First attempt to Locate a Bullet without Surgery: An Application of Electromagnetism to 19th Century Medicine

Physics Education Research Group, Kansas State University

Note: this lesson is complete, but it has not yet been thoroughly tested with students.

Medical imaging without surgically opening the body is now very common practice. X-rays were discovered in the late 19th Century and very quickly applied to medical diagnosis. In the 20th Century application of basic physics principles let to other methods such and computer tomography (CT), magnetic resonance imaging (MRI) and positron emission tomography (PET). Before any of these techniques were available a man who was famous for something else – Alexander Graham Bell – attempt to use some basic ideas of electromagnetism to locate a bullet without surgical procedures.

On July 2, 1881, US President James Garfield was beginning a trip by train from Washington, DC. Charles Guiteau who was disgruntled because Garfield had not appointed him to a diplomatic position in Paris shot Garfield while the President was waiting to board a train. The President was a large man, and the bullet went deep into his body. The physicians needed to know where the bullet was located relative to the vital organs before they attempted to remove the bullet. In those days the standard way to find a bullet was for the physician to put his finger in the bullet hole and feel for it. This method was unsuccessful.

Figure 1: A contemporary drawing of the assassination attempt of President Garfield. The assassin is being held in the back left; Garfield has his hand on his back in the foreground right. (From Frank Leslie's Illustrated Newspaper, July 16, 1881. Downloaded from the Library of Congress.)

Alexander Graham Bell who had invented the telephone just a few years earlier had an idea. He knew that a metallic object near an inductor changes the value of the inductance. If a listening device, such as a telephone, was connected to an audio frequency source, the change in induction would also change the audio signal. This change would be heard by the listener. With Bell's recent invention, the telephone, he thought that he could hear that change.

The bullet was quite small. It was made of lead which is diamagnetic and has a rather small magnetic susceptibility. Thus, finding the bullet with a simple inductor-telephone circuit would not work. However, another recent discovery called a bridge circuit might be sensitive to very small change. Bell created several such inductance bridges to use in this situation. One of Bell's versions is shown in Figure 2.

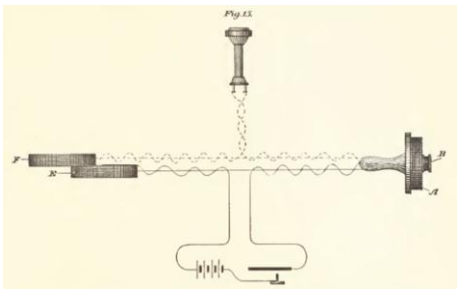

Figure 2. A drawing from one of Bell's papers showing one of the devices which he used to attempt to find the bullet in James Garfield. (From A. G. Bell, *American Journal of Science* **25** (145-150), 22-61 (1883)

Bell successfully detected bullets in sides of beef and shrapnel in Civil War veterans. He made several attempts with variations on the basic apparatus to locate the bullet in the

President's body. A drawing of one such attempt is shown in Figure 3. But, he was unable to find the

