Hypothesis–Experiment Classboook

When You Find Flee Electrons

Metal and Free Electrons

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First Edition in Japanese 1989,　English Edition 2025

Association for Studies in Hypothesis–Experiment Class

About the HEC Classbook "When You Find Free Electrons"

This HEC Classbook is designed to teach not merely that all metals contain an abundance of free electrons and conduct electricity but also why they conduct heat and can freely deform. It aims to broaden students' perspectives beyond simply teaching "this conducts electricity, this doesn't," as has been done conventionally.

That said, the Classbook isn't that difficult. Its content is perfectly understandable by any student in upper elementary school or above. Naturally, this includes middle and high school students — even university students who have not yet mastered the concept of free electrons. This Classbook has been used and welcomed in classes for all levels, from middle school to college students.

It has also garnered an excellent reputation for being used in lectures aimed at company employees, mothers, and teachers. It is recommended, but not essential, to have already learned the HEC Classbook "Batteries and Circuits" before beginning this one for elementary school students. We recommend continuing onto the HEC Classbook "Problems of Degree" for junior high and above.

In Part 3: Free Electrons, Heat, and Electricity, we present several problems relating to the electrical and thermal conductivity of metals that are to be completed solely by reading, without experimentation. However, we thought it would be preferable for middle and high school students to have experiments to perform; accordingly, we have developed a series of experiments on the electrical and thermal conductivity of metals. A new version of this HEC Classbook has been made but has not yet been translated.

Some other print materials, including actual class records in Japanese, are available from us for reference purposes. Should you require them, please get in touch with us.

We appreciate your interest in the Hypothis-Experiment Class. If you conduct a class, we would appreciate it if you could provide the Association for Studies in HEC with a record of the class (the Classbook title, target age group, country/region, students' impressions, number of students on each 5-point scale*, your impressions as a conductor, etc.). Your record is valuable and needed to improve the HEC Classbooks. For queries, please email contact2ashec@kasetsu.org

Translation project Group manager

Mariko KOBAYASHI

Association for Studies in Hypothesis–Experiment Class

Relax! Enjoy Hypothesis–Experiment Class (HEC) together with your students.

The teacher proceeds with the lesson by showing the Problems, Readings, and Hands-on in this HEC Classbook, one at a time, following the order.

Problem

Problem 5			
a. The bulb lights up brightly.	5	②	7
b. The bulb does not light up.	28		26
c. Other ideas. (lights up dark)	2		2

1. The teacher reads the problem.
2. Students choose the options for their expectations.
3. Count the number of students who chose each option and show the tally to the students.
4. Ask students who wish to speak to give their reasonings or thoughts.
5. Discussion. The teacher should not correct or guide the students to the correct answer.
6. Before the experiment, if a student wishes to change the choice, the teacher records it.
7. Experiment. The teacher declares the result but does not explain it at the stage.

Readings

The teacher reads the reading. In Hypothesis–Experiment Class, the explanations and summaries necessary for the student's understanding are given as Readings at the essential stages in the sequence of problems in the HEC Classbook.

After Class

At the end of the class, ask the students to rate their enjoyment of the class on a five-point scale and write down their impressions.

Please refer to the instructions at the end of this booklet for a safe and enjoyable class.

When You Find Free Electrons

Metal and Free Electrons

Part 1: What Carries Electricity and What Doesn't?

Of all the many and various things in the world, there are those (like wires) through which electricity flows readily and others (like air and glass) through which it barely flows.

In this part, we'll investigate what kinds of things allow electricity to flow through them and what kinds don't.

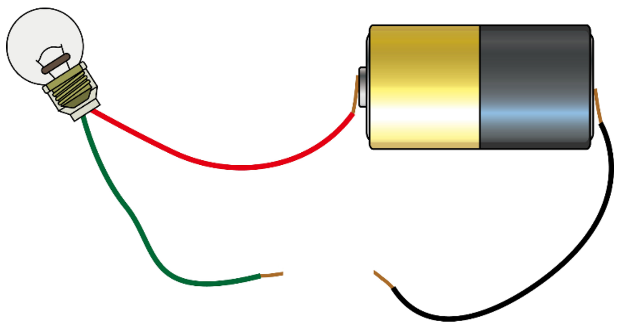
What kinds of things do you think will carry electricity? Think carefully about each of the upcoming problems. Make predictions and carry out experiments.

Question 1

We have a 1.5 V battery, a miniature light bulb, and a buzzer. Wiring the battery to the bulb makes it light up; wiring the battery to the buzzer makes it buzz.

We can investigate what kinds of things carry electricity by cutting the wire connecting them, inserting different objects, and seeing whether the bulb lights up (or the buzzer goes off).

First, try putting a metal spoon between the two halves of the wire to make a new connection. Does the bulb light up? Does the buzzer buzz?
Please give it a try.



Problem 1

These are coins of various countries made of aluminum.

