1. A lightweight metal ball hangs by a thread. When a plastic rod that has been rubbed with wool is held near, the ball moves toward the rod, touches the rod, then quickly flies away from the rod. The same thing happens when a glass rod that has been rubbed with silk is used instead. Construct a model for these situations and use it to explain the observations.

Objects	Simplification
Metal ball	Rigid body, conductor
Plastic rod	Rigid body, insulator
Glass rod	Rigid body, insulator

Interactions	
Electric between metal ball and plastic rod	Qualitative electrostatic interaction
Electric between metal ball and glass rod	Qualitative electrostatic interaction
All gravitational and tension interactions	Ignore

The plastic rod that has been rubbed with wool has an excess of electrons and is negatively charged. When the rod is brought near the metal ball the ball polarizes and is attracted to the rod. When the ball touches the rod some of the rod's excess electrons are transferred to the ball. Since the rod and ball now have the same charge they repel. The situation with the glass rod is explained in the same way, except that the glass rod is missing some of its electrons to begin with and has a positive charge. When the ball touches the glass rod some of the electrons from the ball transfer to the rod. Again, the rod and ball end up with the same charge (positive this time) and they repel.

2. You put an empty soda can on a wooden tabletop. You rub one end of a plastic rod with wool and bring it close to the side of the can without touching it. You observe that the can rolls toward the rod. Rub one end of a glass rod with silk (to get an opposite charge) and repeat the experiment with the can. You observe the same phenomenon. No matter what charge is on the rod, the can is attracted to it. Use the models we developed in class to explain these observations. Repeat the experiment using a plastic bottle instead of the soda can. You observe that the bottle is attracted to both rods, but not as strongly. Construct a model for these situations and use it to explain the observations.

Objects	Simplification
Soda can	Rigid body, conductor
Plastic rod	Rigid body, insulator
Glass rod	Rigid body, insulator
Plastic bottle	Rigid body, insulator

Interactions	
Electric between soda can and plastic rod	Qualitative electrostatic interaction
Electric between soda can and glass rod	Qualitative electrostatic interaction
Electric between plastic bottle and plastic rod	Qualitative electrostatic interaction
Electric between plastic bottle and glass rod	Qualitative electrostatic interaction

When either of the charged rods are brought near the soda can the soda can polarizes and is attracted to the rod. The same thing happens to the plastic bottle except that because plastic is an insulator its electrons cannot move freely about the material. This leads to a significantly smaller amount of polarization and therefore a smaller attractive force.

3. A $10.0cm$ aluminum sphere is charged with a Wimshurst generator so that it has +4 units of charge. A second otherwise identical sphere is charged so that it has -6 units of charge. The two spheres are brought

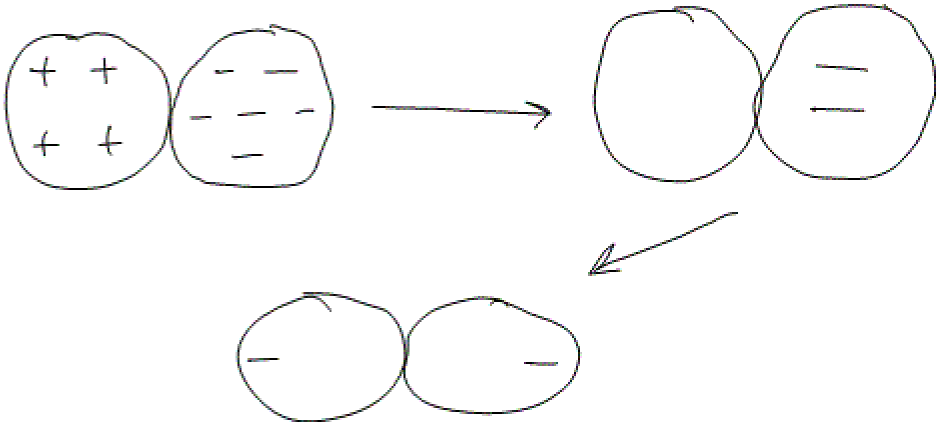
into contact with each other. Construct a model for this situation and use it to predict step by step what will happen. Explain your reasoning, and draw diagrams showing what, if anything, the charges will do.

