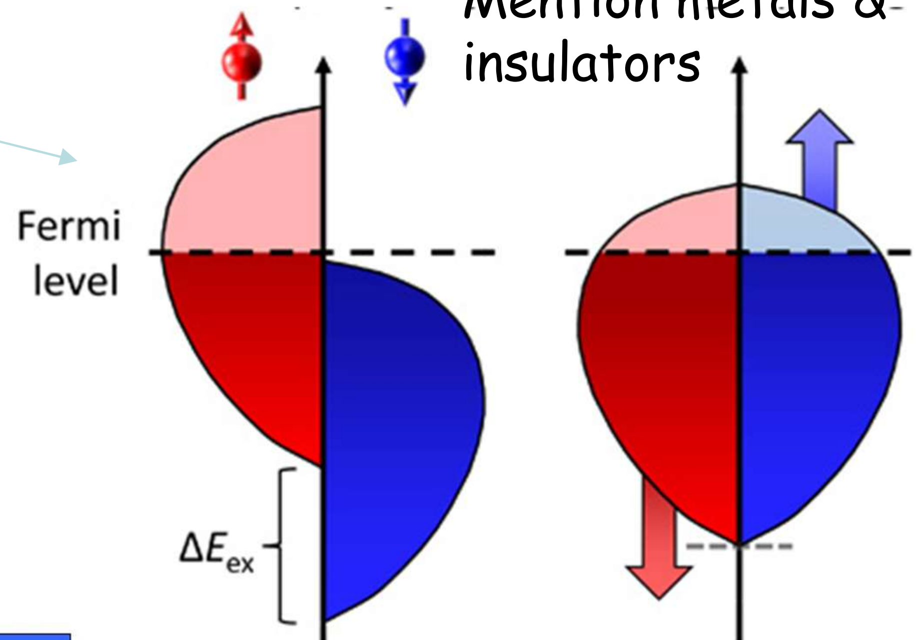
In materials these levels become bands of potential energies.

And these bands can be different for spin up/down.

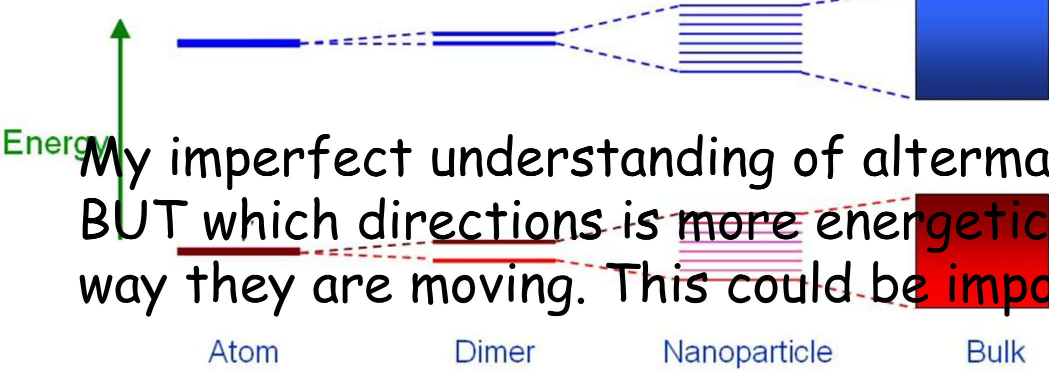


Single atom levels

Mention metals & insulators



Ferromagnet Antiferromagnet



My imperfect understanding of altermagnets is that they look like ferromagnets, BUT which directions is more energetically favorable (lower) depends on which way they are moving. This could be important for advanced circuits!

How Could You Help?

M vs H and M vs T measurements would be useful, but not sufficient to identify an altermagnet. In fact, one of the reasons altermagnets went unnoticed for so long is that their bulk magnetic measurements often look a lot like those of ordinary antiferromagnets.

What would M vs T tell you?
An M vs T measurement could reveal a magnetic ordering temperature (analogous to a Néel temperature).

For example:
- Above the ordering temperature: paramagnetic behavior.
- Below the ordering temperature: a transition into an ordered magnetic state.

An altermagnet should show a magnetic phase transition, but so would a conventional antiferromagnet.

Bristow has plans to do optical measurements on these samples to determine if they can probe the different behavior.

Past Research Options (probably easily convinced)

- Explore this new discovery either in a new way or with related materials. I can make recommendations if you want.
- Rice: could look at capping magnets, LSMO
- USF: nanorods and cones, particle geometry
- Oak Ridge: MnBi2Te4, shows a large non-compensated moment and complex defect chemistry.
- Forensics Project with Marshall.
- CMU has a few: LSMO and others (slide)
- Open to others. Know people that grow.

Past example projects (CMU)

- (Ba,Mn)O3 thin films --- If it can be made with 70% Mn, it's predicted to be ferromagnetic. It should be AF if it's not FM. The science of interest would be in looking at the ordering T as a function of composition.
- RuO2 thin films --- These are predicted to be altermagnetic, which would only show up in spin polarized measurements. With VSM they should look antiferromagnetic. Interestingly, the altermagnetism effects have been seen in rutile TFs but not bulk. Is there something at the surface that's different?

Simple Version (Allows Time Flexibility)

Get a sample from the location of your choosing.

Everyone does magnetization versus temperature and magnetic field. These are the bare minimum needed to understand magnetic properties in general.

I will also teach about x-ray diffraction (and a few others) and you can do those measurements too if you like, but not required.

