PHYS 420 – James Ward 28890144
Ferrofluid Demonstration Notes

NOTE: this is not a script in that it should not be read aloud verbatim; it is intended to be a guiding outline which should help you plan what you want to say. Fill in what is written here with detail as needed. Having it printed out for reference was a major help for me as I practised my demo, helping me get back on track if I got lost during the lesson.

Before demo:

- Set up solenoid, power supply, plug all cables in

- Have the coil already in the stand, at the correct height for the fluid in the dish (set this up before).

- If your equipment stand has iron in it, have the stand visible, as it is a useful ferromagnetic surface for the first part. If it doesn't, find something else on hand to use as an example instead of the stand.

- Possibly have the ferrofluid dish out of view until it is used later – more suspense!

0. Preamble

Today I'm gonna talk to you about magnetism, and later we will look at some really beautiful applications. I find this stuff exciting and a lot of fun, but first we gotta start with something more familiar.

1. Magnets

What are magnets? Magical objects - spooky action at a distance?
>Ask Class: Can anyone give me a simple practical definition of a magnet.
>Demonstrate: Play with magnets in the familiar fashion
I'll suggest that they are things that attract each other this way, but repel that way.
If I bring my magnet close to this metal stand, what do you predict will happen? **>stick magnet to (iron) stand**
How about this wooden chair/desk/table? **>try to stick to chair**

>Ask Class: Can anyone come up with a rule for what will stick and what won't?
>Introduce the aluminum and copper pieces, ask class, will the magnet stick to these?
So this doesn't work for all metals.

2. Magnetization

Now here's a question: when my magnet sticks to the stand, is the stand a magnet? Clearly, the stand is pulling my magnet towards it, otherwise, my magnet would just fall down. Watch: I can attract something THROUGH the stand too.
>Stick the magnet to the stand, and a paperclip on the other side of it
Give some reasons why. Take some time to think about it. See if you can answer on the sheet.
>Does anyone have an answer they want to share, and why?
This is called induced magnetization. So there's 3 kinds of things. Permanent magnets, things that can be magnetized, these things are SUSCEPTIBLE to magnetization, and things that can't.
So I will try to explain to you, what's going on here. *How do magnets work.*

3. Magnetic fields, Dipoles

Every magnet produces something called a magnetic field. Have you heard of it? It projects out into space surrounding the magnet and it represents how strong the magnet is and where it can interact with other matter. The basic field we will look at is a dipole field, it'll become clear why in a moment. Most permanent magnets form a dipole field, roughly speaking.

> *Optional: do the iron filings demo to see a magnetic field – it is difficult to do this consistently and to let everyone see it*

A bar shaped magnet is a very good example of a dipole. > *Hold one up*

Let me draw the field! I use these field lines to show it.

- lines must go from N to S outside the magnets, and come back through the magnet S to N
- lines should not cross, and want to spread out
- each magnet has 4 lines entering and leaving

> *On the board – draw a simple dipole field diagram, with a bar magnet. Use north and south poles*

Now, on your sheets I have 3 other situations with extra dipoles. See if you can draw them too.

> *Give them time to work on this on the worksheet*
>
> *Eventually, give them a tip: lines can go from one magnet to another if it works.*
>
> *Would anyone like to draw theirs on the board? Ask for volunteers for the double dipole and antiparallel dipoles at least*

Now, having a big field uses a lot of energy, but in physics, we have a guiding principle: **systems tend to minimum energy**. Like, a ball rolls down a hill to minimize potential E.

Rank the diagrams from biggest field to smallest field, and therefore highest to lowest energy.

> *show phet slides*

Now, with this in mind, what way do 2 dipoles prefer to be aligned? **Small field – low energy – is preferred**

This is more or less why north attracts south: lowest energy field possible!

>*demonstrate with 2 bar magnets being aligned and anti aligned – they should want to attract anti-parallel but not parallel*

The fields of anti parallel dipoles CANCEL almost entirely! Its like they're not magnets anymore.

4. Electrons, Interactions

Right. Why do we care about dipoles? How does a dipole get its field anyway?
What is everything made of? Atoms
What are atoms made of? *(Protons neutrons and...)*
Lets look at electrons, they're light and like to move. Electrons are fundamental particles and they have a built in magnetic field! A Dipole field! Yes, every election is a tiny tiny dipole.

Neat. But what do two dipoles near each-other want to do? Pair up in opposing directions. Now, do electron pairs seem familiar? Remember your chemistry? 1s2 2s2 2p6 3s2.. yes! Electrons form pairs in opposite directions. This is why.
Some electrons end up unpaired, but in a bunch of atoms, they'll all sort of cancel out. But, if all the electrons pair up like this, then magnetism is forbidden!