Objects	Simplification
Aluminum spheres	Rigid body, conductor

Interactions	
Electric between charges in the spheres	Qualitative electrostatic interaction

Since the two spheres are conductors charge will easily transfer between them. Electrons from the negatively charged sphere will transfer over to the positively charged sphere since they are attracted by the positively charged sphere and repelled by the other extra electrons in the negatively charged sphere. This reasoning gets the spheres to where their charges are neutral and -2. One more unit of negative charge will transfer to the now neutral sphere since it's repelled by the other unit of negative charge. Each sphere now has 1 unit of negative charge, and they are located on opposite sides of the spheres since they repel.

Diagram



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4. You've been given an unknown piece of material, roughly the size of a pencil. Design two experiments that could be used to determine whether the material is an insulator or a conductor. Construct a model for each of the experiments and use it to describe specifically what the outcome of each experiment will be if the material is an insulator or a conductor.

Experiment 1: One of the videos we watched during the first class involved a Wimshurst machine, a soda can/plastic bottle, and an aluminum disk. Here's the link: http://paer.rutgers.edu/pt3/experiment.php?topicid=10&exptid=128. This setup could be used to determine if the unknown piece of material is a conductor or an insulator by replacing the soda can/plastic bottle with the unknown material. If it is a conductor, the disk would be repelled from the material. If it is an insulator it would not.

Objects	Simplification
Unknown material	Rigid body, conductor or insulator
Wimshurst machine contacts	Rigid body, conductor
Aluminum disk	Rigid body, conductor

Interactions	
Electric between Wimshurst machine and unknown material	Qualitative electrostatic interaction
Electric between unknown material and aluminum disk	Qualitative electrostatic interaction
All gravitational, normal, and tension forces	Ignore

Experiment 2: Another video we watched showed two electroscopes being connected by a plastic rod and then by a metal rod. Here's the link: http://paer.rutgers.edu/pt3/experiment.php?topicid=10&exptid=126. This can also be used to determine if the unknown material is a conductor or an insulator by replacing the plastic/metal rod with the unknown material. If the unknown material is an insulator the second electroscope will not become charged. If the unknown material is a conductor, the second electroscope will become charged.

Objects	Simplification
Unknown material	Rigid body, conductor or insulator
Electroscope contacts	Rigid body, conductor

Interactions	
Electric between the electroscope contacts and the unknown material	Qualitative electrostatic interaction
All gravitational and normal forces	Ignore

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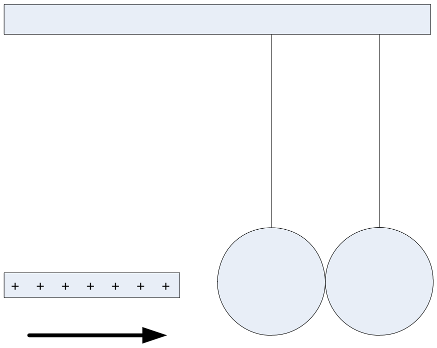
5. Two aluminum spheres hang by threads as shown. A glass rod that has been rubbed with silk (making the rod positively charged) is brought closer and closer. Construct a model for this situation and use it to predict **a)** what will happen when the rod is close (but not touching them) to the spheres, and **b)** what will happen when the rod is allowed to briefly touch the left sphere and then is moved far away from the spheres.



Objects	Simplification
Glass rod	Insulator, rigid body
Aluminum spheres	Conductor, rigid body
Threads	Ignore
Earth	Ignore

Interactions	
Electric between charges in the rod and the spheres	Qualitative model

a) When the rod is close electrons from both spheres (because they are in contact) will be drawn toward the rod. The left sphere will have a net negative charge and the right sphere will have a net positive charge. The left sphere will be attracted to the rod, and the right sphere will be attracted to the left sphere. So, the two spheres remain in contact but will swing slightly to the left toward the rod.

b) When the rod touches the left sphere, some electrons will transfer from the sphere to the rod. Not too many will transfer since the rod is an insulator, so the spheres will still be attracted to each other. Once the rod is moved away the charges on the spheres will equalize. Since some electrons were transferred to the rod, both spheres will have a net positive charge so they will repel one another and there will be a small gap between them.