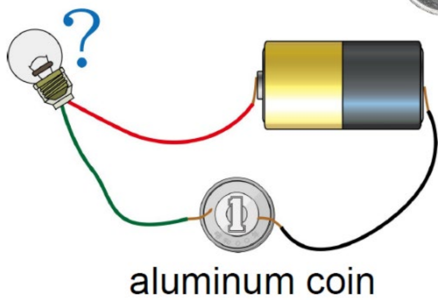
Do you think the bulb will light up when you put an aluminum coin between the two halves of the wire?

Expectation

a. The bulb lights up.

b. The bulb does not light up.

c. Other ideas.



Why do you think so?
Please share your ideas with the class, then experiment.

Results

Problem 2

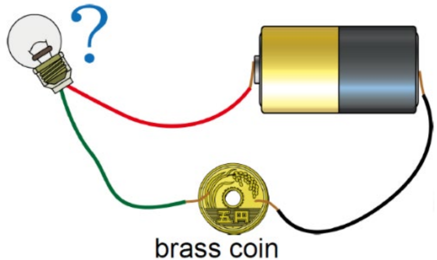
These are brass coins. When you put one of these coins between the wires, will the bulb light up? What do you think?

A mixture of two or more metals is called an alloy. Brass is an alloy of copper and zinc.

Expectation

a. The bulb lights up.

b. The bulb does not light up.



Please share your ideas with the class before the experiment.

Results

Problem 3

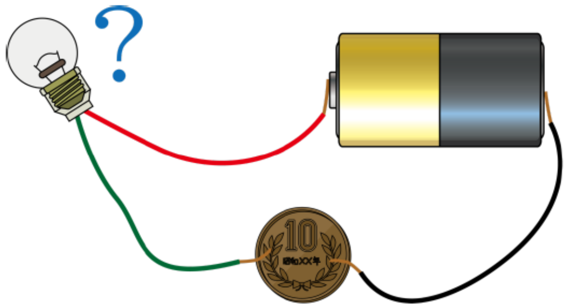
We call these coins "copper" or "bronze" coins. Bronze is an alloy of copper and small amounts of other metals, such as tin.

When you insert a bronze coin between the wires, do you think the bulb will light up?

Expectation

a. The bulb lights up.

b. The bulb does not light up.



Results

Problem 4

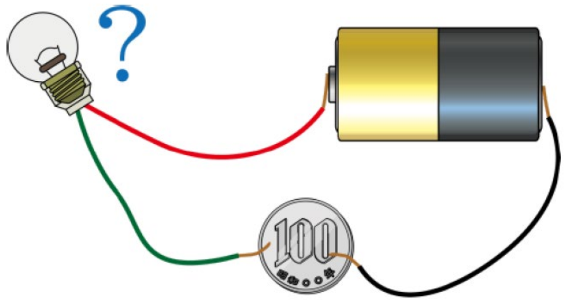
Finally, what about these coins? These are made of cupronickel, an alloy of 75% copper with 25% nickel.

When you bridge the wires with one of these coins, do you think the bulb will light up?

Expectation

a. The bulb lights up.

b. The bulb does not light up.



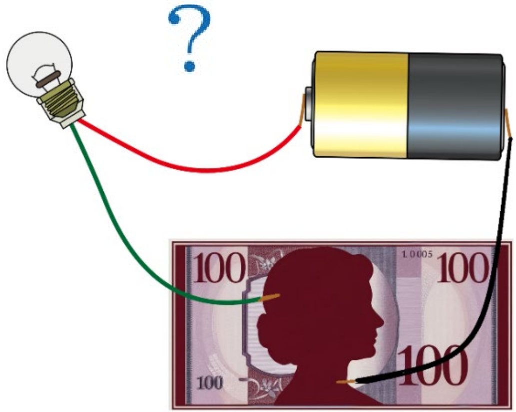
Results

Problem 5

The experiments so far have shown us that all coins allow electricity through.

What do you think will happen with a paper banknote? Will it also let electricity through?

Paper notes often feature portraits of historical figures. When you connect one wire to their chest and the other to their head, do you think the bulb will light up?



Expectation

a. The bulb lights up.
b. The bulb does not light up.

Why do you think so? Please share your ideas with the class, then experiment.

Results

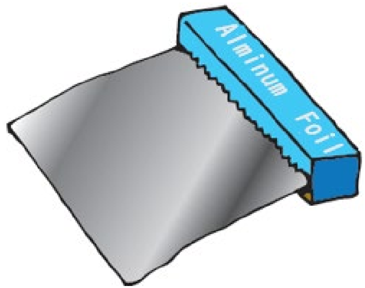
Problem 6

The experiment in Problem 5 demonstrates that electricity doesn't flow across a paper note. The fact that it's made of paper means it doesn't carry electricity.

So, what about aluminum foil?

Its color is very similar to the aluminum coin since both are made of aluminum. But it is as thin as a paper banknote. Do you think foil conducts electricity?

Do you think the bulb lights up when you place a piece of aluminum foil between the wires?



