The Jumping Ring as an inquiry project: A learning-opportunities perspective

Dorothy Vivienne LANGLEY and Rami ARIELI

1 Holon Institute of Technology, Holon, Israel
2 (Retired) Davidson Institute of Science Education, Rehovot, 76000, Israel

Abstract. Incorporating authentic inquiry into high school physics instruction has been advocated for over a century, and has become an integral part of science instruction standards world-wide. The Inquiry Physics program in Israel is a 3 year, elective course for high school physics majors. Students acquire scientific research knowledge and skills primarily by performing inquiry projects of increasing complexity and finally devoting a full year to researching a significant issue under the guidance of expert mentors. Selecting a suitable research topic requires management of tensions related to complexity of content, experimental practice, data analysis and project logistics. The Jumping Ring phenomenon, in which a metal ring is launched vertically due to a magnetic force generated by a coil carrying AC current, was the subject of a final inquiry project in 2018. The phenomenon offers dramatic appeal and motivation, rich inquiry options and diverse experimental skills, considerable knowledge consolidation and extension (magnetic fields and forces, electromagnetic induction and AC circuits) along with technological and logistic manageability. Mentoring the project involved exploring an uncharted learning-opportunities' path, balancing direct instruction and independent exploration, as well as dealing with time constraints and variations in the project team's attendance and commitment.

1. The high school Inquiry Physics framework

The call to include inquiry in physics education has been sounded repeatedly since the beginning of the 20th century [1, 2, 3]. A variety of rationales has been presented, including: reflecting the true nature of the professional scientific endeavour; adding personal interest and challenge; improving cognitive processes through direct experience; contributing to social and work skills through team collaboration; educating future scientists; educating future citizens and policy makers to prioritize investment in research; The incorporation of inquiry projects into physics education in high school and higher education raises many issues regarding the framework in which the projects are carried out, the authenticity of the inquiry from the disciplinary and personal aspects, the sources and level of support, the evaluation criteria and process and many others [4]. The complexity of the implementation brings into question the sustainability of incorporating inquiry into physics instruction. One of the outcomes is the reduction of content coverage and traditional problem solving practice. In practice, the implementation has taken on a variety of forms, and has been regarded by teachers, students and administrators with varying levels of enthusiasm and consistency [5, 6].

The Inquiry Physics framework initiated by the Inspectorate of physics education in Israel has been implemented in various forms since 2014. Unlike programs that have aimed at integrating inquiry into the high school advanced level physics curriculum, the Inquiry Physics program was intended as an
elective, additional specialization for high school physics majors, and has recently been awarded a university entry bonus credit. In this paper we shall refer to the program version which was implemented in a regional academic centre where students met in years 10-12, for 3-hour weekly sessions. The program started in year 10 by introducing the students to the core elements of physics inquiry. The Inquiry Project was developed by student pairs in years 11 and 12, under the supervision and guidance of expert academic mentors. At the end of year 12 the project was evaluated by an official Ministry of Education evaluator, and the grades were included in the students' matriculation certificate.

Selecting topics for long-term physics inquiry projects presents a challenge for inquiry mentors and program coordinators. Several aspects should be considered: appeal of the phenomenon, richness of the inquiry options and required skills, content knowledge opportunities and limitations, technological and logistic manageability. Inquiry Physics mentors proclaim different approaches to the selection of projects themes. Some insist that the topic should be in the Zone of Proximal Development [7] of the students and well within the mentor's realm of knowledge and skills, while others claim that the topic should present a challenge to both students and mentors [8]. The personal relevance aspect of the inquiry topic is an additional consideration, since it can be expected to influence the students' long term motivation and stamina for dealing with frustration and "dead ends". A student team may change the inquiry topic either due to external circumstances (a change of mentor) or because the initial topic leads to a dead end and/or a new topic becomes attractive. Sometimes the team chooses a project topic that is presented in an attractive, exciting manner but becomes frustrated when the inquiry process demands delving into complicated theory or non-trivial, meticulous measurement methods. Changing the inquiry topic can be problematic considering the limited time available for completion, and inquiry mentors and program coordinators should detect early signs of this tendency.

2. The Jumping Ring phenomenon

This phenomenon, also known as the Elihu Thomson phenomenon (1877), is said to have served as a demonstration of the effectiveness of AC voltage, in an era where DC power was the dominant electrical source [9]. The system consists of a cylindrical vertical coil of copper wire connected to an AC source, an iron cylinder inserted into the coil and extending about 20 cm above it, and a non-ferrous ring (e.g. aluminium) that is placed on the iron cylinder. When the AC source is switched on, the ring is propelled upwards to a considerable height, even clearing the iron cylinder [YouTube video].