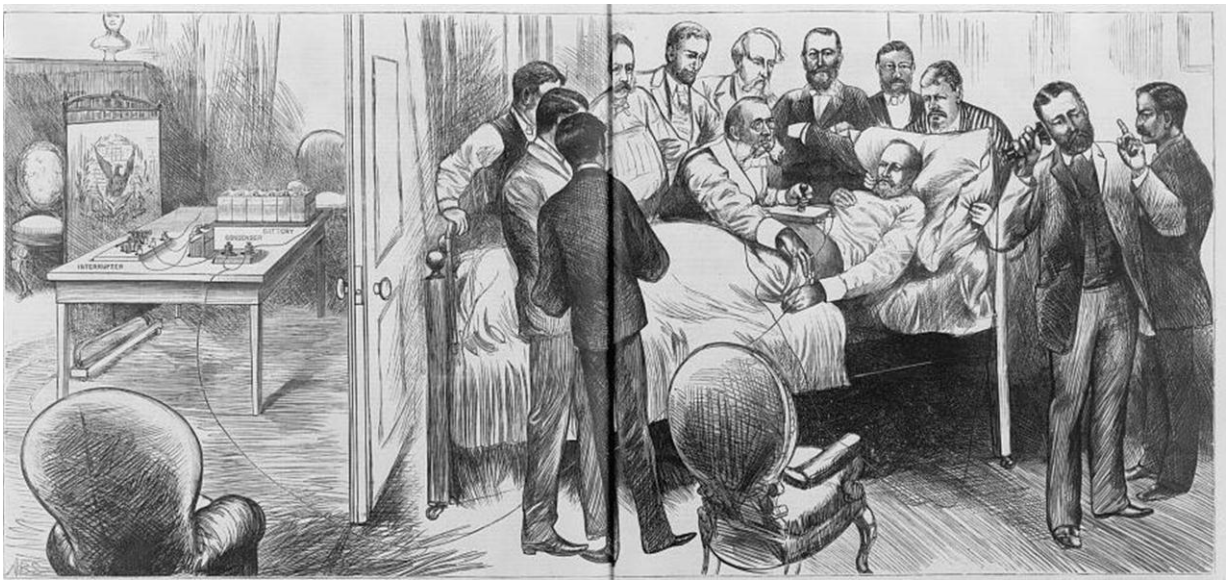

Figure 3: This drawing shows one of Bell's attempts to locate the bullet. The electromagnetic apparatus is located in the neighboring room on the left with wires running under the door. Bell is holding the telephone receiver on the far right while his assistant is moving a coil on the President's stomach. (Frank Leslie's Illustrated Newspaper, August 20, 1881, Downloaded From the Library of Congress)

location of the bullet in Garfield. The physicians in attendance attempted to find the bullet by inserting their fingers into the bullet hole. While the idea of sterilization had been developed by Joseph Lister in England by this time, most doctors in the United States did not take it seriously. Thus, on September 19, 1881, eleven weeks after being shot President Garfield died.

Many interesting side stories are part of this saga. For example,

- James Garfield never wanted to be President. He was drafted after 35 attempt over tow days failed to pick a nomination at the Republican convention of 1880. He basically did not campaign for the office but was elected anyway.
- Dr. Willard Bliss who was the lead physician was particularly autocratic. He carefully controlled all of the treatments, many of which would be considered malpractice by today's standards.
- Dr. Bliss died of blood poisoning which he contracted when he cut himself while treating President.
- A physician, Dr. E. L. Patee from Manhattan, Kansas, wrote to the President's wife imploring to stop the probing of the wound with unsterile fingers of instruments.
- Shortly before President Garfield's death, Alexander Graham Bell was to make one more attempt to locate the bullet. However, his wife was in Boston and having a difficult child birth, so he had to leave Washington.

For details on these and other aspects of the treatment of President Garfield, see *Destiny of the Republic: A Tale of Madness, Medicine and the Murder of a President* by Candice Millard (Doubleday Publishers, 2011)

Two years later Bell presented a lengthy paper on his process for detecting the bullet to the American Association for the Advancement of Science. He gave his paper the title, "Upon the Electrical Experiments to Determine the Location of The Bullet in the Body of the Late President Garfield and upon the successful form of Induction Balance for the painless detection of Metallic Masses in the Human

Body." Because of what happened we might wonder why Bell used the word "successful" in this title. Apparently he knew something two years later that he did not know when Garfield died. In this series of activities we will look carefully at Bell's procedures, what went wrong, and why Bell could claim that the process was successful.

Learning Objectives

1. To learn how the presence of a metallic object can affect the current in a circuit which includes an inductor
2. To understand how one can balance and unbalance current in a circuit containing induction coils
3. To learn how scientists obtained the equivalent of alternating current before generators were readily available.
4. To explain what went wrong with Alexander Graham Bell's attempt to find the bullet in James Garfield. (This objective is intentionally left vague so they we do not give away ending of the story.)

