On Improving Students' Understanding of the Photoelectric Effect

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Abstract

We report our research findings on Singaporean student understandings of a topic in modern physics – the photoelectric effect, discuss the possible basis of their understanding, and suggest ways to improve their understanding of this topic. This on-going research involved four junior colleges (JC). The level of the treatment of this topic in JC is similar to that of an introductory undergraduate course. The research was done using pre-test, tutorial instruction and post-test on experimental and control groups in each JC. It was found that there is a significant improvement in the experimental group over the control group for both categories of questions i.e. conceptual questions which are less familiar to our students and questions which are typical of the GCE A-Level exams.

Introduction

In 2006, a new Singapore-Cambridge General Certificate of Education (Advanced Level) Examination (GCE A-Level) physics syllabus (H2 Syllabus 9745) was introduced by the Ministry of Education Singapore. This examination is taken at the end of Junior College (JC) education after 12 years of formal education. In the new syllabus, the weight of modern physics has been increased substantially and the topics include Quantum Physics, Lasers & Semiconductors, and Nuclear Physics. In addition, a new component called 'Essentials of Modern Physics' (H3 Syllabus 9811), was introduced. It is meant to challenge the top physics students and has 6 topics: Special Relativity, Quantum Theory of Light, Matter Waves, Quantum Mechanics, Solid State Physics and Photonics.

With the introduction of the new syllabus, we felt the need to research on student learning of the topics to help guide the development of curriculum. Since the inquiry approach in the teaching of science has been recognized as being effective and is being adopted in science education with considerable success (National Research Council, 1996; National Science Teachers Association Press (USA), 2001), we decided to use the Photoelectric Effect resources found in '*Tutorials in Introductory Physics*' developed by the Physics Education Group (PEG) of the University of Washington (McDermott et. al., 2002), with some appropriate modifications, to implement inquiry-based tutorials in the JCs.

Research Procedures

Selection of the modern physics topics. A survey was conducted among 16 teachers from eight JCs to identify physics topics which face pedagogical challenges. Based upon the survey results and the existing resources such as textbooks, college notes, online resources, research papers (Steinberg et. al., 1996; Keesing, 1981) and the well established content found in '*Tutorials in Introductory Physics*', we chose the teaching and learning of the photoelectric effect to be the first topic to research on.

Adaption of PEG instructional materials. The '*Tutorial in Introductory Physics*' instructional materials consist of pre-tests, tutorials, homework, post-tests and instructor's guide materials. We studied these materials, including role-playing, with some members of the research team acting as students and others as teachers, to understand the probable issues faced during implementation as well as to get a feel of the structure of the materials. In the process, the materials were modified, in consultation with PEG, to suit the Singapore context in terms of the format, common diagrams, terminologies and sentence structures. Here is an example of a modification of a tutorial question.

<u>Original structure</u>:

Is the number of electrons that leave electrode B in case 2 *greater than, less than, or equal to* the number that leave electrode B in case 1? Explain.

<u>Modified structure</u>:

Fill in the following signs (>, <, =) in the boxes. Justify your reasoning for each case.

Number of electrons that leave plate B in case 1.	$\boxed{}$	Number of electrons that leave plate B in case 2.

Explanation:

Another example of the modification is that an A-Level exam type question is added into the post-test. The main purpose is to see how students who have undergone the inquiry-based tutorial (experimental groups) and students who have undergone the traditional college tutorial (control groups) compare in their performance of the traditional exam type question. Some of the differences between the two types of questions can be observed from the example below.

<u>An inquiry-based question from '*Tutorial in Introductory Physics*'</u>:

The electrode B is replaced with one made of cesium (Φ = 2.1 eV) and the stopping voltage is again measured. Does the stopping voltage *increase, decrease,* or *stay the same*? Explain.

<u>An A-Level exam type question</u>:

What will be the change in the stopping voltage if the wavelength of the incident light is reduced from 476 nm to 426 nm? Show your calculations clearly.

We believe that one of the key factors in the success of the teaching and learning by inquiry is that facilitators should aim not to reveal the answers to the learners but instead pose guiding questions that lead learners to their own realisations. PEG does not provide us with the answers to the tutorial questions in their materials. Instead, our research team generates the possible solutions as well as our own facilitation questions to be used later on in the field trials. It is also with this same mindset that we collaborate with the participating teachers. This means that the teachers themselves in turn generate their own answers and facilitation questions under the guidance of our research team. One of the simpler tutorial questions and its possible facilitation questions are as follows.