2.1. The physics of the Jumping Ring in a nut-shell

The alternating current in the coil generates an alternating magnetic field in and around the cylindrical iron core. The metal ring placed on the iron core "experiences" a changing magnetic flux, with the fountain-shaped magnetic field having radial and axial components. Changes in the axial field induce an electromotive force (EMF) and current in the ring. The radial component does not affect the flux through the ring. However, it creates an axial force on the ring when the current is induced. Producing the jumping effect requires generating a repulsive net axial force between the coil and the aluminium ring. This requires currents in opposing directions flowing in the coil and ring. According to Lenz's law, opposing currents will exist during the two cycle quarters in which the coil current increases. During the other two quarters, the currents will be in the same direction and the ring will be attracted to the coil. In total – one might expect a zero net force along the full cycle! To understand why the net effect is repulsive, one needs to recognize the phase difference and time lag between the alternating induced EMF and the induced current, determined by the ring's properties [10]. The phase difference can be increased by controlling the inductance and resistance of the metal ring, which depend on the ring's geometrical and material properties including temperature. The size of the force also depends on the size of the primary and induced currents and the distance between them.

3. The Jumping Ring phenomenon as a rich inquiry topic

The Jumping Ring phenomenon scores high on all of the required inquiry project aspects. It is dramatic, clearly visible, and requires particular conditions to succeed. These attributes can contribute to initial
motivation and long term determination. The lack of novelty of the well-documented effect [9, 11] does not render it unacceptable, since understanding and reproducing the effect are non-trivial, and the available resources can provide support for students and mentors. During the 2016-2018 Inquiry Physics program [12] it was chosen as the final project by a team of two, year 12, male students, following their abandonment of an inquiry project on electrical motors they had started in year 11.

The experimental system is simple consisting of four main components: AC voltage source, primary coil, cylindrical iron core and a metal ring (figure 1). The attributes of the components (e.g. voltage, resistance and weight) can be systematically manipulated to enable an inquiry of the dependence of the effect on selected variables. The richness of the inquiry options and related skills manifests itself in the variety of measurement instruments that can be utilized, from basic multi-meters to digital sensors and motion trackers. The experimental system's compact size and simplicity facilitate the assembling, dismantling and storage which are necessary between weekly sessions, at a designated academic centre or in the school lab.

The relevant content knowledge integrates electromagnetics and mechanics, so it offers the complexity expected of a serious inquiry project and challenging knowledge extension opportunities beyond the school physics curriculum. The physics content includes standard topics (such as electric circuits, magnetic field and force and electromagnetic induction) and advanced topics (such as AC circuits, impedance and phase difference). Owing to the lack of synchronization between the school curriculum and the inquiry program, even the basic physics knowledge may not be readily available. Students may remember formulas, but have little practice in translating this knowledge into practical measurement routines. Thus, the mentoring process combines an orchestration of providing reading materials (text-book excerpts and published articles), explaining the new content, and guiding the design of a sequence of experiments for measuring the attributes of the experimental system.

4. The mentoring process: following a "learning opportunities" path

Mentoring the inquiry project was not a systematic, well organized process. Rather, it progressed along an uncharted meandering path, with mentors seizing opportunities to engage the students in authentic learning and inquiry, yet being prepared to embrace direct instruction responding to students' apparent difficulties.

4.1. Extending and reinforcing physics knowledge

The students' relevant prior knowledge included simple DC circuits with Ohm's law as the main problem solving tool, and the Faraday and Lenz electromagnetic induction laws. This material had been presented in their school physics lessons, but it was not well anchored. The final matriculation exam took place at the end of year 11, and the "forgetting curve" was well advanced 6 months later. The students totally lacked knowledge about AC circuits or transitional states of DC circuits with coils, as this was material beyond the school curriculum. Mentoring involved balancing direct instruction and self-exploration.
Quite early on in the inquiry process, the students were directed to online resources about the Thompson Jumping Ring phenomenon, which they were expected to try to use as a basis for their theoretical analysis. In their report the students commented: "The most difficult part was learning the theory on our own. The content was difficult and beyond what we had learnt at school. The formulas we found were complicated, and the material was in English, which increased the difficulty of learning the new concepts." Thus, the students were confronted with the unfamiliar challenging content prior to direct instruction. We did not expect the students to be able to self-study this content. We provided high school level textbook materials in the students' native language, and direct instruction, linking to the students' knowledge of electromagnetic induction and DC circuits. The instruction progressed in stages, as new knowledge was required for the inquiry process (simple AC circuits with resistors, transient currents in coils and the concept of inductance, coils in AC circuits and the concepts of impedance and phase shift, transient currents in DC circuits with capacitors, and finally solving the RCL AC series circuits). The method we adopted for solving Kirchhoff's law in AC circuits consisted of using a visual phasor diagram for representing the various voltages and applying trigonometry to obtain the relationships between the circuit parameters, voltages and current. However, this was all unfamiliar content and the instruction served mainly to facilitate the students' ability to understand theoretical derivations they encountered in published papers.