Expectation

a. The bulb lights up.
b. The bulb doesn't light up.
c. (something else)

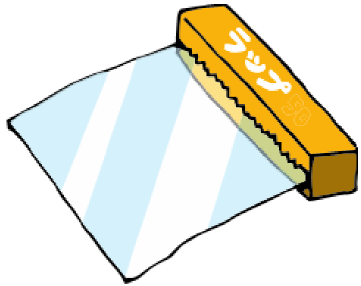
Why do you think so？ Please share your ideas with the class, then experiment.

Result

Problem 7

What do you think will happen with plastic food wrap?
While aluminum foil is opaque, this wrap is transparent.

Will the bulb light up when you place a piece of plastic food wrap between the wires?　What do you think？


plastic food wrap

Expectation

a. The bulb lights up.
b. The bulb doesn't light up.
c. (something else)

Why do you think so? Please share your ideas with the class, then experiment.

Result

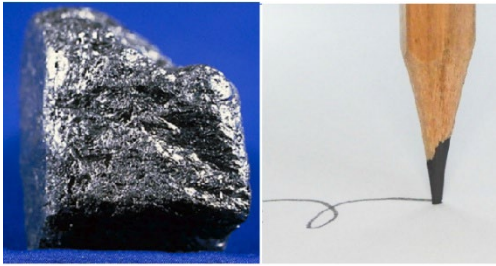
Problem 8

This time, please consider the following everyday objects. First, make all your predictions, then perform all the experiments.

Can you think of any other everyday objects that people might wrongly predict about whether to carry or not carry electricity? Pool your ideas, then make predictions and perform experiments for those objects.

Object	**Prediction**	**Result**
Wooden chopsticks		
Iron nail		
Steel wool		
Teacup		
Pencil lead		

Graphite



Pencil lead is composed mainly of graphite, which carries electricity well despite not being a metal.

Graphite was historically known as 'black lead' because it resembles black lead ore mined underground, and its ability to make marks on paper like the pen is reflected in its name: it comes from the Ancient Greek *graphein*, meaning "to write" or "to draw."

Scientists have long known that graphite is composed solely of carbon atoms. Industrially produced graphite is used for carbon rod electrodes inside batteries.

Pure carbon can also form diamonds, depending on how the atoms are arranged. However, only graphite carries electricity well.

How can we tell which materials do or don't carry electricity?

The results of the previous experiments have taught us that:

1. All "metallic" materials carry electricity well.
2. Wood, plastic, paper, glass, and ceramics do not carry electricity.
3. Only one non-metal carries electricity: graphite.

More rigorous experiments carried out by scientists agree with these findings. That is, it is usually only metals that carry electricity well enough to light up a bulb, with graphite being the sole exception.

'Metal' as a scientific term

Metal is a non-graphite material that carries electricity

Scientists define a metal as any opaque (not transparent) material, even when as thin as an aluminum foil; it has a characteristic golden or silvery "shininess" known as metallic luster and readily changes shape when a strong force is applied to it.

We use a variety of objects made of metal every day: pots and kettles, knives and forks, aluminum foil, wire, electrical cables, coins, cans, cars, and so on.

Scientists understand that the essential property of metals is that they can carry electricity well. However, as graphite carries electricity but isn't a metal, it is better to say that, except for graphite, any material that carries electricity is a metal.

It may be easy to tell that something is metal from its golden or silvery luster. However, the scientific definition of metal as a non-graphite material that carries electricity is much more precise.

Metal and Free Electrons

So why exactly do metals allow electricity to flow through them?

It all comes down to so-called free electrons, which abound inside metals like gold, silver, aluminum, iron, and copper and act as carriers of electricity.

Electrons are tiny particles found in every atom, but they're usually tightly bound to the center and can't move freely; these electrons are called ***bound electrons**.* In metals, on the other hand, some of the electrons can move around freely; these are called ***free electrons*.** Any material whose atoms contain lots of free electrons will have a silvery luster.

No microscope, no matter its magnification, will allow us to see electrons. However, from now on, we can imagine all the free electrons, tiny particles, moving around and giving off their silver shine whenever we see a material with that golden or silvery luster.

Problem 9

Dragees are tiny silver beads (about 1mm across); sometimes, we see them placed on top of cakes and sweets for decoration.

Do you think a silver dragee carries electricity? What do you think will happen when we place it in the circuit with the light bulb as we did before?

Prediction

a. The bulb lights up.

b. The bulb does not light up.

Please share your ideas with the class, then experiment.

Result

Dragees

Despite being a foodstuff, dragees carry electricity very well. This is because the silvery surface of a dragee is coated with real silver.

Perhaps you've also seen sweets or sparkling wine with gold leaves. Silver and gold don't react inside the body, unlike other metals, so they're safe to consume in small amounts. They are your only choice if you want a sparkling metallic sheen on your food.

What's the difference between water flowing through a hosepipe and electricity flowing through a wire?

Thus far, we have been saying that something "carries electricity" or that "electricity flows well" through something — but what does it actually mean to say this?

