Utilizing Public Scientific Web Lectures to Teach Contemporary Physics at the High School Level – A Case Study of Learning

Supplemental Material

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Appendix A (p. 2)

Appendix B (p. 4)

Appendix C (p. 6)

Appendix D (p. 7)

APPENDIX A

CONTENT KNOWLEDGE TESTS

1. Lecture A (quantum mechanics)

1. According to the theory of quantum mechanics a particle can behave like a wave. Why does this claim contradict the classical conception of particles?
2. What conditions should be fulfilled to observe the wave property of particles? Explain.
3. Describe a few phenomena (at least one) that demonstrate the wave property of particles.
4. The Aharonov-Bohm experiment suggests supporting evidence for which claims?
5. Describe the results of the Aharonov-Bohm experiment that support the claims that you listed in your previous answer. Explain why they support each claim.
6. According to what you learned in electromagnetism in high school, a magnetic force can be exerted on a charged particle only if this particle moves in the space where the magnetic field exists. In the Aharonov-Bohm experiment, the magnetic field is localized in the center of a conducting loop, whereas the electrons are in the conductors that form the loop, so there is no magnetic field where the electrons are. However, the magnetic field affects the electron currents. How does this phenomenon take place?

2. Lecture B (Astrophysics)

1. What property of the atom/molecule does the phrase "the spectrum is the fingerprint of the atom or molecule" refer to? What is the explanation for this property?
2. When observing the sky through a telescope, celestial objects seem very different from one another. And yet, it is possible to consider many of these seemingly different objects as the same kind of objects. Explain why.
3. What is the source of the variety of atoms that can be found in the universe and on Earth? Describe the creation process behind this variety.
4. On what evidence is the scientific explanation of the variety of atoms in the universe based? Describe the evidence that supports each stage in the process that you listed in your previous answer.
5. In recent years scientists have come to believe that there are complex molecules in space. On what evidence do scientists base this assertion? Explain.
6. How does the finding of complex molecules in space challenge existing theories? How does the modern science of astronomy deal with these challenges?

The following question was not discussed at all during the collaborative activity. It was graded but its score was not included in the average grade on the astrophysics lecture. The grading was used to exclude the effect of repeated testing.

7. What is the difference between traditional astronomy and many of the natural sciences? What are the significant additions to research practices in modern astronomy compared to traditional research methods in astronomy?

APPENDIX B

A SUMMARY OF THE QUANTUM MECHANICS LECTURE

The lecture entitled “Quantum mechanics in a nutshell” presented two key ideas: 1) The wave property of a quantum particle implies that the particle lives through many “parallel histories”; namely it can move in many paths simultaneously. Its behavior at a given time is the sum of these histories; 2) This peculiar behavior can be observed only if the quantum particle does not "leave a mark" (a proof of its passing) in any of its parallel paths (histories). The lecturer presented the Aharonov-Bohm effect [B1] as an example of empirical evidence for the wave property of quantum particles and for the restrictive condition regarding its observation.

The Aharonov-Bohm experimental device that was schematically presented in the lecture was composed of a parallel current loop with a localized magnetic field in its center. The lecturer stressed that there is no magnetic field in the conductor, only in the hole in the center of the current loop. The lecturer also reminded the students that a magnetic field, understood classically, can only affect a charged particle when the particle is in the field. Therefore, from a classical point of view (Lorentz force) the localized magnetic field in the experiment should have no effect on the electrons in the conductor and hence have no effect on the current that is measured. The lecturer stressed this latter point. He also explained that in the experimental device, the current loop used is very small (~µm), and is cooled to a very low temperature (~mK^{o}). The students saw experimental results that showed that as the magnetic field gradually increased, the current (measured in the intersection of the two branches of the loop) repeatedly increased and decreased. The oscillations in current due to changes in the magnetic field were explained to the students as different interference patterns of the electron wave. They were told that under conditions of small scale and low temperature, the probability that the electron in the device will hit another electron is very low and it can move without “leaving a mark”; thus its wave property comes to bear. The students also saw that when the temperature increases, namely the chances of “leaving a mark” increase, and the current oscillations disappear.

It is worth noting that the explanation of the effect that appears in most textbooks [e.g. B2] requires an advanced knowledge of physics, which high school students do not have. To explain to students with only a high school background in physics how the electron can “feel” the localized magnetic field; i.e., be affected by it although there is no magnetic field in the conductor, the lecturer had to generate an alternative explanation. He used the following analogy for this purpose: a person who has one foot on the road and one foot on the sidewalk simultaneously can feel the height difference between the road and the sidewalk. If this person stood with both feet on the sidewalk or both feet on the road, she could not detect the difference in height. Thus standing on the road and the sidewalk *simultaneously* allows the person to “feel” the height difference between the two. Similarly, if the electrons in the conductors are indeed waves, each electron can be in the two parallel branches at the same time, which allows the electron to “feel” the magnetic field between these branches.

References

B1. Y. Aharonov and D. Bohm, *Further considerations on electromagnetic potentials in the quantum theory*, Phys. Rev. 123, 1511 (1961).

B2. R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics* (Addison Wesley, Reading, MA, 1971), Vol. 2.