Question: While the laser is switched *off,* is the current *zero* or *non-zero?* Explain.

Possible facilitation questions:

- For this answer of yours, what are the assumptions that you have made?
- Imagine that you are actually doing the experiment. If the laser is switched off and you saw a non-zero reading on the ammeter, what are the possible reasons for the reading?

Implementation of Field trials. The classes provided by the 4 JCs are grouped into experimental and control groups for field trials which involved four main phases.

Phase 0: Teacher familiarization with instructional materials
Phase 1: Administration of pre-test to both groups of students
Phase 2: Tutorial instruction and homework distribution
Phase 3: Administration of post-test

For the experimental groups, to ensure that students are not deprived from benefitting from their usual JC tutorial homework, the teachers return to their normal routine after our intervention. To aid the participating teacher in planning the flow of lessons for the classes, we have also penned out the teaching and learning activities of the topic for both experimental and control groups in chronological stages.

Stage	Control Group	Experimental Group
A	JC Lecture	JC Lecture
B	UW-NIE Pre-test	UW-NIE Pre-test
C	JC Tutorial homework#	UW-NIE Tutorial session
D	JC Tutorial session	UW-NIE Homework
E	NIE Post-test	NIE Post-test
F	UW-NIE Tutorial*	JC Tutorial homework
G	UW-NIE Homework*	JC Tutorial session

* Optional, available upon teachers' request.
\# Refers to the usual JC tutorials that are given to students to be done before coming for their next tutorial sessions.

The familiarisation session, Phase 0, is to allow participating teachers to become familiar with the facilitation procedure and tutorial materials through first-hand experience, where they sit for the pre-test, work through the tutorial questions and finally sit for the post-test, just like what the participating students will do. While the teachers attempt the tutorial, they are allowed to discuss with each other. Research team members were present to listen to their discussions. At various checkpoints of the materials, the research team will intervene by asking for a re-iteration of discussed concepts followed by specific guiding questions to ensure the accuracy of the concepts or to enhance the learning. The teachers are also reminded to pay attention to the kinds of facilitation questions that are posed to them, as well as the mannerism in which these questions are asked to encourage discussion. One 3-hr familiarisation session is conducted for each JC.

The administration of the pre-test takes about 15 minutes. There is no strict adherence to time for the pre-test and students are requested to hand in once they are ready. In addition to finding out more on student understanding, the pre-test help to set the stage for the tutorial and to motivate students to attempt earnestly the tutorial questions. It will also familiarise students with inquiry-based questions, and the recalling of concepts taught during the lecture.

For the convenience of the teachers, Phases 1 and 2 are conducted on the same day. After the pre-test has been administered, the inquiry-based tutorial is conducted for 1½ to 2 hours, depending on time made available by individual class schedules. Students typically form groups of five. Each student is given the tutorial handout. A large sheet of mah-jong paper and markers are given to each group for students to pin down their thoughts during their discussions. The writing on the paper also allows for better facilitation as the facilitators move from one group to another.

At the end of the tutorial session, a homework handout is given to each student to attempt on their own. On a separate day, the post-test is administered by the teacher before he reverts to discussion of the normal JC tutorial questions. The time taken for the administration of the post-test is strictly 30 minutes.

Development of investigative experiment/demonstration. During Phase 0, feedback from teachers prompted us to develop an easy-to-use, hands-on demonstration for photoelectric effect in time for a demonstration session to be included in Phase 2. Teachers found it beneficial and mentioned that it has enhanced the students' learning experiences. The main equipment of this set-up is the phototube which can be purchased online.

Pre-test. The eight concepts that are assessed in the pre-test are as follows:

Qn	Concepts	Brief Description
1	1.1	Constant non-zero current flows in a closed/complete circuit only.
	1.2	Electrons do not have enough energy to escape from the surface of the electrode.
2	2.1	When there is light shining on electrode B, electrons are emitted from it i.e. from B to A.
	2.2	Direction of electron flow is opposite to the direction of conventional current flow.
3	3.1 (only one)	Electrons are released from electrode B in all directions, so not all may reach electrode A.
4	4.1 (only one)	Because the applied voltage is more negative than the stopping voltage, the electrons do not have enough K.E. to reach electrode A.
5	5.1	The lower the work function, the higher the K.E. of the emitted electrons.
	5.2	The higher the K.E. of the emitted electrons, the higher the absolute value of the stopping voltage.