Contributors	Lab	Possible Materials (If two materials listed, it starts with thin film on top of substrate)
Holcomb	WVU	LaSrMnO3/SrTiO3 (various thickness and oxygen pressure); original discovery
Holcomb	WVU	LaMnO3/SrTiO3; not yet published but we have a lot of related work by us
Holcomb	WVU	BFO (I have a range of samples with this main thin film); magnetoelectrics
Mohindar Seehra	WVU	Ni(OH2) nanoparticles; published; Seehra is interested in working with you
Mohindar Seehra	WVU	FePt; published; Seehra (retired) is interested in working with you
Mohindar Seehra	WVU	CoMgO; published; Seehra (retired) is interested in working with you
Lane Martin	Rice	LaSrMnO3/(SrTiO3 or LaAlO3 or LSAT)
Lane Martin	Rice	SrRuO3/(SrTiO3 or LaAlO3 or LSAT)
Lane Martin	Rice	some capped CoFe(B) on any substrate; discuss why might you want it capped
Matt Brahlek	Oak Ridge	MnBi2Te4, shows a large non-compensated moment and complex defect chemistry
Hari Shrikant	U. South Florida	Iron oxide nanoparticles, including rods, spheres and shells, strain tuning

You may also request a new collaborator if you like, but not everyone might agree

This work was submitted, but we still have the powders if there is interest.

Meet Your Group

Times are not expected regularly.

Groups (do any of these not work?):

- Friday 5pm: Melissa, Shelby, Leeam
- Tuesday 10:30am: Evan, Jeffrey, Austin
- Monday 5pm: Ryan, Gavin, Alp
- Tuesday 4pm: Bryce and Tyler
- Monday/Friday 5pm: Nickolai and Durham

Meet your partner(s) and discuss any ideas you currently are thinking about for your projects. Take some notes to remember.

Many of you have other overlap too, fyi.

Extra Slides (might use some later)

More on the mathematics of the temperature dependence of different types of magnets

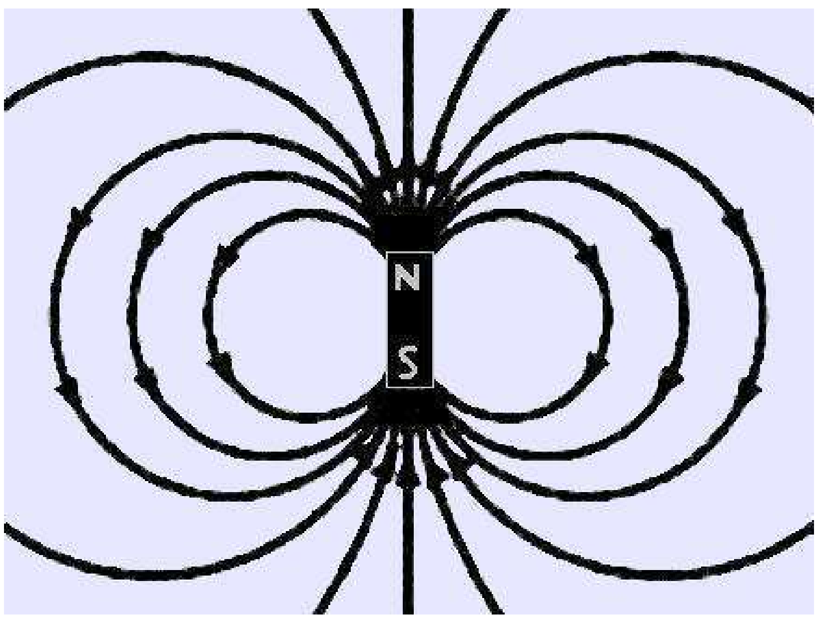
Very Early Magnetism

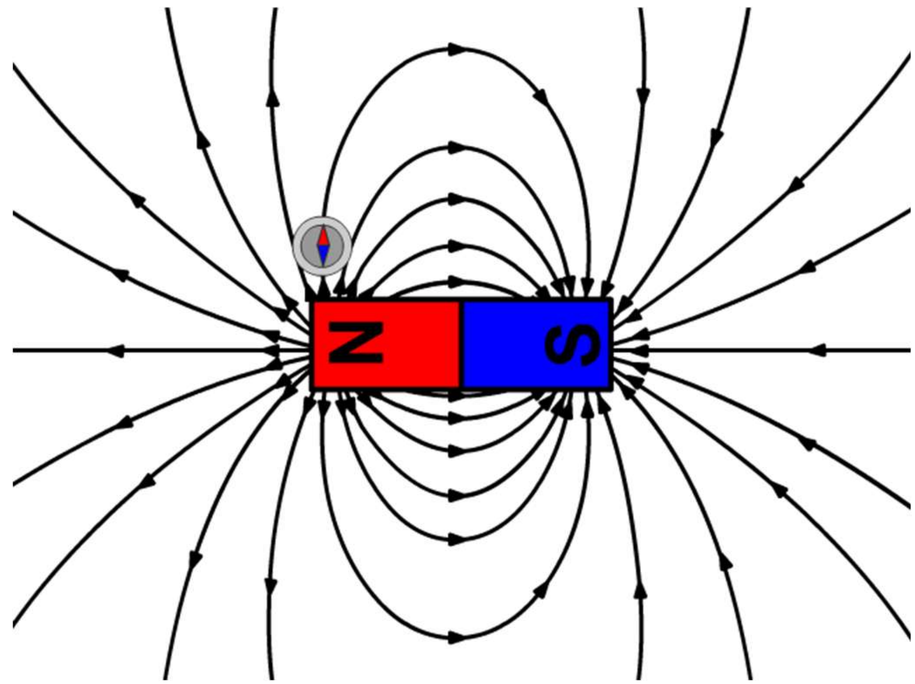
The first known magnets were naturally occurring lodestones, a type of iron ore called magnetite (Fe_3O_4).

People of ancient Greece and China discovered that a lodestone would always align itself in a longitudinal direction if it was allowed to rotate freely. This property of lodestones allowed for the creation of compasses two thousand years ago, which was the first known use of the magnet.

In 1263 Pierre de Maricourt mapped the magnetic field of a lodestone with a compass. He discovered that a magnet had two magnetic poles North and South poles.