Prerequisites

1. A basic knowledge of DC circuits
2. Be able to explain how and why the presence of a ferromagnetic object changes the induction of a coil.
3. Be able to explain how a changing current in one coil of wire can induce a current in another coil.

Activity 1: Electromagnetic Induction

The basic idea of any type of current balance is to create a circuit which will not have a current moving through some part of it when the components are in balance. When the components do not balance a current does move. One advantage to these types of circuits is that the change from nothing to something can be easier to detect than a change from one number to the next. For example in Bell's case he hoped to detect a change from no sound to a sound. That is much easier than a change in the loudness of a sound.

One of Bell's early induction balances is shown in Figure 4. Some of the objects in this circuit, such as the clock, can be replaced with more modern equipment. We will do so for now and come back to its purpose later. Figure 5 extracts the essential

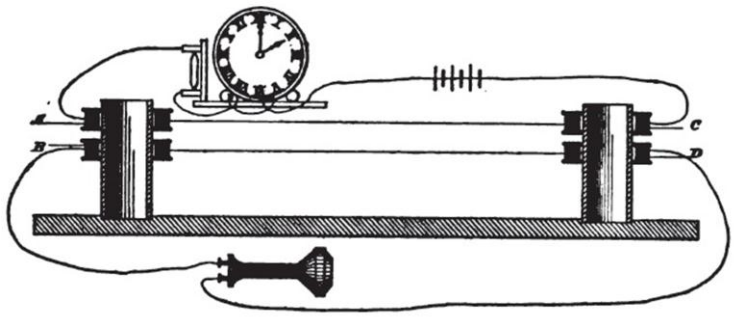

Figure 4: Bell's circuit for an induction balance. For now we will focus on the coils and telephone receiver. We will investigate the purpose of the clock later. A simplified version of this circuit is shown in Figure 5. (A. Graham Bell, *Proceedings of the 31st Meeting of the American Association for the Advancement of Science*, 1882)

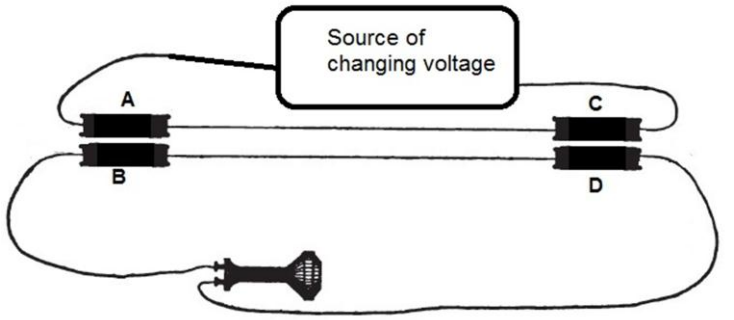

Figure 5: The essential circuit components of Figure 4.

components for our present study.

To begin our study we will use part of the circuit in Figure 5. In place of the old-fashioned telephone receiver we will use either headphones, a speaker of a galvanometer. (The effect here is rather small. Unless you have a very strong magnet and some amplified speakers, the best choice is a galvanometer.). Using the arrangement in Figure 6 investigate how the sound from the headphones or speaker depends on

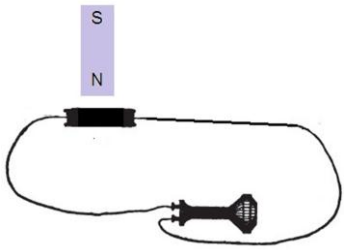

Figure 6: Arrangement of the first experiment.

- Whether the magnet is moving or stationary near or inside the coil

- The speed with which the magnet goes through the coil

- The polarity of the magnet as it passes through the coil

Record your observations in the spaces above.

A simulation of a similar experiment can be found at

- http://www.magnet.fsu.edu/education/tutorials/java/electromagneticinduction/index.html
- http://phet.colorado.edu/en/simulation/faraday

The second simulation is rather useful because it shows the motion of charges in the wires and the magnetic field lines.