Post-test. The post-test has two questions consisting of several parts. The first question, an adaptation of PEG material, is more conceptual and unfamiliar to our students. The second question is typical of the A-Level exams. There are a total of 26 concepts that are assessed. Several of these are listed below.

Qn	Concepts / Calculation	Brief description
1b(i)	1b(i).1	Increasing intensity (with the same wavelength) means increasing the rate of photons incident on electrode B.
	1b(i).2	Therefore, more electrons are emitted per second and this leads to greater current detected by ammeter.
1c(i)	1c(i).1	Lower work function means greater maximum K.E. of emitted electrons.

	1c(i).2	Stopping voltage increases as it is now more difficult to stop the electrons from reaching electrode A.
1c(ii)	1c(ii).1	Correct use of $eV_s = \frac{hc}{\lambda} - \phi$.
	1c(ii).2	Correct computation.
2e(i)	2e(i).1	Shape (S): Shape of individual I-V curve is correct
	2e(i).2	Relation(R): The I-V curve of the smaller wavelength should correspond to a more negative stopping voltage. Proper labelling of curve by wavelength is required.
	2e(i).3	Axes (A): Proper label for axes by physical quantities.
	2e(i).4	Units (U): Proper units for physical quantities of the axes.

Marking of Pre-test and Post-test. Mark schemes are generated for the pre-test and post-test. They involve concepts that are looked out for in the students' answers, rather than specific answers. For the scoring system, sets of rubrics are formulated for both the pre-test and the post-test. In general, if the concept in the mark scheme is absent, Level 0 is given. If the concept is present, Level 1 is given. If the answer is indeterminate, whereby the marker is unsure if the student has the correct conceptual understanding or that the answer is incomplete, Level × is given. For computational steps in calculation, instead of levels, marks of 0, ½ or 1 are given. Computational scores are given basically to see if the student, with the use of the correct concept or formula, substitutes values without carelessness, uses the calculator well and gets the correct values of the quantities asked for. Graphical representation skills are also given the marks of 0, ½ or 1. Note that the pre-test involves no calculation.

As a way to compare the performance of the experimental group and the control group, we assign the three levels 0, × and 1 the values 0, 0.5 and 1.0, and normalize to 1 the total score of pre-test and the total score of each question of the post-test.

For both pre-test and post-test, 5% of the scripts are randomly selected for round-table standardisation among all the research team members. Upon marking half of the scripts, another 5% are randomly selected for moderation among all team members. To ensure consistency throughout the marking, reference notes are also jotted down for scores given for certain types of answers. For example:

Marker's notes: If student explains correctly mathematically, e.g. by the equation $V_s = (h/e)f - (\varphi/e)$, when the work function of the metal decreases, then the stopping voltage would increase, he will be given Level × for both Concepts 5.1 and 5.2 because the student have not demonstrated that they understand them.

Research Findings

Pre-test Analysis. The entire experimental group size is 152 and that the control group size is 181. The percentages of students who obtained Level 0, Level × and Level 1, of both groups are very similar and thus their data are combined in Figure 1 below.

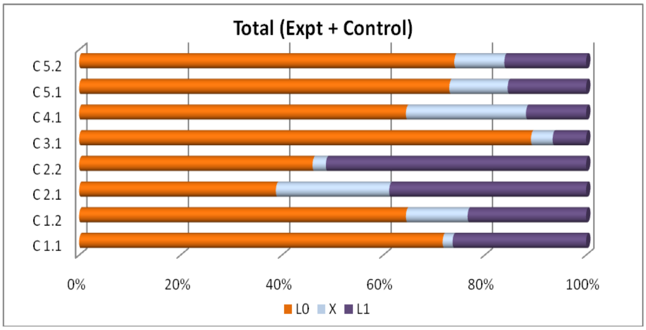

Figure 1. Percentage of students who obtained levels 0, × and 1 in the pre-test

As can be seen from Figure 1, the highest percentage of student (~90%) do not show an understanding of Concept 3.1 which is assessed by Question 3: "Do *all of the electrons*, *some of the electrons,* or *none of the electrons* emitted from electrode B reach electrode A? Explain." This may be due to a combination of factors. Students may not realise that photo-electrons are emitted from the electrode in all directions. They may have difficulty with the structure of the question – that it is talking about electrons which have already been emitted, and if so, perhaps the question may be modified to "Among those electrons that have been emitted from plate B, do all, some, or none reach plate A? Explain."