The ends of a magnet are where the magnetic effect is the strongest. These are called "poles." Each magnet has 2 poles – 1 north, 1 south.





MAGNETIC DIPOLE:

Any two opposite poles separated by a finite distance constitute a magnetic dipole.

Some Interesting Websites

How speakers work http://www.geo.umn.edu/orgs/irm/bestiary/index.html
Bestiary of magnetic minerals http://sprott.physics.wisc.edu/demobook/chapter5.htm
History of magnets http://www.webmineral.com/data/Magnetite.shtml
Magnetite http://pupgg.princeton.edu/~phys104/2000/lectures/lecture4/sld001.htm
Slide show http://www.physics.umd.edu/deptinfo/facilities/lecdem/demolst.htm
Best ever site for pictures, simple explanations, etc.__http://www.trifield.com/magnetic_fields.htm
Another good site for how magnets work http://bell.mma.edu/~mdickins/TechPhys2/lectures3.html
Equations and such http://schools.moe.edu.sg/xinmin/lessons/physics/default.htm

See also:

http://www.micro.magnet.fsu.edu/electromag/java/index.html
http://www.micro.magnet.fsu.edu/electromag/java/detector/
How a metal detector works http://www.micro.magnet.fsu.edu/electromag/java/compass/
How a compass is oriented magnetically http://www.micro.magnet.fsu.edu/electromag/java/faraday2/
How Faraday did his current experiment http://www.micro.magnet.fsu.edu/electromag/java/harddrive/
How a hard drive works http://www.micro.magnet.fsu.edu/electromag/java/magneticlines/
How magnet lines is working http://www.micro.magnet.fsu.edu/electromag/java/magneticlines2/
How two magnets repel and attract
http://www.micro.magnet.fsu.edu/electromag/java/nmr/populations/index.html
Nuclear spin up/down http://www.micro.magnet.fsu.edu/electromag/java/pulsedmagnet/
Pulsed magnets http://www.micro.magnet.fsu.edu/electromag/java/speaker/

http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/elemag.html http://library.thinkquest.org/16600/intermediate/magnetism.shtml

http://www-geology.ucdavis.edu/~gel161/sp98_burgmann/magnetics/magnetics.html

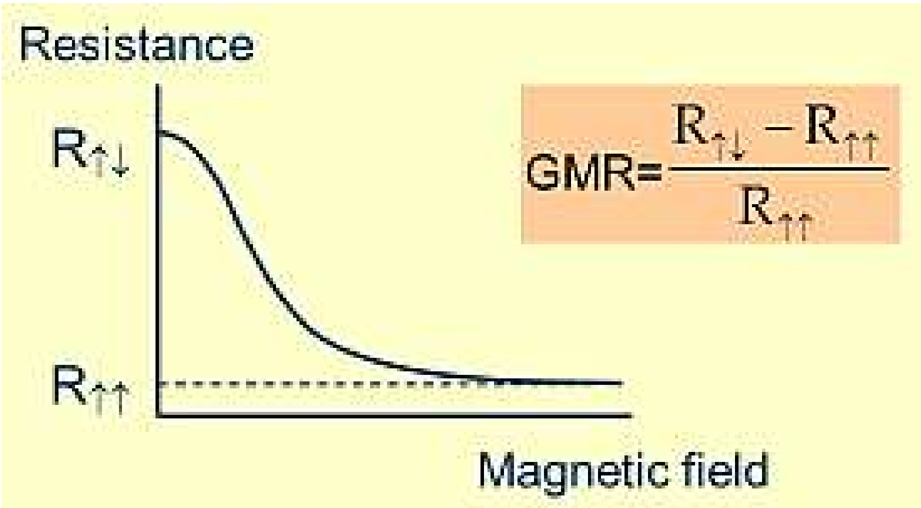
http://www.micro.magnet.fsu.edu/electromag/java/index.html http://webphysics.davidson.edu/Applets/BField/Solenoid.html

http://www.ameslab.gov/News/Inquiry/spring96/spin.html http://cfi.lbl.gov/~budinger/medTechdocs/MRI.html

http://www.wondermagnet.com/dev/images/dipole1.jpg

More details on magnetic applications

GMR = Giant magnetoresistance



d in multilayers composed
agnetic and non-magnetic

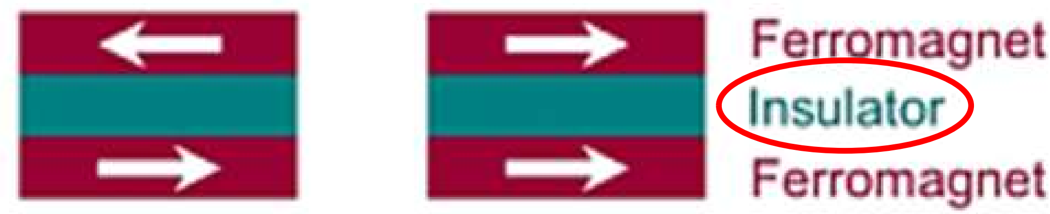
Fert and Peter Grünberg.