Now use more than one magnet to investigate if the strength of the magnetic field is important is determining the properties of the sound. Record you observations below.

Set up the arrangement in Figure 7. *Before conducting the experiment* predict if a sound will be heard for each of the situations below. Explain your predictions based on your knowledge of electromagnetism.

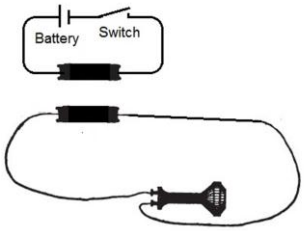

Figure 7: Second experimental arrangement

- When you close the switch and then open it quickly

- When you close the switch and keep it closed.

- When the switch is opened after it has been closed for a while.

Now try the experiments. In the space above note how your predictions compare with the results. For any of the results that are different from, your predictions, discuss them with your instructor. Then, in the space below write a short comparison of your reasoning when you made the prediction(s) with your understanding now.

These preliminary experiments are an introduction to some of the basic ideas of electromagnetic induction. If the reasons behind any of the results that you have observe ar not clear, read about electromagnetic induction in your textbook or visit an appropriate web site such as

- http://hyperphysics.phy-astr.gsu.edu or
- http://ocw.mit.edu/high-school/physics/electromagnetism/electromagnetic-induction/

Activity 2: The Induction Balance

Now, we are ready to create a balanced circuit. The first one that we will try is shown in Figure 8. Set up this circuit and arrange the coils so that no sound is produced in the speaker or headphone when the switch is tuned on or off. To accomplish this you may need to manipulate the wires to control the direction of the current in both sets of coils. Once you have been successful, draw the circuit and indicate the direction of the current in each of the four coils. Use your drawing to explain why your arrangement results in a balance with no sound emitted by the speakers or headphone.

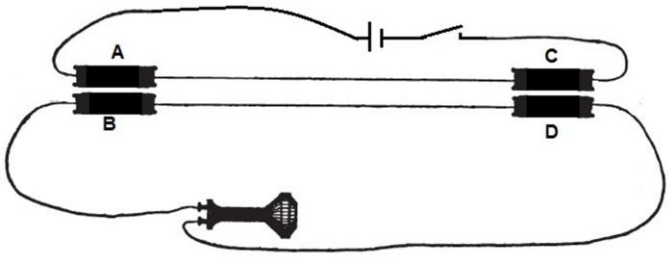

Figure 8: An inductance balance circuit similar to one of Alexander Graham Bell's.

Now place a piece of metal between coils A and B. Test to see if the circuit becomes unbalanced. Then experiment with the metal to see if different locations of the metal result in different levels of a lack of balance. Record your observations below.

Explain why the piece of metal causes the circuit to become unbalanced.

To use this device on President Garfield, Bell put three of the coils in fixed positions. As shown in Figure 3 Bell's assistant moved the fourth coil over the President's body while Bell listened to the telephone receiver. You will duplicate this effort but you will use a modern changing voltage source (function generator) instead of the one that Bell used. (We will come back to Bell's voltage device soon). Your instructor will give you something which has a piece of metal hidden in it. Locate the metal and draw its location below.

Summarize how electromagnetic induction allows you to find the locations of the metal.

In effect Alexander Graham Bell had invented the metal detector. The ideas which you have worked with in this activity are the basic concepts used in some modern metal detectors.

Activity 3: Why Did Bell Fail?

Your instructor will provide you with a piece of poster board. Lay the object with the hidden piece of metal on top of this poster board. Repeat the previous experiment and try to locate the hidden metal. Summarize your results below.

You probably had difficulty in locating the metal in this situation. The difficulty arises because the poster board is a sandwich of two piece of poster board with a metal as the filling of the sandwich. Thus the hidden metal is lying on a uniform distribution of metal. Using ideas from electromagnetism, explain why this arrangement makes it difficult to find the hidden metal.