Students also fair poorly on Concepts 1.1, 5.1 and 5.2, with about 73% of the students getting Level 0. For question 5, more students find it difficult to express their understanding qualitatively, that is, about 10% of students obtained Level × as compared to 2% for Concept 1.1. This is expected as Question 5 is more demanding in terms of the conceptual understanding of photoelectric effect. It is somewhat surprising that only about 50% of the students got Concept 2.2 right since it is a well-known fact that is covered in Year 8.

Students have difficulty explaining Concepts 2.1 and 4.1 clearly as close to one-quarter of them obtained Level × for these concepts. This may be due to the strict marking scheme as necessary to reflect conceptual understanding. For example, in explaining why *none of the electrons* emitted from one electrode reaches the other electrode, if the student states that this is because the electrons are *repelled away* from the other electrode, the answer is classified under indeterminate (Level ×), the reason being that electrons can experience repulsion and yet have enough energy to overcome it to reach the other electrode.

As an additional check that the experimental and control groups are comparable in ability before the intervention, we assign the three levels 0, × and 1 the values 0, 0.5 and 1.0, and normalize to 1 the total score of pre-test. The resulting pre-test scores of the two groups in each school and the corresponding p-value from the t-Test are shown in Table 1. It is seen when the four JCs are considered as a whole that the difference in scores between the two groups are not significant (p=0.230). Thus, this result is consistent with the claim made just before Figure 1 and it is safe to consider the 2 groups comparable in ability before the intervention, when each group is considered as a *whole*. Note that if considered individually, the odd-man out is JC D, with a significant level of p=0.045, meaning that the experimental group in JC D has a higher ability than the control group.

Table 1. *t*-Test comparison between control and experimental groups on pre-test

JC	Pre-test Mean Score		
	Expt.	Ctrl.	*p*-value
A	0.28	0.24	0.314
B	0.36	0.32	0.606
C	0.39	0.44	0.346
D	0.25	0.11	0.045
All	0.33	0.29	0.230

Post-test Analysis. The entire experimental group size is 136 and the control group size is 137. The performances on the post-test of the experimental group and the control group for each JC are summarized in Table 2.

Table 2. *t*-Test comparison between control and experimental groups on post-test

JC	Post-test Mean Score								
	Q1			Q2			Combined Q1 & Q2		
	Exp.	Ctrl.	**p-value**	Exp.	Ctrl.	**p-value**	Exp.	Ctrl.	**p-value**
A	0.42	0.27	**0.003**	0.39	0.31	**0.084**	0.40	0.30	**0.009**
B	0.62	0.48	**0.023**	0.54	0.29	**0.000**	0.57	0.36	**0.000**
C	0.68	0.59	**0.088**	0.52	0.43	**0.099**	0.58	0.49	**0.060**
D	0.52	0.29	**0.000**	0.43	0.36	**0.120**	0.46	0.33	**0.003**
ALL	0.56	0.41	**0.000**	0.47	0.35	**0.000**	0.50	0.37	**0.000**

When the four JCs are considered as a whole, it is seen that the difference in scores between the experimental and control groups are significant (p=0.000) for Q1, Q2, and Q1 and Q2 combined. The fact that the difference in scores between the two groups is significant for Q1 implies that the intervention is effective in bringing about greater conceptual understanding of the photoelectric effect. This in itself may be expected because the adapted UW tutorial materials emphasize more on the conceptual knowledge. However, the fact that the experimental group outperformed the control group in Q2 shows that improved conceptual understanding of physics improves students' performance in A-Level exam type questions which have a strong emphasis on the quantitative aspects of physics.

If each JC is considered individually, and if each question is considered separately, the situation is more varied. For example, the differences in scores between the experimental and control groups for JC C are insignificant at p=0.088 and 0.099 for Q1 and Q2 respectively but nearly significant at p=0.060 when the questions are combined. Also the case of JC D must be reconsidered since the two groups in JC D have different ability before intervention. These results will be analysed and discussed in more detail in future.