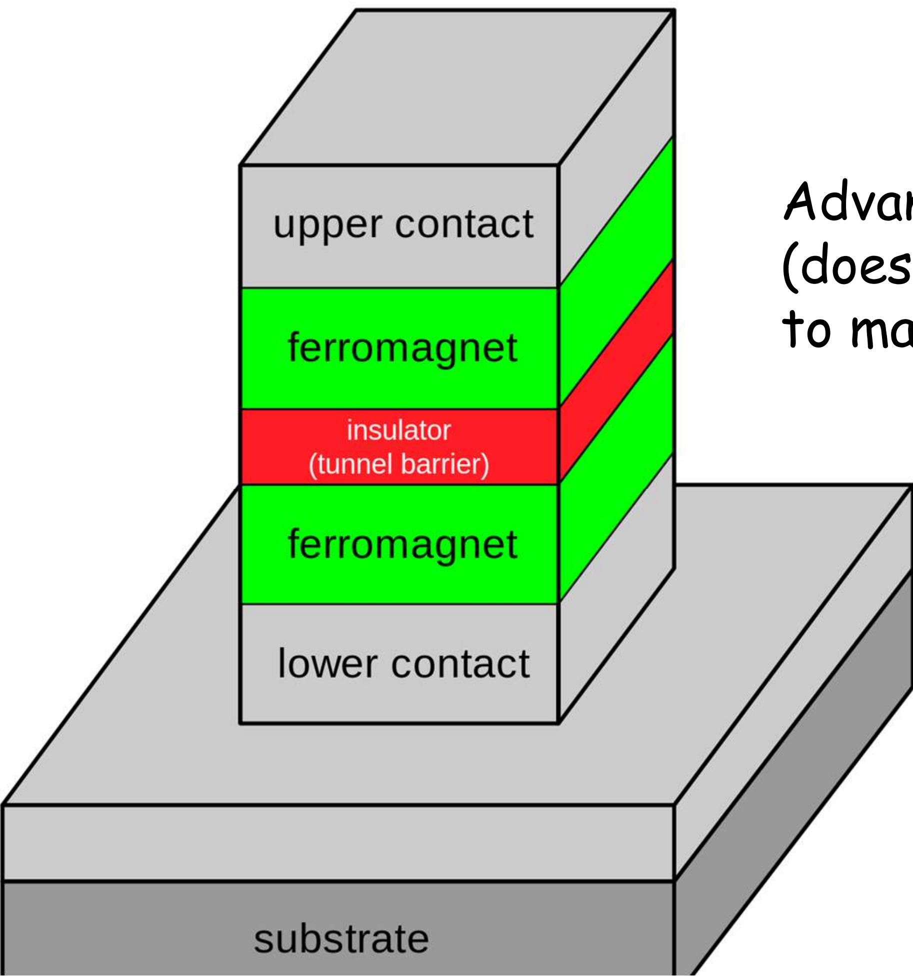
- The effect is observed as a significant change in the electrical resistance depending on whether the magnetization of adjacent ferromagnetic layers are in a parallel or an antiparallel alignment.
- Apps: hard disk drives and biosensors
- Similar tunnel magnetoresistance w/ insulator

IBM

Tunnel Magnetoresistance & Magnetic Tunnel Junctions

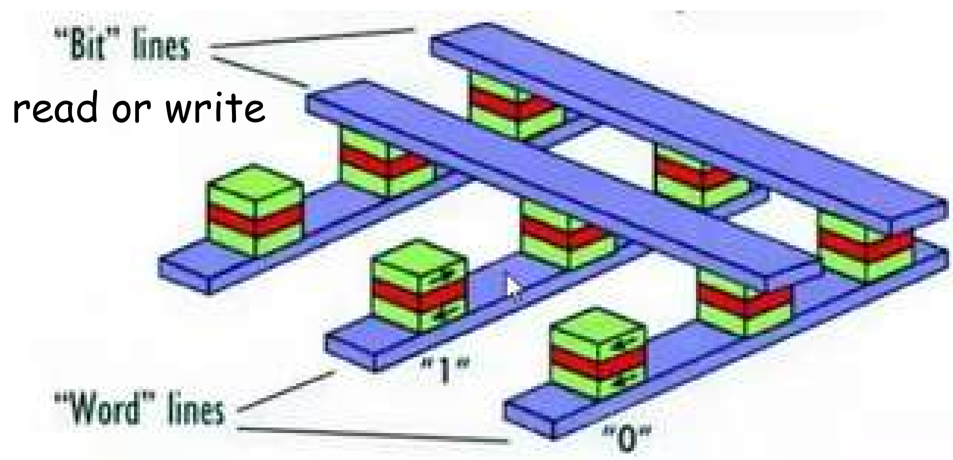
MRAM invented in the 80s but only recently more competitive





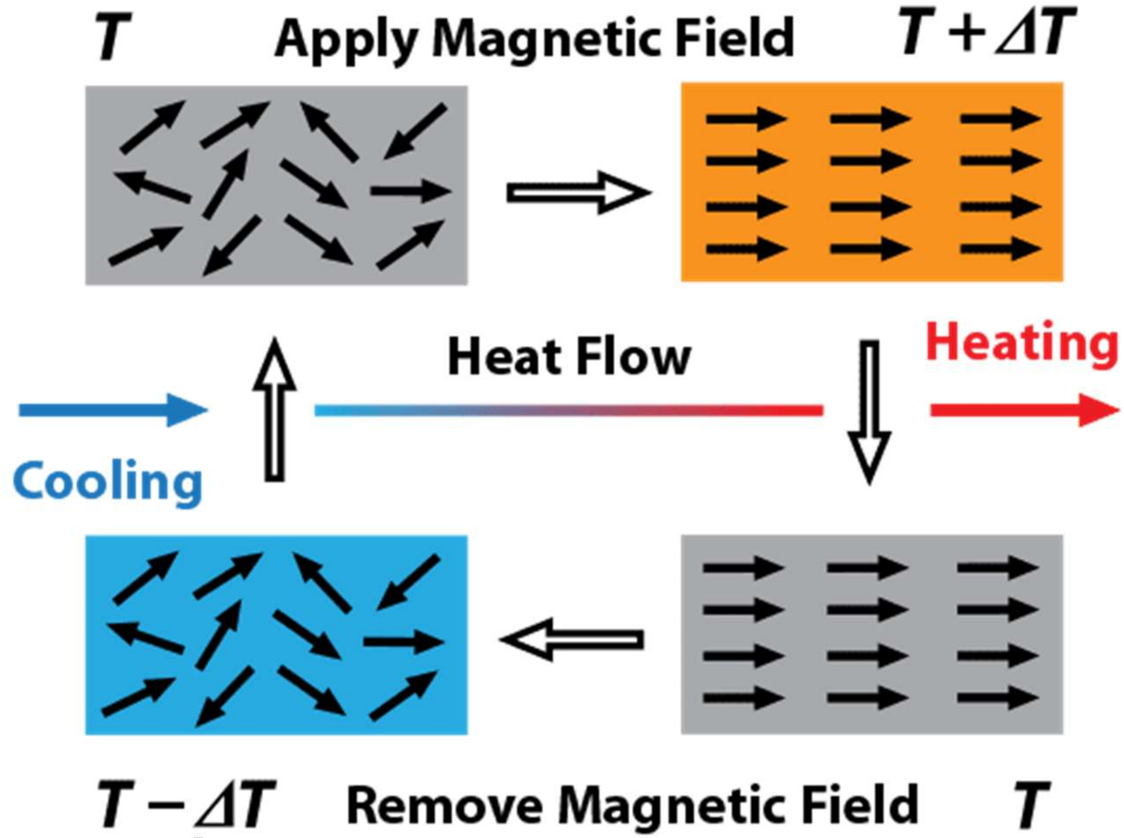
Advantage: Non-volatile (doesn't need current flow to maintain information)