APPENDIX C

A SUMMARY OF THE FOLLOW-UP ACTIVITY AFTER THE QM LECTURE

The participants were engaged in six guided discussions in the following sequence: 1) Identifying the lecture claims, 2) Reconstructing a negative analogical explanation [C1-C2]. 3) Describing the empirical evidence that was presented to support the claim, 4) Recalling and listing scientific principles that support the claim, 5) Reconstructing a positive analogical explanation, 6) Justifying why 3 & 4 support the lecture claims.

The activities on the analogies (2 & 5) were integrated into the activity of the argumentation to highlight central ideas that were important to understanding the argument. For instance, in order to identify what empirical phenomena support a specific claim the students had to understand the difference in the behavior of a classical particle and a quantum particle. A negative analogy that was presented in the lecture highlighted this difference (see note C1), and thus was processed prior to this phase (activity 2).

References

C1. A positive analogy is a systematic mapping between two situations: target (the novel situation) and source (the familiar one). The mapping is governed by the causal, mathematical, and functional interrelations shared by the two situations. In a negative analogy the analogy consists of properties or relations that the source and target do not share and the analogy is used to highlight these properties in the target domain. For example the QM lecturer made a direct mapping between a car moving on a road and an electron moving in a conductor. Nevertheless the difference between the source (car, road) and target (electron, conductor) was the main explanatory issue. An electron in the appropriate conditions can be in two places at the same time whereas a car cannot.

C2. M.B. Hesse, *Models and analogies in science* (University of Notre Dame Press, IN, 1966).

APPENDIX D

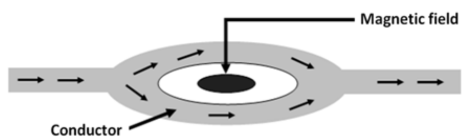
A WORKSHEET MEDIATING AN ANALOGY

The activity that mediated the analogy adhered to the following generic structure:

1. Presenting the problem

A question is asked, and the analogical comparison that was provided as an explanation is briefly mentioned. Figure D1 presents a specific example.

In the Aharonov-Bohm experimental device electrons move in a conductor that diverges into two conductors and then converges, creating a conducting loop. These electrons are affected by the magnetic field that is only localized inside the loop, where there are no electrons. Their hypothesis was that the electron behaves like a wave, splitting into two coherent waves where the conductor diverges, and the magnetic field inside the loop changes the phase shift between these two waves.



According to what we know about electricity, a magnetic force can only act on a charged particle if this particle is inside the magnetic field. How then can the magnetic field affect the electrons, if it exists only where there are no electrons?

This question is answered in the lecture using an analogical explanation that compares a man who simultaneously has one foot on the sidewalk and one foot on the road (source), and an electron that is simultaneously in both branches of the conducting loop (target).

Figure D1. Presenting the problem

2. Mapping (individual and pair/triads)

A. Identifying the relevant components of the analogy: The learner is presented with the relevant component of the source, and is asked to supply the relevant component of the target. Figure D2 presents a specific example.

Source		Target
Man	≈	
Sidewalk	≈	
Road	≈	
Height difference	≈	

Figure D2. Identifying corresponding components

B. Identifying the common structure: The pair/triad is presented with a schematic representation that reflects the common relations between the analog components. They are asked to map the source components onto this representation and to map the target components on the same schematic representation. Figure D3 presents a specific example.

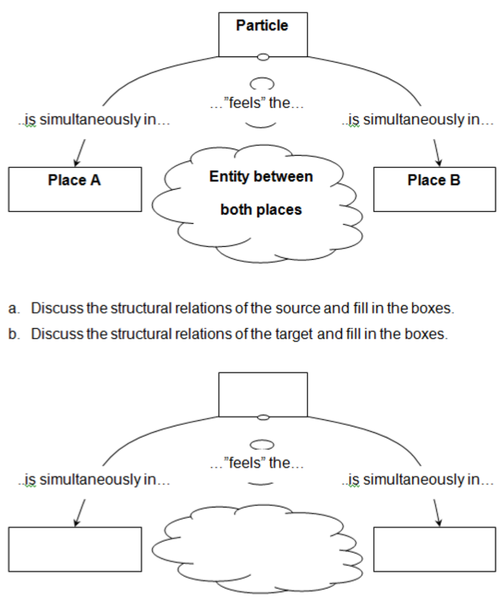


Figure D3. Mapping the structural similarities

3. Harnessing the structural commonalities (pair/triads)

The structural commonalities between the source and the target are used to answer a question that requires the generation of an analogical explanation.

Example: “Use the structure of the similarity relations to answer the question: Why are the electrons in the conducting loop affected by the magnetic field that is in the center of the loop (where there are no electrons)?”

4. Identifying the limitations (pairs/triads)

The students discuss in pairs/triads the places where the similarities cease to exist.

Example: “The similarity between the source and target is not perfect. Discuss and explain to each other were the similarity breaks down. Write your conclusions”.

5. Class discussion

A. Refining the analogical explanation that was created in phase D.

   Example: “Why are the electrons in the conducting loop affected by the magnetic field that is in the center of the loop (where there are no electrons)? Present your answers to the class and ask for feedback”.

B. Refining the recognition of the limitations of the analogy.

   Example: “Present the class the limitations of the analogy that you have identified. Ask for feedback and summarize the class conclusions”.

C. Connecting the analogical explanation to the lecture’s main claims.

Example: “How does the effect of the magnetic field in the center of the loop over the electrons that are in conductor (in the Aharonov-Bohm device) further support the wave property of electrons?”