Remarks. For question 1b(i), most of the students who obtained Level 1 for at least one of the two concepts, explained that the number of photons increases, hence the number of electrons increases. Though they are given Level 1, a more accurate answer should involve the rate at which the photons or electrons are released and not merely the number.

For question 1c(i), some students made used of the formula $eV_s = \text{K.E.}_{max}$ to explain why stopping voltage increases when K.E._{max} increases. We feel that such an approach, while giving the correct answer, involves mainly rote memory and does not reveal the necessary conceptual understandings. There are also a significant proportion of students who simply state that stopping voltage increases when K.E. increases, without any explanation. This is probably because they do not feel the necessity to explain since it is often quoted and remembered as a fact. For questions 1c(ii) and 2c, we find that students are often confused by the units eV and J, applying them incorrectly.

Limitations of analysis

There are various factors that can affect our comparative analysis and it is difficult to clearly determine which factor has bigger influence on the results. As such we do not aim to make any definite conclusions but rather, while highlighting possible relationships, we also raise the limitations of our analysis. They are as follows.

a) It was our intention to return marked homework back to the students before they take the post-test. However, as participating teachers have to keep to their schedule of the JC tutorials, while the inquiry-based homework was distributed, it was not evaluated and returned to the students before the post-test.
b) The experimental groups have received more support in terms of teaching manpower. While the control group has just one class teacher for the tutorial, the experimental group has several researchers as facilitators in addition to the class teacher.
c) Gross nature of marking scheme that does not differentiate number of conceptual mistakes. For example, a student who just wrote the complete and correct formula is given Level ×, while a student who substituted in values into the formula but contains error in the substitution e.g. use of inconsistent units of joules and eV, also receives Level ×. Perhaps, a more differentiated marking scheme can be explored for a more in-depth analysis of students' conceptual understanding.

Conclusions

The University of Washington Physics Education Group (PEG) photoelectric effect curriculum materials found in '*Tutorials in Introductory Physics*' are adapted by the authors for use in Singapore JC with some appropriate modifications to implement inquiry-based tutorials in the junior colleges. Despite the limitations, the preliminary data and analysis presented here show that the modified materials, when delivered by the inquiry approach, are potentially effective instructional materials. Replacing traditional teaching materials and methods, our inquiry-based materials and teaching approach not only enhance students' conceptual understanding, but also improve their performance in A- Level exam type questions.

From our enriching experience with our research partners, we note several key points with regards to the facilitation of inquiry-based learning and teaching:

1. It is crucial that in the inquiry approach the conceptual understandings are derived from within the student. This would mean that for the facilitator, it is under little circumstances that she will reveal the answers to the students. Instead, the facilitator constantly poses guiding questions to enable the students to make their own justifications. This is important because if the answers are revealed in a rather straightforward manner, not only are the teaching moments lost but this seemingly convenient way of information delivery can also become habitual.

2. Many teachers note that learning by inquiry is a time consuming process. To overcome this difficulty will require much resourcefulness and careful planning. For example, some teachers who carried out learning by inquiry have made use of students as facilitators. We believe that teachers need not incorporate such a teaching style for all topics. A teacher may begin adopting learning by inquiry for one or two of the topics or even sub-topics, to expose the students to the critical thinking procedures and from the group interactions, understand what it really means to do in-depth thinking. Returning to the conventional teaching methods for the other topics later does not mean the loss of the critical thinking skills. In fact, it can serve as an opportunity where students execute the critical thinking skills on their own or in groups.

3. The terms 'learning by inquiry' are usually associated with a kind of teaching and learning process in the schooling environment. But it is really about how we continually acquire knowledge, make realisations, cultivate and improve ourselves at each and every moment throughout our entire lives. Learning by inquiry is a process of self-reflection. However, at the foundation of this learning process, it requires a set of thinking principles that the person must be clear of himself. It is with these principles that he can then critically assess and question his surroundings and phenomenon. We believe that directly telling and describing to the students what inquiry is and how to learn something by inquiry and expecting them to do so, is not effective. It is necessary to let the students experience learning by inquiry in the classrooms in order to enable them to acquire these thinking principles.

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