This problem was exactly the one that Alexander Graham Bell faced. In his papers on the experiments Bell wrote:

> [The negative result] led me to fear that the extensive area of feeble sound might have be n due to some extensive area of metal that was unsuspected at the time, and I proceeded to the Executive Mansion next morning (August 2) to ascertain from the surgeons whether they were perfectly sure that all metal had been removed from the neighborhood of the bed. It was them recollected that underneath the horse-hair mattress one which the President lay was another mattress composed of steel wires.

Bell obtained a copy of the mattress with steel wires. After looking at it he concluded that it should not be the problem. However, because of his wife's health, he left Washington and never conducted the necessary experiment. (Bell mentions in a footnote that the bullet might have been too deep in the body to be discovered by his method.) James Garfield died on September 19, 1881. The immediate cause of his death was infection which had occurred from the physicians trying o find the bullet by probing the bullet hole with their fingers and unsterilized instruments. Charles Guiteau used this information at his trial. He claimed that while he had shot the President, he did not kill him; the physicians did. The defense was not successfully, and Guiteau was found guilty of assisinating the President.

Bell continued his research on his induction balance. On October 7, 1881 in the presence of several doctors he was able to successfully find the locations of bullets in two Civil War veterans. So, the apparatus was a success but not in time to save the President.

Activity 4: What about the Clock in the Circuit?

In 1881 alternating current was not readily available neither were any of the generators that we can use today. Without a source of changing voltage and current experiments with electromagnetic induction are extremely difficult. So, scientists needed to be cleaver to obtain a source of constantly changing voltage and current. Bell used two different approaches – the ticking clock and the "automatic interrupter." We will briefly look at each of these.

Unfortunately, finding a clock that ticks is very difficult today. So instead of doing an experiment we will just talk about the circuit. The part of the circuit which includes the clock is reproduced in Figure 9. Note that the wire from the battery goes around the bottom of the clock but is not connected to the clock. Instead, this wire is attached to a device on the left side of the clock. This device is essentially a small microphone. Each time the clock ticks the microphone picks up the tick and changes the circuit. Thus, with each tick the voltage and current in the two coils changes.

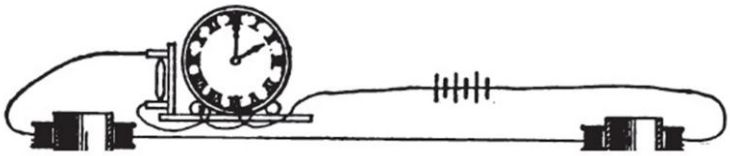

Figure 9: upper half of the induction balance circuit. (A. Graham Bell, *Proceedings of the 31st Meeting of the American Association for the Advancement of Science*, 1882)

The clock and microphone play the same role as you did when you opened and closed the switch in your circuit.

The circuit for the automatic interrupter is shown in Figure 10. The item labeled 1 is a metal strip that has some spring properties so that it is straight (Figure 10A) unless it has other forces acting on it. When these other forces cease to act, the metal strip returns to the position in Figure 10A. The item labeled 2 is an electromagnet, a coil of wire with a metal core. When current is moving through the coil the iron core becomes a temporary magnet, thus it can attract other pieces of iron and steel. The wire in the coil of the electromagnet is insulated so it does not make electrical contact with the iron core of the electromagnet. The devices labeled 3 and 4 are made of metal so they are electrical conductors.