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6. You are a photographer for an archaeological team working in an ancient tomb in Egypt. You need to set up a small floodlight down in one of the tunnels so you can take pictures of a wall full of amazing hieroglyphics that the team has just discovered. The problem is that the wall is $2000m$ from the entrance to the tomb, which is where the team's electric generator is. You know the specs for the generator and the floodlight: The generator produces a potential difference of $100V$ and the floodlight has a resistance of 100Ω. Normally you know this results in a current of roughly $1.00A$ through the floodlight and a power output of roughly $100W$. But, you've never had the floodlight anywhere near that far from the generator. You have enough wire to do it, but you know if the power output of the floodlight drops below $95.0W$ your pictures will come out too dark. You know the power cable for the floodlight uses 10 gauge copper wire (diameter $d = 2.59mm$, resistivity $\rho = 1.7\times10^{-8}\,\Omega\cdot m$). Construct a model for this situation (include a

diagram) and use it to decide whether or not the floodlight will be bright enough so that good pictures of the newly discovered hieroglyphics can be taken.

Objects	Simplification
Electric generator	Ideal power source with no internal resistance
Wires	Conductor with non-negligible resistance
Interactions	
Electric	Potential model

I'll use Kirchhoff's loop rule to determine the current in the circuit.

$$\sum \Delta V = 0$$

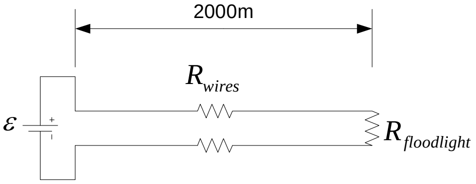
$$\Delta V_{generator} + \Delta V_{wires} + \Delta V_{floodlight} = 0$$

$$\varepsilon - IR_{wires} - IR_{floodlight} = 0$$

$$I = \frac{\varepsilon}{R_{wires} + R_{floodlight}} = \frac{\varepsilon}{\rho \frac{L}{A} + R_{floodlight}} = \frac{\varepsilon}{\rho \frac{L}{\pi \left(d/2 \right)^2} + R_{floodlight}} = \frac{\varepsilon}{\rho \frac{4L}{\pi d^2} + R_{floodlight}}$$

$$I = \frac{100V}{\left(1.7\times10^{-8}\Omega\cdot m\right)\frac{4\left(4000m\right)}{\pi\left(2.59\times10^{-3}m\right)^2} + 100\Omega}$$

$$I = 0.886A$$



The power output of the light is then

$$P = I^2 R_{floodlight} = \left(0.886A\right)^2 (100\Omega)$$

$$P = 78.4W$$

The floodlight will not be bright enough. The wires connecting it to the generator are just too long and have too much resistance.

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7. You are given a spool of wire, wire cutters, a DC power supply, a galvanometer, a rectangular piece of unmagnetized iron, and an unmarked bar magnet. Design an experiment that will allow you to decide which end of the magnet is its north pole. Construct a model for the setup you come up with. Describe in detail how you will be able to tell which end of the magnet is its north pole based on the results of the experiment. Your experiment does not need to use all the equipment given to you.

Cut a length of wire and orient it with respect to the bar magnet as shown. Connect the wire to the power supply so a large current flows into the page. If the north pole of the magnet is closer to the wire then the wire will be bent upward by the magnetic field of the magnet. Since the magnetic field points to the left and the current is into the page, the right hand rule says the magnetic force on the wire will point up. If the south pole of the magnet is closer to the wire then the wire will be bent downward by the magnetic field of the magnet. Since the magnetic field points to the right and the current is into the page, the right hand rule says the magnetic force on the wire will point down.

Objects	Simplification
Wire	Conductor, semi-rigid since it has to be able to bend so the direction of the force is observable.
Bar magnet	Magnetized rigid body
Earth	Ignore

Interactions	
All gravitational interactions	Ignore
Magnetic between the magnet and the wire	Qualitative field model

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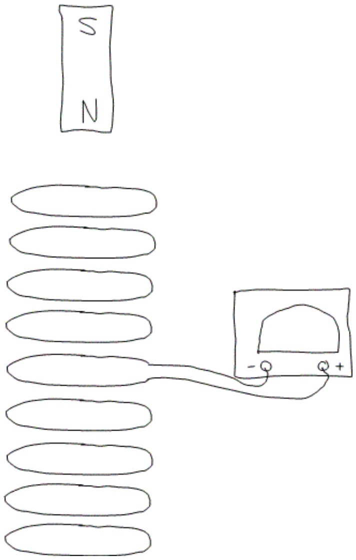
8. A large number of circular wire loops are stacked on top of each other as shown. One of the loops in the middle of the stack is connected to a galvanometer. A bar magnet is dropped north pole first through the loops.
   a. Construct a model for this situation.
   b. Predict what the galvanometer will read as the magnet falls through the loops. Make your prediction in the form of a graph.
   c. As the magnet falls through the loops, you notice that it falls with an acceleration considerably less than $9.8\,m/s^2$. Explain this.