$$TMR = \frac{R_{AP} - R_P}{R_P}$$



MRAM stores data in magnetic domains

Magnetic Refrigeration
(used by NASA)



- A magnetocaloric
  magnetic field is a
  field is removed, t
  original state, rea
  returning to origin
- To achieve refrigeration, the material is allowed to radiate away its heat while in the magnetized hot state. Removing the magnetism, the material then cools lower.
- 1st observed 1881, 1st fridges by 1933, <0.3K
- Still active field, particularly in nanoparticles

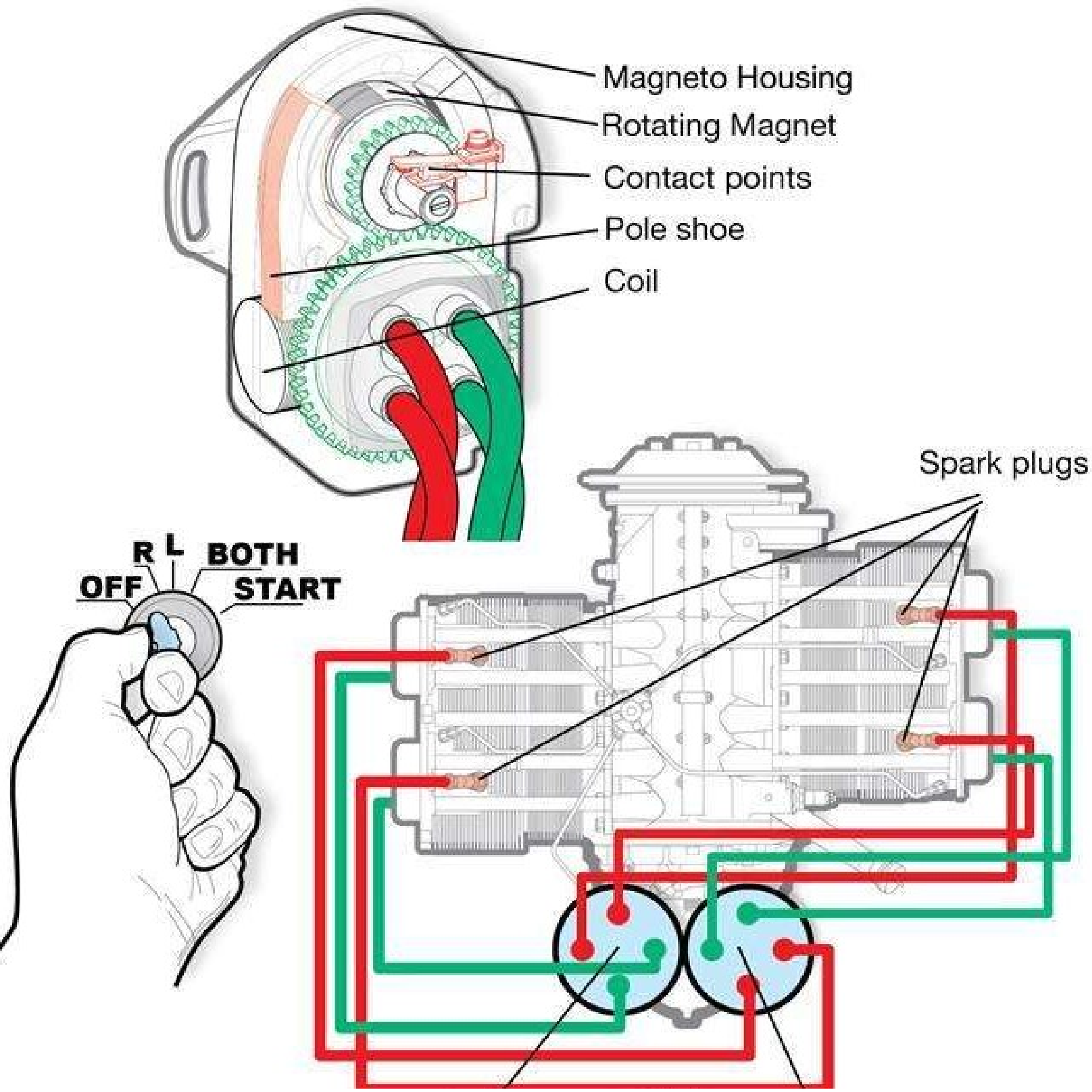
Examples of strong:
Gd, manganites

Every magnetic material may have this effect, but it's normally pretty weak particularly around room temperature.