4.1.1. Overcoming barriers to understanding the upward propelling force. Understanding the Jumping Ring phenomenon requires students to become aware of and reframe several naïve conceptions involving the coil's magnetic field and resulting forces, Lenz's law, and the relationship between the primary and induced currents. Some online resources [e.g. 13, p29] present the phenomenon simplisticly as a manifestation of Lenz's law i.e. "The induced current opposes the primary current". At first glance this may seem plausible, until a systematic analysis of the periodic changes is performed. The following table [figure 2] was used to guide the students' thinking. Each empty row deals with the changes in the primary and induced currents during one of the cycle quarters.

The mentoring process required the students to explicate their thinking concerning the relationship between: current direction and magnetic field direction; the direction of the induced current and the direction and change of the primary current; and the current directions in current loops and the resulting mutual forces. The students found it useful to represent the winding currents as bar magnets, with the polarity depending on the current direction. The unexpected conclusion of this analysis was that the net force should cancel out during a full cycle – thus failing to explain the Jumping Ring phenomenon. To reach a satisfactory explanation it was necessary to revisit the principles of AC circuits and focus on the phase difference between the induced EMF and the induced current in the ring.

| Cycle Quarter | Coil Current | Loop Current | Coil-Loop Force |
|---------------|--------------|--------------|----------------|
|               | Direction    | Change       | Direction      | Change | Attraction/Repulsion/None |
| I             |              |              |                |        |                            |
| II            |              |              |                |        |                            |
| III           |              |              |                |        |                            |
| IV            |              |              |                |        |                            |

**Figure 2. Induction process analysis**
4.2. Encouraging documentation

Each inquiry project was allocated a designated site in the Moodle LMS, with the basic skeleton structure created by the course instructor [14]. The students were instructed and encouraged to upload all their materials to their allocated site to maintain a continuous record of their work and to enable monitoring and feedback by the project mentors, who had access to the individual sites. The response to this directive was varied, depending on the industriousness of the team. In their report the students wrote: “We tried to upload all our material to our project site, but we did not always find the time to do so. But now finally all the files are there. We also found the files that R. uploaded to the site useful in preparing experiment reports, work plans and presentations.”

4.3. Extending and reinforcing experimental inquiry skills

The experimental system (figure 1) consisted of several components which the students needed to explore to discover the relevant electrical and magnetic properties, using a variety of measurement devices.

![Figure 3. Measuring coil inductance (12.4mh) and resistance (3.39Ω)](image)

4.3.1. The AC power source. The students were given a non-digital school-lab power source connected to the 50Hz mains supply and capable of delivering 6 discrete DC and AC voltages between 3V-30V (with a limited maximum current). The students needed to explore this equipment, especially in the AC range, and relate the numbers on the panel to physical quantities. The coil they used had a 2A current limit, so the students needed to find out how to stay within the safety limits. At this stage mentoring involved open-ended leading questions such as "How can we find out the actual frequency and maximum voltage?" or "Which of the selector positions can we use?" The exploration involved setting up a suitable circuit and connecting a digital measurement system already known to the students, to obtain graphs of the time dependence of the output voltage. The sinusoidal graphs showed the periodic nature of the voltage and the difference between maximum voltage and the effective value. The students were able to measure the frequency using on-screen timing of 10 periods, and verify that it was 50Hz. By repeating the process for different selector states (3V, 4.5V, 6V), the students were able to verify the relationship between effective and maximum values, and to learn that the numbers on the power supply
panel were an approximation of the effective value. This exploration set the basis for answering additional inquiry questions regarding AC circuits containing a coil.