When you connect a hose to a tap, water flows through it. Could electricity flow in the same way?

A hose is usually empty before the water starts flowing, but the wires are not. They're full of atoms and free electrons. So how is it possible for electricity to flow through it? The "flow of electricity in a wire" could equally be called the "flow of free electrons." Free electrons constantly move freely between metal atoms, jostling around randomly. However, when a generator or a battery is connected to a metal wire, the free electrons flow in one direction. This flow is called electric current.

The free electrons have always been there; the generator simply makes them travel in a single direction. In the case of the water supply, what leaves the tap is water that has been stored in a reservoir. By contrast, the generator doesn't store any free electrons. As long as it's connected to the circuit, it can send the free electrons around the wire to do their work in one direction.

Batteries, too, work by moving free electrons in one direction through wires. When the wire on the negative side of the battery runs low on free electrons, it replenishes them using a chemical change induced in the battery metal. The battery will no longer be usable once this metal has been used up.

Free electrons are an intrinsic part of metals, moving around freely between the metal atoms. Hence, electricity (free electrons) can flow freely through metals despite containing no empty space.

For these reasons, scientists say that metal conducts electricity or that the metal is conductive. A material that conducts electricity is called a conductor. All three of these words come from the Latin word '*conducere,'* which means "to lead" or "to direct." In a real sense, the battery and generator lead and direct the free electrons around the circuit to generate electric current.

Part 2: When You Find Free Electrons

Problem 1

Origami is usually made by folding paper, which does not conduct electricity well. Some origami paper, however, is silver- or gold-colored.

Since it's silvery, it may give the impression of having lots of free electrons moving around inside. But equally, it looks like just an ordinary piece of paper.

Do you think that silver-colored origami paper conducts electricity?

What do you think will happen when we try the same experiment as before?

Expectation

a. The bulb lights up.

b. The bulb doesn't light up.

Why do you think so? Please share your ideas with the class, then experiment.

Result

Problem 2

Silver-colored origami paper conducts electricity very well. It is coated with aluminum foil, and the free electrons moving around make the paper conductive.　So, what do you think of gold-colored origami paper?

Three students presented their ideas.

Alice says, "Golden origami paper must have some gold on it. So I think it'll conduct electricity very well."

Bob says, "Surely gold is far too expensive to put on origami paper. I don't think it'll conduct electricity."

Carol says, "There must be some lacquer or paint on the aluminum foil. I bet it'll conduct electricity if you remove the top layer."

What do you think?

Expectation

a. The bulb lights up.
b. The bulb doesn't light up.
c. The bulb lights up only if you first remove some of the surface of the material with sandpaper.

Result

Free Electrons and Silver/Golden Origami Paper

Golden origami paper does not conduct electricity unless you rub away some of the surfaces with sandpaper, which turns it silvery and conductive.

While gold is one of the most common golden-colored metals, it's much too expensive for origami paper. Instead, the silver-colored aluminum foil is coated with a thin coat of transparent yellow paint to make it appear gold. Since the paint has no free electrons, electricity can only flow through once removed.

You can be sure that anything with a metallic luster has free electrons moving around inside it. However, if a metal has a thin coating, such as vinyl film or a thin layer of paint, it will retain its luster but not conduct electricity. In cases like these, sandpaper or something similar to remove the coating from the surface of the metal will allow electricity to flow once more.

Hands-On

Copper wire is often coated with a thin layer of hard, glossy material as protection.

Some of this wire is brown, so you can immediately tell it has been coated with something. However, it sometimes has a transparent coating, which makes it impossible to tell it apart from a bare copper wire just by looking.

coated wire

brown Transparent

Let's make a circuit using the latter type (with the copper color visible) and see whether the miniature light bulb lights up. Surely it can't.

Now, try again after you've rubbed the end of the wire with some sandpaper.

You may have difficulty removing the coating and making the bulb light up, as the transparent coating can be hard to see.

Problem 3

Kettles, pots, and the like are sometimes made of aluminum. Aluminum is also commonly used for window frames, fixtures, and fittings.

However, aluminum has one major drawback: it's liable to corrode when exposed to water. To prevent this, aluminum products usually undergo a process called anodizing. The result of this process is called anodized aluminum.

Do you think the surface of an anodized aluminum pot will conduct electricity?

Expectation

a. The bulb lights up.

b. The bulb doesn't light up.

c. The bulb lights up only if you remove some of the material's surface with sandpaper.

Result

Problem 4

Do you know ferrite magnets?

ferrite magnets

These dark black ferrite magnets are today's most widely used magnet type. For example, it is often used for pins to attach paper to a blackboard or whiteboard. Ferrite magnets are black not only on the outside but also on the inside.

Do you think that ferrite magnets conduct electricity? When we perform the same experiment as before, do you think the miniature light bulb will light up?

Expectation

a. The bulb lights up.

b. The bulb doesn't light up.

c. The bulb lights up only if you remove some of the material's surface with sandpaper.