Magneto: Rotating Magnet

Faraday's Law:

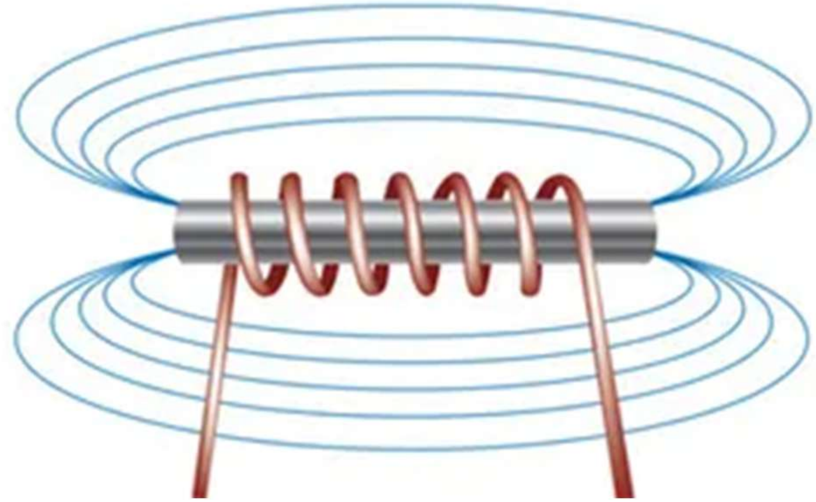
Any relative motion between magnet and wire induces current and flow in the wire.



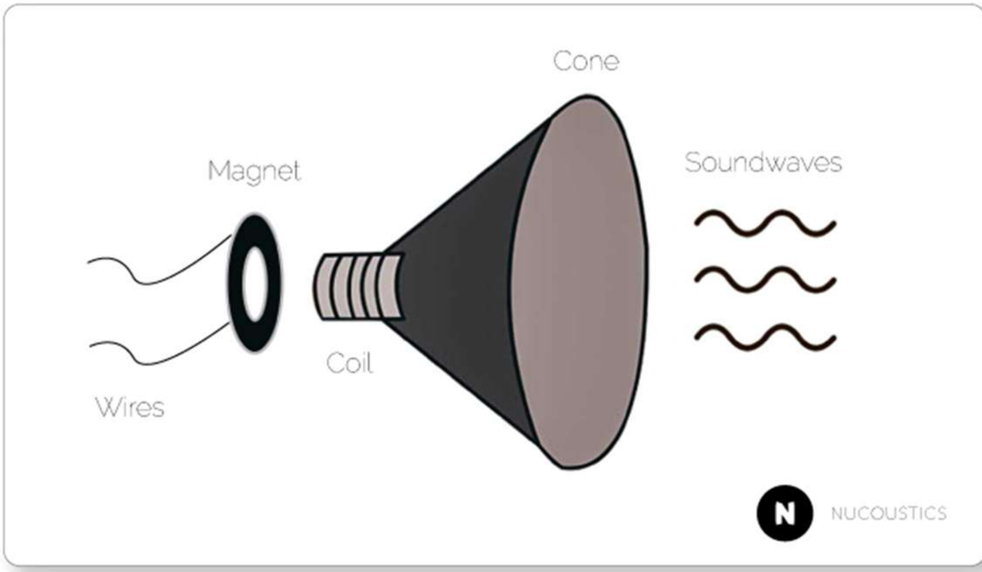
>100 years old, used in aircraft, lawn mowers, chain saws and old tractors.

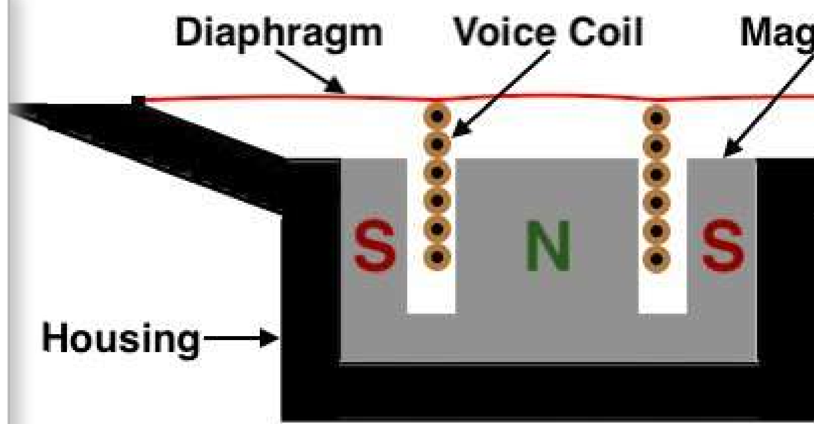
The magneto is a generator of high voltage that provides ignition to an engine through spark plugs. A magnet spins in close proximity to a coil of wire. As the magnet spins, it generates a strong magnetic force that is "held back" by a primary coil. The moment the contact points open, a rapid magnetic flow generates a high voltage in the secondary coil, which ignites the spark plug, thus firing the engine. There are two magnetos so that if one fails the engine continues to run, but will be less efficient.

Electromagnets



- A solenoid with a ferromagnetic material inside
- The addition of the FM increases the magnetic field that the current flowing through the coils can produce.
- Uses: Motors and generators, transformers, switches, electric bells and buzzers, actuators such as valves, MRIs, magnetic recording (tape recorders, VCRs, hard disks)





Electromagnetic induction states that a voltage will be produced across an electrical conductor in a changing magnetic field. Conversely, it means that a voltage across a conductor (that comes with current passing through a conductor) will cause a magnetic field around that conductor.

So if we can pass alternating current (audio signal) through a conductive wire or coil, we can produce a magnetic field around it. If this coil is placed in proximity to a magnet, the two magnetic fields will cause the coil and magnet to repel or attract one another.