Objects	Simplification
Wire loops	Conductor, rigid body
Bar magnet	Magnetized rigid body
Earth	Ignore

Interactions	
All gravitational interactions	Ignore
Magnetic induction between the magnet and the loops	Qualitative model (Lenz's law)
Magnetic between currents in the loops and the magnet	Qualitative field model

The reason the second "hump" is larger than the first is because the magnet will be falling faster by that time and therefore causes a larger induced EMF.

As the magnet falls toward the loops, counterclockwise currents begin forming. The current loops have magnetic fields that are similar to bar magnets and therefore effectively have north and south poles. However, the north poles of these current loops face the north pole of the falling magnet, causing a repulsive force and therefore a smaller downward acceleration. Once the magnet falls into the region inside the loops, clockwise currents form in the loops above the magnet. These have their north poles facing down and attract the south pole of the magnet. This further decreases the acceleration of the magnet.

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9. Imagine that you have used a Wimshurst machine to charge the plates of a parallel plate capacitor so that it has an approximately uniform electric field of magnitude $5.00\times10^4\,\frac{N}{C}$ in the region between the centers of the plates. The plates of the capacitor are squares $5.00\,cm$ on a side and are separated by $2.00\,mm$. The negative plate is heated at a spot near its middle. As a result a few electrons are freed from its surface and begin moving towards the positive plate.
   a. Construct a model of the situation. Use it to predict what the speed of the electrons will be the instant before they strike the positive plate. Use Newton's 2nd law as your process model.

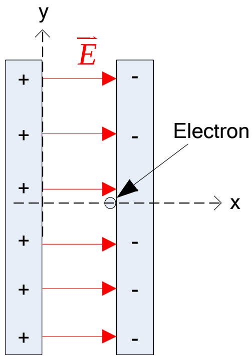
b. Change your model so that it uses the potential model for the electric interaction. Use this new model to make the prediction again, but use conservation of energy as your process model. (Hint: As a first step, find the potential difference between the two plates.) Do the two predictions agree?

Part a.

Objects	Simplification
Capacitor	Conductor, rigid body, infinitely large plates
Electrons	Point particle
Air	Ignore
Earth	Ignore

Interactions	
Electric between capacitor and electrons	Field model

The plan will be to use Newton's 2nd law to find the acceleration of the electrons, then use kinematics to find their speed the instant before they strike the positive plate. I often like to start at the end and work backwards, that way I'm only taking the steps I need to. So, I'll start with kinematics. Kinematics is a process model since it relates the position/velocity of a point particle at an initial moment to its position/velocity at a later moment. Since I'm not predicting how long it takes the electrons to reach the positive plate I'll use this part of the model:



$$v_f^2 = v_i^2 + 2a\left(x_f - x_i\right)$$

I'll assume the electron initially is at rest. Just before it strikes the positive plate it will be at the origin of the coordinate system shown in the diagram. So

$$v_f = \sqrt{2a\left(-x_i\right)}$$

$$v_f = \sqrt{2\frac{\sum F}{m}\left(-x_i\right)}$$

$$v_f = \sqrt{2\frac{\left(q_e E\right)}{m}\left(-x_i\right)} = \sqrt{2\frac{\left(-e\right)E}{m}\left(-x_i\right)} = \sqrt{\frac{2eEx_i}{m}}$$

$$v_f = \sqrt{\frac{2\left(1.6\times10^{-19}C\right)\left(5.00\times10^{4}\,\tfrac{N}{C}\right)\left(0.002m\right)}{\left(9.11\times10^{-31}kg\right)}}$$

$$v_f = 5.93\times10^{6}\,\tfrac{m}{s}$$

Part b.