4.3.2. The coil and iron core as circuit components. The students were given a coil with 600 copper wire windings, and a 2A current limit. The coil was to be the source of the alternating magnetic field for the Jumping Ring phenomenon. The students needed to become aware of the coil’s inductance and the related behaviour of the current in an AC circuit. Mentoring at this stage consisted of guided self-discovery of the difference between current behaviour in AC and DC circuits. The first step was measuring the coil's resistance using a digital multi-meter (figure 3), and using this to calculate the appropriate voltage. The next step was measuring the alternating current using the digital lab equipment, and discovering the decrease in the maximum current for the same maximum voltage. This surprise preceded the related direct instruction of the theory. An additional surprise was the unexpected effect of the iron core on the current, since it is not a conducting component of the coil circuit. The students measured the inductance with and without the iron core using a digital meter, and continued to verify the theoretical effect of frequency on the current by using a signal generator as a power source. They discovered that for each frequency the presence of the iron core reduced the current and that with the increase in frequency, the effective current was reduced until it approached zero for frequencies of around 900Hz. This experimental evidence supported the theoretically derived formula of the coil's impedance.

4.3.3. Mapping the magnetic field. The students needed to explore the magnetic field in and around the coil to gain understanding of its magnitude and spatial distribution. They also needed to decide on the significance of the Earth's magnetic field in the system. The students started by using a compass to map the coil's magnetic field with DC current with and without the iron core. The compass needle deflected near the external side of the coil indicating the difference between the finite coil and the infinite solenoid discussed in school physics. To gain a quantitative mapping of the coil's magnetic field in the AC circuit, the students used a digital magnetic field sensor and discovered the effect of the iron core on the intensity and distribution of the magnetic field (figure 4).

![Figure 4. Mapping the magnetic field with a compass and sensor](image)

4.3.4. Affecting the jump height of the metal ring. Naturally, the students wished to maximize the height of the jumping ring. In fact, they were quite disappointed with the effect in the early stages, before they had learnt to manipulate the system variables with the assistance of the expert lab technician. The metal ring placed on the iron core has several physical properties that determine the magnitude of the jump: weight, material, dimensions and temperature. The material that was chosen was non-ferromagnetic aluminum. The students wanted to increase the height of the jump, with a given set-up of the primary circuit. In principle, a reduction in the ring's resistance would increase the height of the jump, due to the
expected increase in the induced current. This was done in two ways. The students varied the ring's width between 0.5 and 2 cm as a means of increasing the conductor's cross-section and showed an increase in the height of the jump (figure 5).

![Image](image_url)

**Figure 5.** Ring widths and weights:
0.5cm 26.4g; 1cm 47.4g; 2cm 84.6g.

A better control of the resistance without affecting the mass was performed by varying the ring's temperature by immersing it in dry ice for different periods and measuring the effect on the jump. And indeed as the immersion time increased from 0-60s, the height of the jump increased from 10cm to 17cm. This is a semi-quantitative measurement, as the temperature does not change linearly with time. An additional idea the students proposed was increasing the induced EMF by controlling the rate of change of the primary current, by means of a fast capacitor discharge in a DC circuit. No actual implementation of the proposal is presented in the final report.

5. Reflective Summary

Responding to the call to involve physics students in authentic inquiry requires diverse resources and thoughtful approaches. There seem to be built-in tensions in selecting appropriate long-term inquiry projects for high school physics students. The physics content should extend beyond the traditional school level, and present an intellectual challenge, but if it is too advanced the students may not be able to integrate the content and it might present an intellectual barrier for the mentor. The authenticity of the research questions can be based on genuine disciplinary issues, but equally on the personal relevance of the problem to the students [4]. The complexity of experimental practices and equipment should be significant, but it is important to safeguard the long term sustainability of the activity within the available material and temporal resources available to the students and mentors. The Jumping Ring phenomenon has many attributes that contribute to its suitability as a long term inquiry topic for high school physics students. Two of the main attractive features are the dramatic effect of the ring jumping high into the air and the apparent simplicity of the experimental system. The physics content extends beyond the school curriculum, but mentors can guide the students toward integrating the additional content into their conceptual framework, using available printed and online materials. However, mentors should leave sufficient time for this process, depending on the students' level and ability to learn independently and the available communication channels. Finally, despite the simplicity of the experimental system, the inquiry field it offers is very wide. Achieving the dramatic effect depends on selecting appropriate parameters for the system components. The students can implement many inquiry skills they acquired previously, as well as take advantage of opportunities for exploring new methods and equipment. Mentors need to employ a flexible approach for allowing the students to proceed independently while simultaneously monitoring the situation (based on direct observation and perusal of student documentation), and preventing students from wandering too far off the track – especially when deadlines need to be met.