Result

Ferrite and anodized aluminum

No matter how much you rub a ferrite magnet with sandpaper, it will never become a good conductor of electricity. No amount of rubbing will allow you to see the free electrons.

The reason ferrite magnets don't conduct electricity isn't because they're magnets. Some magnets have a metallic luster, and such magnets do conduct electricity.

"Ferrite" is derived from the Latin "ferrum" meaning iron. However, ferrite magnets are not iron. It is made of iron oxide, a combination of iron and oxygen atoms.

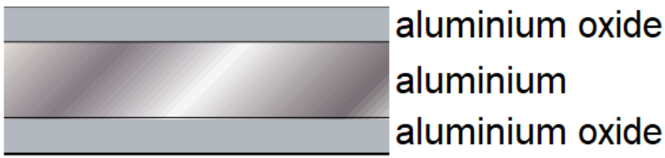
Since iron is such a good conductor of electricity, you might think that ferrite (iron oxide) should also be a good conductor. When iron binds with oxygen, however, the free electrons in the iron are no longer free to move around because they are busy binding together the oxygen and iron atoms. In other words, the free electrons become bound electrons. The metallic luster that indicates the presence of free electrons also disappears and no longer conducts electricity.

Anodizing is a process in which the surface of aluminum is oxidized to form a thin film of aluminum oxide — that is, aluminum bonded to oxygen. Thus, as we saw with ferrite, the free electrons in the aluminum stop being free, stopping anodized aluminum from conducting electricity.

That said, anodizing oxidizes the aluminum only on the surface; the aluminum underneath remains unchanged. Scrubbing the surface of an anodized kettle with sandpaper exposes the underlying aluminum, allowing the kettle to conduct electricity.

Similarly, aluminum window sashes will not conduct electricity as they are, but if you try connecting electric wires to a part of the surface that's been scratched or cut off, you'll find that it conducts electricity very well.

Aluminum oxide is not metal, so it has no metallic luster. Anodized aluminum appears to have a metallic luster, but this is because the oxide film is so thin that the aluminum's luster (that is, the free electrons) is visible underneath.



Corrosion and Free Electrons

This phenomenon is not limited to iron and aluminum. Generally, when any metal bonds with oxygen, its free electrons become bound electrons, and it loses its metallic luster. Moreover, when a metal naturally bonds with oxygen, the bonding is often not uniform, which in most cases results in a rough, jagged surface. Metal that has bonded naturally with oxygen and changed in this way is called corrosion. We say that the metal has corroded. When metal corrodes, it not only becomes coarse and unsightly but also loses its strength, which has long been a headache for engineers.

Note that it is not the case that all metals inevitably corrode like this when they bond with oxygen. The bonding can produce a smooth surface when done artificially and with care. Anodizing is a good example of this.

Anodizing prevents the aluminum atoms from bonding to oxygen atoms in the air. The surface atoms are already bonded with them, preventing the surface from corroding. In other words, anodizing is the way to protect aluminum by artificially coating it with a "clean layer of corrosion" before undesirable, natural corrosion can occur. It is a remarkably clever idea.

Problem 5

Have you ever seen letters or pictures on dry cell batteries or beverage cans printed in shiny metallic silver or gold? Metallic-colored text is also sometimes printed on the covers of magazines and books.

Is it true that this metallic luster is evidence of an abundance of free electrons? Are these things made of metal? Do they conduct electricity?

What do you think? Let's try making predictions for a handful of familiar objects and then experiment on them.

Expectation

a. The bulb lights up.

b. The bulb doesn't light up.

c. The bulb lights up only if you remove some of the material's surface with sandpaper.

	Expectation	**Results**
1) Batteries	( )	
2) ________	( )	
3) ________	( )	

Metallic Luster and Free Electrons

Have you ever heard of mercury, a liquid metal? Mercury is solid below -39°C but is a liquid that glows silver at room temperature. With lots of free electrons, the metal conducts electricity well, whether solid or liquid.

The picture on the right shows an electrical component called a mercury switch. Although mercury is toxic and is not used today, it can be turned on and off simply by tilting a glass tube containing an electric wire and mercury.

So, what about when a metal turns into gas? When this happens, the metal atoms separate and spread apart. This prevents electrons from moving around freely, which prevents the gas from conducting electricity.

There is a technique called "evaporation deposition," in which metal atoms are evaporated and deposited onto the surface of plastic or other materials as a skinny film. Although ordinarily opaque, metals deposited as a thin film using this technique are see-through when held up to the light, and objects coated in this way have a metallic luster but usually don't conduct electricity well.

Another example is gold and silver paint, which is made by mixing fine metal particles with plastic or oil. Despite having a metallic luster when applied to a surface, these paints do not conduct electricity because the metal particles are covered in a non-conductive substance.

These notable examples aside, we can safely say that "anything with a metallic luster conducts electricity well." Suppose something with a metallic luster is opaque but does not conduct electricity. In that case, it is safe to assume it is metal with a transparent coating or not a metal such as mica powder hardened with resin that reflects light diffusely to give the appearance of metallic luster.