I'll start with conservation of energy. The initial state will be when the electron is just released from the negative plate. The final state will be when the electron is just about to strike the positive plate.

$$E_f = E_i + W$$

$$K_f + U_f = K_i + U_i + 0$$

$$K_f + U_f = 0 + U_i$$

$$\frac{1}{2}mv_f^2 + qV_f = qV_i$$

$$v_f = \sqrt{-\frac{2q}{m}\left(V_f - V_i\right)} = \sqrt{\frac{2e\left(\Delta V\right)}{m}} = \sqrt{\frac{2e\left(-\vec{E}\cdot\vec{l}\right)}{m}} = \sqrt{\frac{2eEl}{m}}$$

And that's exactly the same prediction that the field model gave (x_i and l have the same meaning, the distance between the plates).

10. In thinking about examples of where magnetism plays a role in everyday life you remember the magnets that some people use to attach notes to the door of their refrigerator. To investigate this, you find a bar magnet whose poles have been labeled. You move the magnet north pole first toward your metal refrigerator door. As the magnet gets closer you feel a stronger and stronger force pulling the magnet toward the door. Once they're touching you find that the force is strong enough that the magnet sticks straight out from the door without falling. You repeat this experiment but instead with the south pole closer to the door. The same thing happens. In addition, when you take an unmagnetized piece of iron (a magnetic material) and bring it close to the door no force is felt. Construct a model for this situation and use it to explain *in detail* why these things happened.

Objects	Simplification
Refrigerator door	Rigid body, magnetic material (not magnetized)
Bar magnet	Rigid body, magnetic material (magnetized)
Piece of iron	Rigid body, magnetic material (not magnetized)

Interactions	
Magnetic	Qualitative field model

The bar magnet is a source of a magnetic field. Because the refrigerator door is made of a magnetic material, when the magnet is moved closer to the refrigerator door it causes the atoms (which in a magnetic material are each tiny magnets themselves) to align their magnetic fields with the magnetic field of the magnet. Because the south poles of the atoms are facing the north pole of the magnet, the magnet is attracted to the door. The force is stronger when the magnet is closer to the door since the magnetic field of the magnet is stronger closer to the magnet. This means the door is more strongly magnetized the closer the magnet is. When the magnet is brought south pole first towards the door the same explanation applies except that the refrigerator door is magnetized in the opposite direction. The atoms in the door align so their north poles face the south pole of the magnet. In the case of the unmagnetized piece of iron no magnetic forces are felt since neither the iron nor the door generates a magnetic field for the other to interact with.

11. Nuclear fusion is being researched as an alternative future power source. In nuclear fusion a mixture of deuterium and tritium is exposed to extreme temperature and pressure. (Deuterium and tritium are isotopes of hydrogen, with 1 and 2 neutrons respectively. Hydrogen has none.) Under these conditions, a deuterium nucleus and a tritium nucleus can fuse into a single helium nucleus. This process releases a huge amount of energy. However, it is difficult to accomplish this because the deuterium and tritium nuclei repel each other due to their positive charge. But, if the two nuclei can be brought to within $10^{-15} m$ the fusion will occur. Construct a model for the situation and predict how much energy is required to bring the two nuclei close enough to fuse.

A working nuclear fusion reactor has not been built yet. It is very difficult to provide enough energy to the deuterium and tritium fuel to cause fusion to occur in frequently. However, the payback in energy is huge: 17.59 million eV per fusion. Compare that to how much energy is required to make the fusion happen and you begin to see why it is such an attractive power source. Plus, the primary waste product of fusion, helium, is completely safe.

Objects	Simplification
Deuterium nucleus	Point particle
Tritium nucleus	Point particle

Interactions	

Electric	Potential model
Gravitational and other forces	Ignore

I'll consider the tritium nucleus as the source charge and imagine that the deuterium nucleus is being brought towards it from far away (I'll assume infinitely far away). So, the initial state of the system is the two nuclei at rest infinitely far away and the final state is the two nuclei at rest $10^{-15}m$ away. I'll use conservation of energy as my process model to construct a relationship between the initial and final states. Because the two nuclei are initially at rest there must be work done by external forces (W) to bring the nuclei close enough to fuse. This work is the energy we are looking for.

$$\begin{aligned} E_f &= E_i + W \\ K_f + U_f &= K_i + U_i + W \\ 0 + q_D V_f &= 0 + 0 + W \end{aligned}$$

$$W = q_D\left(\frac{kq_T}{r}\right) = (e)\frac{k(e)}{r} = \frac{ke^2}{r} = \frac{\left(8.99\times10^9 \tfrac{N\cdot m^2}{C^2}\right)\left(1.6\times10^{-19}C\right)^2}{\left(10^{-15}m\right)}$$

$$W = 2.30\times10^{-13}J = 1.44MeV$$

It's not a bad deal at all! If you invest $1.44MeV$ to fuse the nuclei, you get $17.59MeV$ in return.