Reading through the students' final project report several things are noticeable. On the up-side, it seems that (assisted by our feedback) the students were able to organize the collected fragments of theory, experiments and data into a relatively coherent document, with photos, diagrams, tables and graphs guiding the reader along their personal path through the inquiry project maze. While the students needed considerable help to construct their understanding of the many processes involved in the Jumping
Ring phenomenon, there is a clear manifestation of ownership and eventual understanding of most of
the related theory. On the down-side, we noticed some faulty experimental reasoning such as relating
the increase in the ring's width to the increased height of the jump. Their justification was based on the
equation R=ρL/A which they had learnt at school. However, they failed to mention the confounding
effect of not controlling for the ring's mass, which varied linearly with the width and could reasonably
be expected to decrease the acceleration. Another problem related to the increased ring width was the
possible effect of the change in magnetic flux on the induced current. The students also failed to mention
the effect of the resistance on the phase shift which is related to L/R of the ring. As shown previously,
the net repulsive force strongly depends on the phase shift. This lapse indicates that the students were
not able to fully integrate the novel concept of phase shift into their conceptual network of
understanding. Overall, they were mainly able to base their independent explanations on their prior
knowledge of DC circuits with resistors and (to some extent) capacitors. In their summary the students
wrote: "Have the goals of the project been achieved? We have not been able to make the ring jump off
the iron core. We would like to apply the principles of the jumping ring to engineer a new system of our
own design. What was the most fun? We enjoyed designing and carrying out the experiments and getting
more successful at making the ring jump. Which inquiry questions do we want to continue pursuing? Is
the field created along the coil simultaneously? How would a non-ferromagnetic core behave? How
would a copper or iron ring behave? How would the frequency affect the jump height?" The students'
comments indicate their enthusiasm for defining their own inquiry goals, a tendency evidenced in studies
about student engagement in open inquiry [15].

Inquiry projects should provide opportunities for significant extension of content knowledge and
skills. However, these opportunities may not be embraced by the students. Mentors should maintain
realistic expectations about the amount of knowledge integration that will occur during the limited time
frame of the inquiry process. Exceptional students may indeed undergo a deep conceptual
transformation, but that is the exception rather than the rule. Other detrimental aspects that should be
taken into account are dealing with a project team's intermittent attendance and the resulting disruption
team work, a project team's partial response to mentor feedback on the project report and late
submission of the project report, leaving insufficient time for finer corrections. In conclusion, inquiry
projects for high school physics students hold great promise for intellectual, technological and social
enrichment, but realizing that potential requires thoughtful instructional design, sufficient time and a
rich learning environment.

6. References
[1] Barrow LH 2006 Journal of Science Teacher Education 17 265–278
[2] Otero V K and Meltzer D E 2016 The Physics Teacher 54(9) 523-527
[3] National Research Council 2000 Inquiry and the National Science Education Standards: A Guide
for Teaching and Learning (National Academies Press)
[4] Kapon S, Laherto A and Levrini O 2018 Science Education 102(5) 1077-1106
[5] Peterson KD 1978 Scientific inquiry training for high school students: Experimental evaluation
of a model program. Journal of Research in Science Teaching 15(2) 153-159
[6] Campbell T, Zhang D and Neilson D 2011 Model based inquiry in the high school physics
classroom: An exploratory study of implementation and outcomes. Journal of Science
Education and Technology 20(3) 258-269
[7] Vygotsky LS 1978 Mind in Society: The Development of Higher Mental Process (Cambridge,
UK: Cambridge University Press)
[8] Kapon S 2016 Journal of Research in Science Teaching 53(8) 1172-1197
[9] Schneider CS and Ertel JP 1998 American Journal of Physics 66 686-692
[10] Jeffery RN and Amiri F 2008 The Physics Teacher 46(6) 350-357
[11] Ladera CL and Donoso G 2015 American Journal of Physics 83(4) 341-348
[12] Langley D and Arieli R 2018 GIREP-MPTL International Conference, San Sebastian, Spain
[13] Baylie M, Ford PJ, Mathlin GP and Palmer C 2009 Physics Education 44(1) 27-32
[14] Langley D and Arieli R 2018 Proc. World Conf. on Educational Media and Technology (EdMedia + Innovate Learning 2018) Amsterdam, Netherlands

[15] Kota SD, Cornish S and Sharma MD 2018 Physics Education, 54(1), 015007