Lead

Have you ever seen lead used for fishing? Even a small amount of lead is heavy, so it's often used to make fishing weights. It is used in battery electrodes. Lead is also used in solder because it melts easily when heated.

You may have heard that lead is toxic or poisonous. Although touching pure lead metal with your hand is generally harmless, breathing it in or swallowing it is extremely dangerous. Always wash your hands thoroughly with soap after handling lead. Lead is known to be harmful depending on how it's used and/or has been processed, and efforts are well underway to prevent lead-containing products and substances from causing disease and contaminating the environment.

Problem 7

Safety Note: These experiments should be performed under the laboratory safety standards.

1) Do you think lead conducts electricity well?

Expectation

a. The bulb lights up.
b. The bulb doesn't light up.
c. (something else)

2) Lead used in fishing is dull in appearance, but what happens if you scrape away some of the surface with a knife? Do you think you'll see a silvery luster?

Expectation

When the surface of the lead is scraped with a knife…
a. it will reveal a metallic luster.
b. it will not reveal a metallic luster.
c. (something else)

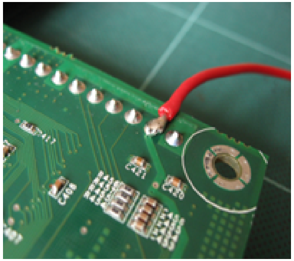
Experiment

Scrape away some of the surface with a knife.

Metal and its many varieties

Lead also has a silvery luster, meaning it has many free electrons moving around inside. It conducts electricity very well. It is, therefore, a member of the metal "family". The word 'metal' likely makes you think of gold, silver, copper, iron, aluminum, and the like, but there are many other kinds of metal. Can you name any others?

Brass, bronze, and cupronickel are metals, but we specifically call these alloys because they're mixtures of two or more metals. Other examples include solder, nichrome, and stainless steel.



Solder is an alloy of lead and tin and is used for connecting wires.

Nichrome is an alloy of nickel and chromium, used as heating wire.

Including alloys increases the total number of metals, but there are still lots of metals made of a single type of atom.

For example, lead, tin, zinc, mercury, and platinum are metals. Tungsten, titanium, nickel, and cobalt are also names of metals.

Calcium or sodium may not feel metallic, but a collection of calcium or sodium atoms has a silvery luster and conducts electricity. Therefore, these are also metals. And when you hear the names 'radium' and 'uranium,' the first thing that comes to mind may be radioactivity. But anything made only of radium, uranium, or cobalt atoms will have a silvery luster, so these three also belong in the metal family.

metallic sodium

While metals come in wide varieties, all are packed with free electrons, have a metallic luster, and conduct electricity well. All of them except gold and copper have a silvery luster, which makes it difficult to distinguish them by sight alone. Only gold and copper have a golden or reddish luster; all other metals are silver.

Part 3: Free electrons, heat, and electricity

Since all metals contain lots of free electrons, they conduct electricity well. However, different metals naturally have different numbers of free electrons; in some metals, the free electrons can move more easily than in others. In other words, some metals conduct electricity better than others.

Therefore, using highly conductive metals when making conductors (like electrical wires) is best.

Problem 1

Which of the following metals do you think most readily conducts electricity?

Which do you think conducts the second most readily?

Try to predict the top two.

Gold Silver Copper Iron Aluminum

Expectation

Most conductive:

Second most conductive:

Why do you think so? Share your thoughts with the class, then read the next section.

Result

Silver is a luxury — use copper!

Of all the metals — not only gold, silver, copper, iron, and aluminum, but all of them, including alloys — the best conductor is silver.

After silver, the next best conductor of all the metals is copper.

However, silver is too expensive to make electrical wires; copper is usually used instead. Although silver is a better conductor, if we assign silver a value of 1, copper conducts with a value greater than 0.9.

Therefore, the use of inexpensive copper is the most cost-effective option.

Problem 2

1) How well do you think iron conducts electricity compared with copper?

Expectation

a. Iron conducts electricity at least half as readily as copper.

b. Iron conducts electricity much less readily than copper.

Why do you think so?

Before you read the next section, try predicting this as well.

2) What would the following three metals look like if you arranged them according to how well they conduct electricity?

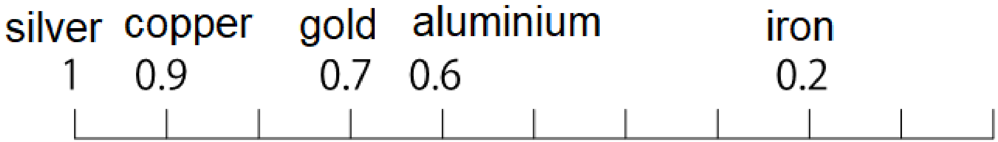
Gold	Iron	Aluminum

Expectation (   )

Why do you think so? Share your ideas before reading the next section.