But there's another effect: in a strong external magnetic field, dipoles really want to line up with that field. Now this is where things get interesting.
Check out these tiny dipoles - compass needles!
>Introduce compass needle array demo (premade) - needles line up when in the field of a strong magnet. Make sure everyone sees this thing

So by that logic, if I put in a strong magnetic field somehow with a permanent magnet, say, it will line up all the electrons all the same way, and like the double dipole earlier, all the tiny fields will add together to create one gigantic field, which will form a big magnet! This is magnetization!

Just like with the iron stand. So when we put something in an external field, we have this competition, a tug of war. On one side, the dipoles want to be anti parallel to minimize field, but they also want to line up with the external field.

Who wins? Well, it turns out, for practical field strengths, always the anti parallel thing, meaning they all cancel and we never induce a field. This is **paramagnetism**.

A disaster! By THAT logic, nothing is very magnetic. Only a few dipoles line themselves up, and most don't.

The key lies in YET another effect, something called an exchange interaction. For solids that form a regular, repeating crystal pattern, and have unpaired electrons in just the right places, an exchange interaction can occur. This is a quantum effect, and I do not want to get into too much detail about this, but the unpaired electrons on neighbouring atoms end up overlapping at a particular distance, and the net effect is that the electrons want to be aligned instead of anti-aligned.

For some solids (iron, nickel, cobalt, and some rare earth elements like neodymium), this effect can overcome the dipole-dipole stuff, and result in what we call **ferromagnetic** materials. Since nearby electrons want to be aligned now, the solid will form domains of parallel electrons. Now, their fields start to add. And, in the presence of a strong enough external field, the ferromagnetic solid can have all its domains line up to become one big domain, with a large field! This is how magnets work. Permanent magnets get stuck this way, but with a strong field in another direction, they can be re-magnetized to point a different way. How exciting!

5. Ferrofluid

Could you make a magnetic fluid? Why or why not? What are some ideas:

Molten iron -> passes the curie temperature – particles move around so much from the heat that ferromagnetism and domains no longer work

Iron solution -> Individual particles can't form the domains since they aren't bound to a crystal structure anymore – need to preserve some tiny pieces of iron for this to work

Iron powder (small grains) in liquid -> Close, but unfortunately it will settle out of solution and clump together quickly. How must this be resolved?

> Bring out the ferrofluid table and any other equipment

Introduce the fluid – discovered by NASA engineers, effects surprised them. Made of tiny nanoscale iron particles suspended in an oil solution, with clumping inhibited by a "surfactant".

MAIN DEMO: remember the work sheet – PREDICTIONS FIRST

1.) Simple magnet under the dish - Use a medium strength magnet first which balances size of effect with number of spikes.

> Get everyone to come up and see, ask for predictions from the students verbally and written on the sheet

> Swap out the magnet for other magnets you have, if students have requests to see a particular magnet or setup, try to do it if reasonable)

> Hold up the dish to show that the magnet is ATTRACTED By the fluid, and sticks under.

>*Ask students to write down their observations*

But why?

> Do slides about field instability.

Explain flux with the dipole picture on the board – A region of high flux is where the field lines are very close together, and the fluid wants to move to a region of high flux. The magnetized field forms its own flux, meaning the fluid wants to stack on top of itself.

This is in competition with gravity and surface tension

2.) Fluid climbs the screw – big (honking) magnet plus extra fluid if needed, screw.
> Explain what you will do and ask for predictions about what will happen, and have them write it down (worksheet row 2)
> Put the screw in the dish, and if its just forming around the base, add fluid such that it gets up into the thread of the screw. If all else fails, add more fluid. Fluid should climb up the thread and collect on the top.
> ***Wear gloves*** *for this part, especially to get the screw back out of the dish. Use paper towel to wrap the screw when you take it out*

3.) Solenoid attracts the fluid – move the solenoid and electrical equipment into view
BRIEFLY explain the solenoid – it acts just like a dipole (draw it and its field on the board!) with varying strength. Remind the students that the high flux will be in the centre – mention how you blocked the end off
>Optional: *Before you move the solenoid right over the dish, turn it on and show how it interacts with a normal magnet*
>Move the solenoid over the dish – it has to be quite close to the fluid
>Before turning it on, ask for predictions about what will happen to the fluid specifically (Write it in the sheet too)
>Carefully and slowly raise the power until you have a static spike in mid air, and then crank it up and let the fluid touch the end of the coil
>Play with the power some more, and do anything else fun you can think of
The fluid stays perfectly still and doesn't fly everywhere for it has reached the region of highest flux.

6. Conclusion

That's about it! Wrap up, conclude, answer any questions about anything.
Show some pretty pictures that people have made with the fluid, discuss applications and specific details if students are interested.

Questions I got from students:
What does the spiky ball feel like to touch? The middle is remarkably firm, like a really tough Jell-O. It doesn't really feel like a fluid.
Where did I get it? 20 bucks on amazon for the bottle.
Whats the math behind this? It involves magnetism, wrote down Gauss' law for magnetism in integral form in the short time I had. Maybe try to give them a qualitative understanding about what it says?