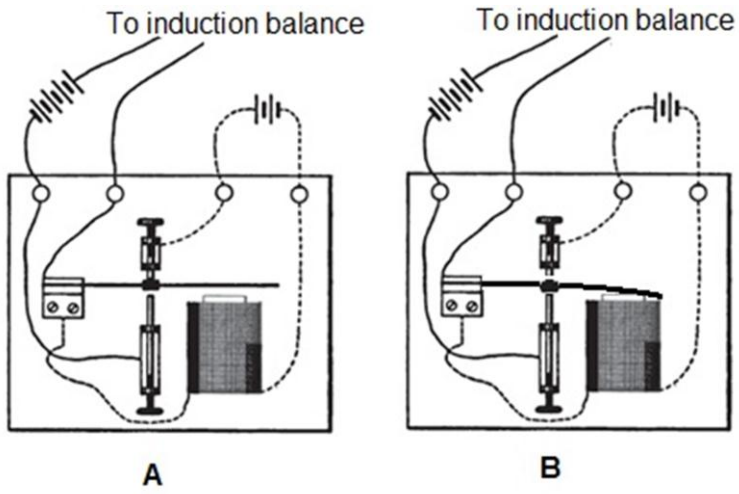

Figure 10: An automatic interrupter which produces a changing current. Figures A and B show tow positions of the steel rod that is across the middle of the device. (Modified from A. Graham Bell, *Proceedings of the 31st Meeting of the American Association for the Advancement of Science*, 1882)

The full device has two sets of batteries and thus two separate electrical circuits. Start with Figure 10A and trace how current moves in the circuit on the right of the figure.

- In which Figure (10A or 10B) will the electromagnet be energized? How will that cause the metal strip (Item 1) to move?

- When the strip does what happens to the current in this circuit? Why?

- Then what happens to the metal strip?

- Summarize how this process causes the right circuit of turn on then off, then on again, etc.

Now look at the circuit on the left side of each Figure. Trace the motion of current in this circuit. Describe how this circuit combined with the right side circuit results in current which will continually change by turning on, off, on, off, …

The automatic interrupter is noisy. The metal strip moving back and forth creates a buzzing sound. Because Bell was trying to hear a very small change in sound, he needed to eliminate all other extraneous sounds. Thus, we see in Figure 3 that he put the devices, including the interrupter, that provide the changing current in an adjoining room and shut the door between the rooms.

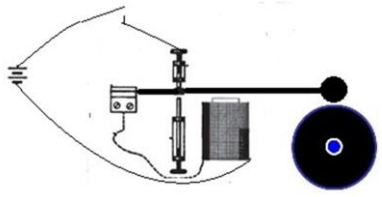

Figure 11: The basic bell ringing circuit for an old-fashioned telephone. The switch would be closed by the telephone switchboard, not be an individual.

As AC sources and function generators became available, the automatic interrupt circuit became less useful to research such as Bell. However, the right side of the circuit was used for much of the 20th Century in Bell's most famous development, the telephone. By adding length to the metal strip so that it would strike a bell, this device could ring each time someone call your telephone number. (See Figure 11.) When the switch is held closed, the electromagnet cause the circuit to interrupt itself and thus the end of the metal rod is striking the bell in a regular pattern until the switch is opened. Similar circuits were (and occasionally still are) used in doorbells, school class-changing bells and other similar devices.

Conclusion

As we have seen Alexander Graham Bell was able to look inside a human body by applying some basic principles of electromagnetism. While he could not make images of the inside of the body, he could detect metal and thus help physicians learn the locations of some foreign objects. His method was ingenious and was for a long time the basis for the creation of metal detectors which were used for a variety of tasks. However, it had limited use in medicine because 14 years later x-rays were discovered. This form of electromagnetic radiation enabled physicians to obtain real images of the interior of a body and to detect many issues in addition to foreign metallic objects. Thus, they became to most common way to look inside us. However, none of the later developments decreases the uniqueness and cleverness of Bell's application of physics.

References

Alexander Graham Bell wrote several papers on this topic. The papers are essentially identical. One example reference is given here.

Bell, A. G. (1883). Upon the Electrical Experiments to Determine the Location of the Bullet in the Body of the Late President Garfield and Upon the Successful Form of Induction Balance for the Painless Detection of Metallic Masses in the Human Body. *American Journal of Science, 25*(145-150), 22-61.

Kuhfeld, A. W. (1991). For Whom Bell Toils: Medial Imaging by Telephone. *IEEE Engineering in Medicine and Biology*, 88-89.).

Millard, Candice *Destiny of the Republic: A Tale of Madness, Medicine and the Murder of a President* by (Doubleday Publishers, 2011)