Conductive metals

How well a material conducts electricity is called its (electrical) conductivity. If we arrange gold, silver, copper, iron, and aluminum in order of electrical conductivity, this is what we find.



The numbers indicate each metal's ability to conduct electricity measured relative to silver, which is assigned a value of 1.

Silver and copper are not very different, but iron, at 0.2, does not conduct half of the electricity as well as copper. Aluminum conducts electricity more easily.

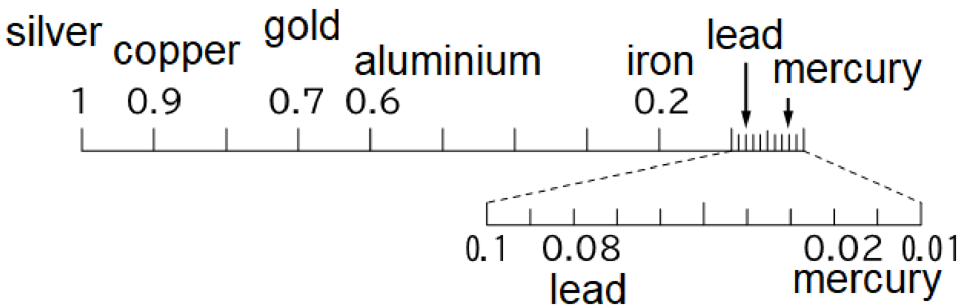
Therefore, steel wire is not usually used in place of copper wire. However, aluminum wires are often used. It is both lighter and cheaper than copper, making it preferable when, for example, running long electrical cables across wide rivers.

Iron is much less conductive than silver or copper. However, this is only true when compared to metals alone. We must not forget that iron also conducts electricity much better than non-metals.

There are even metals that conduct electricity less easily than iron.

If silver's conductivity is 1, iron is 0.2, but lead and mercury conduct electricity only 0.08 and 0.02, respectively.

Note that alloys usually conduct electricity less readily than their component metals.



Problem 3

Metal has been used since ancient times to make all kinds of tools.

One such use is cookware. A pot, kettle, or other vessel for boiling water or food is usually made of metal. Although ceramic pots are sometimes used, metal cookware is more convenient for cooking because it conducts heat more quickly, preventing partial scorching. Therefore, metal has long been considered more suitable for making pots and pans because it conducts heat more easily.
The term "conductivity" is also used to describe the ease of heat transfer.
Which of the following metals do you think most readily conducts heat?
Which is the second best? Try to predict the top two.

Gold	Silver	Copper	Iron	Aluminum

Expectation ______________________________________

Why do you think so? Share your ideas before reading the next section.

Silver pots and copper pots

Some of you may think there is no way you could have predicted which of the five metals conducts heat the best, but it is possible to guess if you have some cooking knowledge. It has long been held that the best pots are silver, followed by copper.

We have learned so far that silver conducts heat best of all metals, with copper a close second, which is consistent with this.

However, making cookware out of silver and copper is much too expensive. Some professional chefs use silver and copper pots and pans, but this is far from the norm.

Now we know that the two metals that conduct heat best are silver and copper, which are in the same order. Is this a coincidence? What do you think?

If not, why do you suppose the order is the same?

Problem 4

Which metals would you say conduct heat the best after silver and copper? Try to put the following metals in order.

Gold	Iron	Aluminum

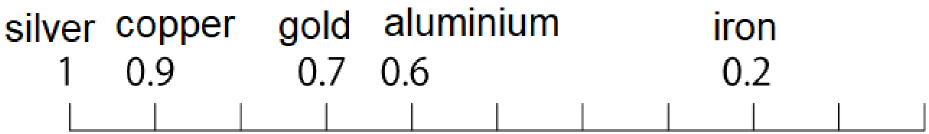
Expectation

I. 2. 3.

Why do you think so? Share your ideas with the class before reading the next section.

Thermally conductive metals

How well a material conducts electricity is called its thermal conductivity. If we arrange gold, silver, copper, iron, and aluminum in order of their thermal conductivity, this is what we find.



The numbers indicate the ability of each metal to conduct heat relative to silver, which is assigned a value of 1.

If you arrange metals by thermal conductivity, the order is precisely the same as when considering their electrical conductivity. This can't be a coincidence.

As some of you may already have realized, this means that in metals, "what conducts heat" is the same as "what conducts electricity."

It is the "free electrons" that conduct electricity through the metal. Actually, "free electrons" not only conduct electricity but also heat. Therefore, it is natural that "metals that conduct electricity more easily also conduct heat more easily.

Question

From the preceding problems and experiments, we've learned that metals contain many free electrons, giving them a metallic luster and making them good conductors of electricity and heat.

So, can every property that metals have in common be explained by having an abundance of free electrons?

In addition to those we've already covered, another property all metals share is that they're somewhat elastic and deformative. This is a big difference from pottery made of clay, which is hard, but breaks without deformation when a large force is applied to them.