When it comes to headphone drivers, having permanent magnets and some sort of conductive diaphragm design would allow us to turn audio signals into sound waves. **Thus, headphones act as transducers of energy, converting electrical energy (audio signal) into mechanical wave energy (sound waves).**

Magnets for Sound

Electric Generators

In a motor we have seen that a current loop in an external magnetic field produces a torque on the loop. In a generator we'll see that a torque on a current loop inside a magnetic field produces a current. In summary:

Motor: Current + Magnetic field → Torque

Generator: Torque + Magnetic field → Current

Turbines in a power plant are usually rotated either by a waterfall or by steam created heat produced from nuclear power or the burning of coal. As the turbines rotate, current loops turn through a magnetic field to generate electricity. This process converts mechanical energy into electrical energy.

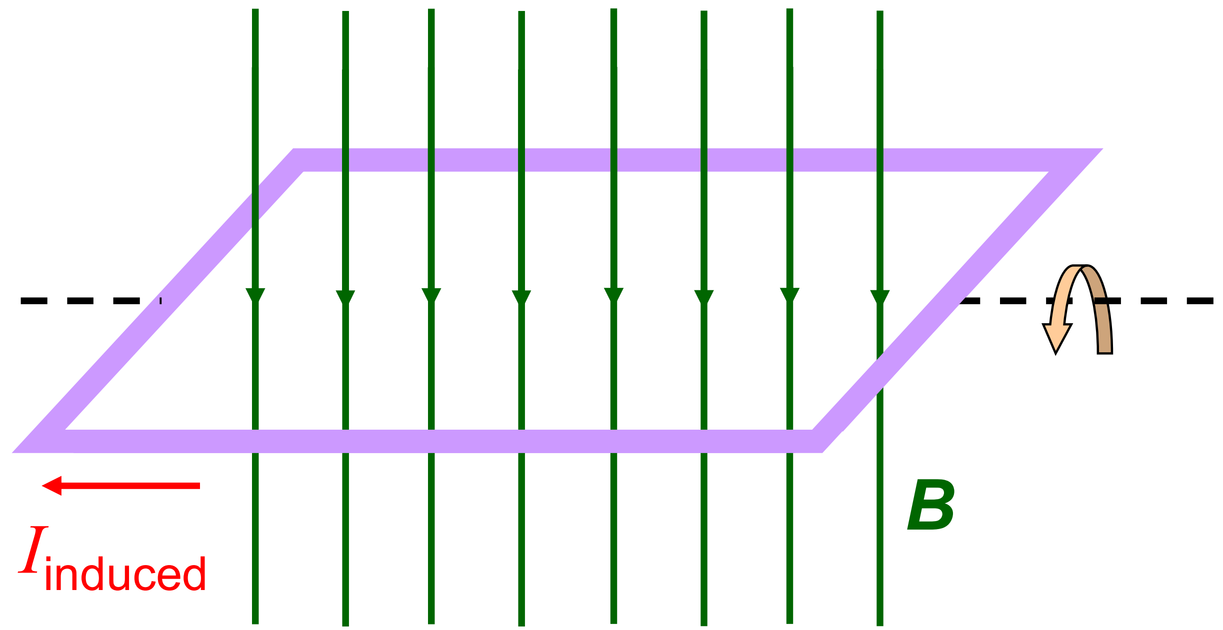
The simplest form of an electric generator is called an alternating current (AC) generator. The current produced by an AC generator switches directions every time the wire inside of it is rotated through a half turn. In the United States, generator generally have a frequency of 60 Hz, which means the current switches direction 120 times every second! A graph of the current output from an AC generator produces a sinusoidal curve due to the periodic nature of the generator's rotation.

Continued…

Electric Generator

(cont.)