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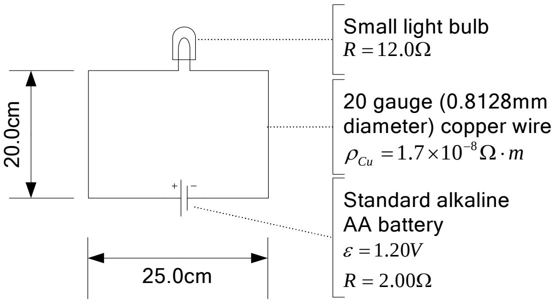
12. Consider the circuit shown. Construct 3 models for the situation by making 3 different sets of simplifications. One of your models should make the fewest simplifications possible.



   a. Carefully describe each of your 3 models.
   b. For each of your 3 models, predict what the current in the circuit will be. Describe any additional assumptions that you made in making your prediction.
   c. Look at your 3 predictions. Of the simplifications you made while constructing your models, which ones were reasonable? Which ones were not?
   d. For the simplifications that were not reasonable, what could be changed in the circuit so that the simplification would become reasonable? Come up with as many possibilities as you can.

<u>Model 1</u>

Objects	Simplification
Battery	Ideal battery (no internal resistance)
Wires	Ideal wires (zero resistivity)
Light bulb	Ohmic resistor (obeys Ohm's law)

Interactions	
Electric	Potential model (Kirchhoff's loop rule)

<u>Model 2</u>

Objects	Simplification
Battery	An ideal battery in series with an Ohmic resistor
Wires	Ideal wires (zero resistivity)
Light bulb	Ohmic resistor

Interactions	

Electric	Potential model (Kirchhoff's loop rule)

Model 3

Objects	Simplification
Battery	An ideal battery in series with an Ohmic resistor
Wires	Ideal wire with an additional Ohmic resistor in series
Light bulb	Ohmic resistor (obeys Ohm's law)

Interactions	
Electric	Potential model (Kirchhoff's loop rule)

For each of the three models, apply Kirchhoff's loop starting at the negative terminal of the battery and going around the circuit clockwise.

Model 1

$$\Delta V_\varepsilon + \Delta V_R = 0$$
$$+\varepsilon - IR = 0$$
$$I = \frac{\varepsilon}{R} = \frac{1.20V}{12.0\Omega} = 0.100A$$

Model 2

$$\Delta V_\varepsilon + \Delta V_{R_\varepsilon} + \Delta V_R = 0$$
$$+\varepsilon - IR_\varepsilon - IR = 0$$
$$I = \frac{\varepsilon}{R_\varepsilon + R} = \frac{1.20V}{2.00\Omega + 12.0\Omega} = 0.0857A$$

Model 3

$$\Delta V_\varepsilon + \Delta V_{R_\varepsilon} + \Delta V_{R_{wire}} + \Delta V_R = 0$$
$$+\varepsilon - IR_\varepsilon - IR_{wire} - IR = 0$$
$$I = \frac{\varepsilon}{R_\varepsilon + R_{wire} + R} = \frac{\varepsilon}{R_\varepsilon + \rho\frac{L}{A} + R} = \frac{\varepsilon}{R_\varepsilon + \rho\frac{4L}{\pi d^2} + R}$$
$$I = \frac{1.20V}{2.00\Omega + \left(1.7\times10^{-8}\Omega\cdot m\right)\frac{4\left(0.90m\right)}{\pi\left(8.128\times10^{-4}m\right)^2} + 12.0\Omega}$$
$$I = 0.0855A$$

Simplifying the battery by assuming it had no internal resistance was not a reasonable thing to do since it changed the predicted current by a large amount (see models 1 and 2). Simplifying the wires by assuming they had zero resistivity was reasonable since the predicted current changed very little when what simplification was relaxed (see models 2 and 3).

If the resistance in the light bulb were significantly greater, or if the resistance in the batter were significantly smaller, then simplifying the batter by neglecting its internal resistance would be more reasonable.