How, then, does the existence of free electrons explain this property of metals?

Can you think of a better explanation?

Free electrons and free water

Scientists believe that the tenacity of metals is due to free electrons.

More precisely, because the free electrons hold the metal atoms together but also move around freely, they can keep the atoms connected even if the arrangement of the atoms changes.

This is similar to making balls of sand in a sandpit: if the sand is completely dry, the sand grains will not stick together, and we cannot ball it up. On the other hand, if there's some moisture between the grains, it allows the grains to stick together and form a ball.

This is similar to making a sandcastle: if the sand is completely dry, the sand grains will not stick together and fall apart. On the other hand, if there is some moisture between the grains, it allows them to stick together and form a stable structure.

And there is more. A moist ball of sand can also change shape slightly in response to a force. Because the moisture that binds the grains together can move, the ball won't easily fall apart if it only slightly changes shape. If you remove all of the moisture, it will not be able to deform. The moisture between the sand grains acts like the free electrons in a metal.

So, the water that can move freely between the grains of sand, "free water," acts in the same way as "free electrons in metal."

By the way, if free electrons act as a glue that sticks metal atoms together, then metals should be able to stick together without glue, right?

Professional welders do this all the time. Have you ever seen people welding steel on a reinforced concrete construction site? They heat the iron to very high temperatures to melt and join. They are easy to spot because they wear iron masks to protect their eyes from heat, light, and flying sparks.

Once the metals have been melted and joined, free electrons enter and fill the spaces between the previously separated metals and connect their atoms.

Soldering works on the same principle: two metals are joined together with solder, a metal that quickly melts. When soldering, the surface of the metals must be clean; if it's dirty or corroded, there will be fewer free electrons available, making it impossible for the free electrons in the metal and the solder to travel back and forth freely.

Melting iron is difficult because it requires extremely high temperatures. These days, a technique known as crimping is frequently used to combine metals without melting them. This technique joins metals together simply by pressing them firmly against each other.

You may think it requires much force, but lead can be attached with just the force of your fingertips.

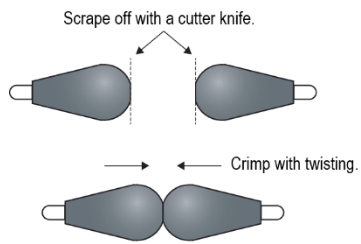
Hands-on

Safety Note: This activity should be performed under the laboratory safety standards.

Prepare two lead fishing weights (lead balls) and try to stick them together using only the strength of your fingertips.

1. It is imperative that the surface of the lead not be dirty or corroded. The first step, therefore, is to scrape away some of the surface with a utility knife. Lead is very soft for a metal and cuts easily. Take a lead ball from the fishing tackle and try cutting the surface with the knife. Make sure that where you've cut is shiny and has a metallic luster.

2. Next, take two lead balls between your fingertips and press the shiny areas forcefully against each other with a slight twist. They should stick firmly together after a few attempts.



3. If the balls fail to stick together twice in a row, oxygen (or other particles) from the air may have become stuck to the surface. In this case,

scrape away the surface once more.

This experiment requires patience, luck, and some skill, so not everyone can do it immediately. If you see someone who's managed it, ask them to show you.

4. Once the lead balls are stuck together, they don't come apart easily. The bond is stronger than using adhesive. Let's hang some weights from them and see how much of a load they can bear.

5. Look at the exposed section when the lead balls split or break. You'll notice that the area where they were attached is rough and uneven as if they were forcibly ripped apart. It looks completely different from the area where the adhesive peeled off.

Conclusion

You've reached the end of "When You See Free Electrons."

Did you enjoy your time learning with the book? Which problems did you find particularly interesting? Please have another read-through from the beginning and share your best memories.

Are there any problems whose answers you think you really ought to remember? Can you remember those answers now? If you think you might've forgotten, remind yourself of the answers now, then have your teacher test whether you can still remember them next time.

You can't see an individual free electron with the naked eye. It isn't even possible with any microscope. But if it's a large group of free electrons, you can see them all together.

1. It conducts electricity!
2. It conducts heat well!
3. It sticks metals together!

And if you find that shiny metallic luster, you've seen free electrons. And when you find free electrons, you can say, "**That's a metal**!".

The End

Dear Teachers,

I appreciate your interest in the Hypothesis–Experiment Class(HEC). If you conduct a class, we would appreciate it if you could provide the Association for Studies in HEC with a record of the class (the Classbook title, target age group, country/region, students impressions, number of students on each 5-point scale*, your impressions as a conductor, etc.). Your record is valuable and needed to improve the HEC Classbooks. For queries, please email contact2ashec@kasetsu.org

Thank you,

Association for Studies in Hypothis–Experiment Class

* Example: Out of 56 students, 43 rated 5, 10 rated 4, 2 rated 3, 0 rated 2, and 1 rated 1.

For more information on this 5-step evaluation, please refer to the HEC Management Guide, available for download from the same site as this document..

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