Animation

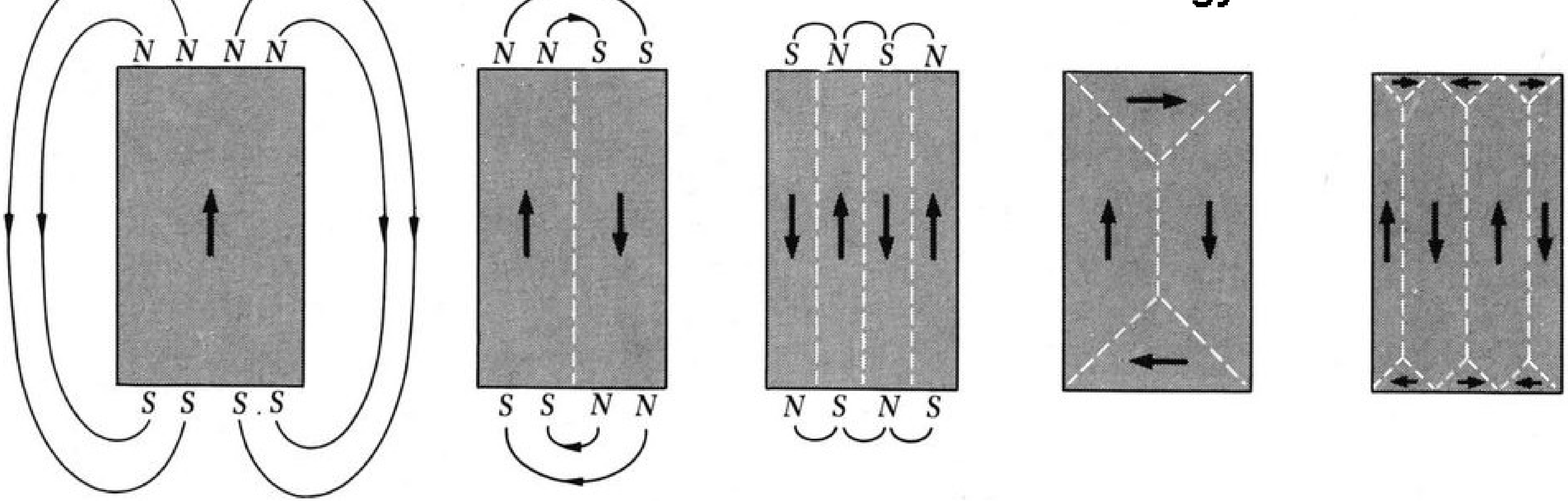


As a turbine turns (due to some power source like coal) a current loop (purple) is rotated inside a magnetic field. The field is static but as the loop turns as the number of field lines poking through it changes. Thus we have a changing flux and a corresponding induced emf and current. The pic shows a loop just after it was horizontal (perpendicular to the field). The flux is decreasing since the loop is becoming more vertical. Since fewer field lines are entering the loop, the induced current is in a direction to produce more field lines downward. Just prior to this, as the loop was approaching horizontal, the number of field lines inside it was increasing, so the current was in the other direction to oppose this change. The current changes direction twice with each turn--whenever the loop is horizontal. The result here is AC, but (direct current) DC motors exist as well in which current only flows in one direction.

Magnetic domains

- Ferromagnetic materials tend to form magnetic domains
- Domain structure minimizes energy due to stray fields, but domains walls also cost energy

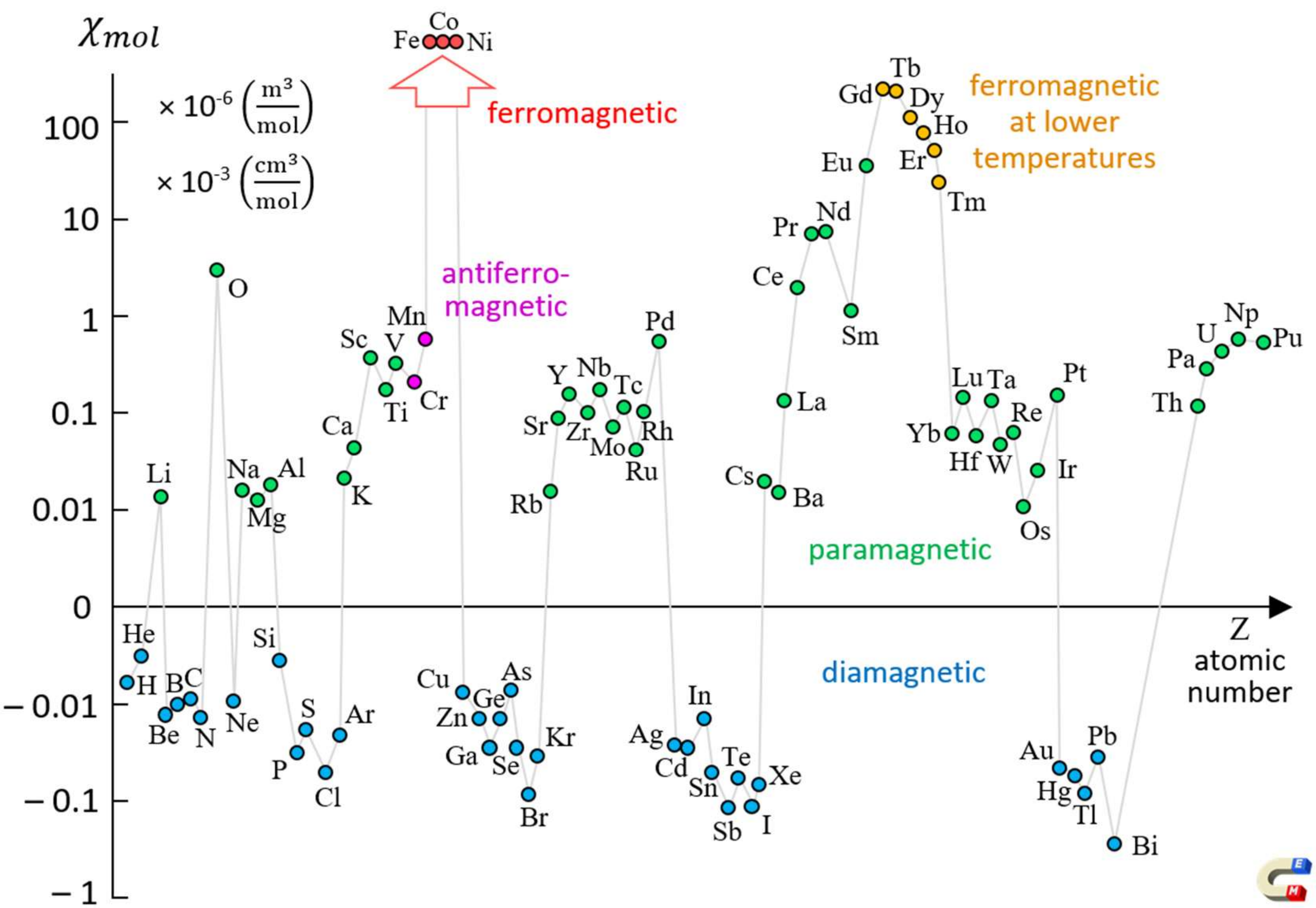
Total Energy = Magnetostatic Energy + Wall Energy

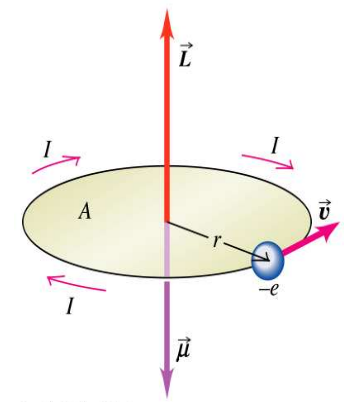


Diamagnetism

but not all

- In many substances, the electron and spin contributions cancel out.





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Physics isn't about knowing all the answers, but about using your curiosity to improve your understanding, one question at a time.