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Improving students' understanding by using on-going education research to refine active learning activities in a first-year electronics course

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Summary. — Interactive Lecture Demonstrations (ILDs) have been used across introductory university physics as a successful active learning (AL) strategy to improve students' conceptual understanding. We have developed ILDs for more complex topics in our first-year electronics course. In 2006 we began developing ILDs to improve students' conceptual understanding of Operational Amplifiers (OAs) and negative feedback in amplification circuits. The ILDs were used after traditional lecture instruction to help students consolidate their understanding. We developed a diagnostic test, to be administered to students both before and after the ILDs, as a measure of how effective the ILDs were in improving students' understanding.

We argue that an on-going critical analysis of student performance (using education research principles) is essential for improving education practice. Our analysis of student surveys, pre- and post-tests, ILD activities and final examinations, have yielded valuable feedback on how well we have designed and delivered our OA ILD interventions. During the period 2006–2013, we have found that:

a) many hours of traditional lectures do little to improve students' conceptual understanding;

b) a few additional hours of ILDs significantly improves students' conceptual understanding;

c) few students attend lectures consistently (either traditional or ILDs);

d) students find the concepts relating to OAs difficult, but students achieved much better scores on the OA examination question after the introduction of ILDs;

e) students recognise the learning benefits of the ILDs.

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Our ongoing education research has driven improvements in our active learning strategy, including:

1) recognising the importance of the facilitator role in active learning,

2) using a lesson plan that is consistent with an active learning pedagogy,

3) reviewing assessment tools and learning activities so that they improve student learning,

4) redesigning ILD equipment and activities to make them simpler and clearer to understand,

5) reviewing lesson plans to make them focused on simple key concepts.

The implications of using on-going education research results to refine the effectiveness of our L&T approach are clear. If we had implemented our initial ILD approach back in 2006 and continued on without the critical review that came from our own education research, we may have assumed that what we were doing was an effective AL approach. Instead, our education research results are an on-going trigger for review of, and self-reflection on, our teaching practices. Our education research gives us a quantitative measure of the success (or otherwise) of the interventions that we try in our teaching.

1. – Background for active learning in electronics at Swinburne University

Over the past eight years, we have tried to implement a partial active learning (AL) strategy for our introductory electronics course at Swinburne University of Technology. This course is taken by a large number of STEM students (from 100 to 300 each semester), although a considerably smaller number consistently participate in our AL activities, assessment tests and surveys. Over that time, we have redesigned our traditional problem-solving tutorial sessions to make them more interactive and collaborative, and to cover both numeric and conceptual problems. We have also redesigned our traditional recipe-style laboratory sessions to be more collaborative, by encouraging students to discuss their predictions before constructing circuits and making any measurements.

While we have continued to utilise traditional lectures for transmissive teaching, we have introduced some Interactive Lecture Demonstrations (ILDs) to supplement the traditional lectures in two key areas of electronics where we know students have significant difficulties with their conceptual understanding: i) operational amplifiers and negative feedback, and ii) AC circuits and resonance.

2. – Interactive Lecture Demonstrations

Students hold conceptions about physical phenomena that they have developed through their experience of the world (Redish, 1994). If at odds with accepted scientific explanations, they are called misconceptions and can be very resistant to being changed by traditional teaching methods (Muller, 2008). The use of ILDs is one strategy that has been developed to directly challenge students' misconceptions (Sokoloff and Thornton, 2004). Each ILD activity follows a similar sequence:

1. Students are presented with some experimental set-up and asked to record a prediction about the outcome of some experimental manipulation.

2. Students discuss their predictions with their peers, and are given an opportunity to reassess and perhaps change their predictions.

3. Students observe the outcome of the experimental manipulation.

4. The lecturer facilitates a discussion to reconcile students' predictions with their observations, and help incorporate the observations into their conceptual frameworks.

ILDs have been found to be more effective than traditional instruction in improving student conceptual understanding (Sharma *et al.*, 2010).

3. – ILDs at Swinburne

At Swinburne, we have developed and evaluated ILDs for the topics "*Operational Amplifiers (OAs) with and without negative feedback*" (Mazzolini and Daniel, 2014; Mazzolini, Edwards, Rachinger, Nopparatjamjomras, and Shepherd, 2011) and "*AC circuits and resonance*" (Daniel and Mazzolini, 2014; Daniel, Mazzolini, Cadusch, and Edwards, 2012; Mazzolini, Daniel, and Edwards, 2012). This paper discusses the evolution of our teaching practices, which has been guided by our physics education research (PER), and the effectiveness of our OA ILDs in improving students' conceptual understanding of amplification and feedback. (We have also discussed some of our AC circuits and resonance ILD results whenever they have added some insight into the interconnection of our PER and teaching practices.) We use a "blended learning" approach to the teaching of the OA section of the course: students undertake 8 hours of traditional lectures followed by 2–3 hours of ILD activities in a large lecture hall. For logistical reasons, the OA ILDs occur near the end of semester as part of the revision of difficult topics. Recently, we have started to use clickers (audience polling devices) to reduce the amount of student transcription and in-class administration, and also to improve the efficiency of data collection and analysis. The students that take our electronics course are non-electronics majors.

4. – What has education research revealed about student learning in our introductory electronics course?

Delivering ILD instruction in our electronics course at Swinburne University for nearly a decade has taught us many things about learning and teaching. In particular, the ability to collect and analyse PER data over that time period has given us many insights into how our students learn; many of these insights have been counter-intuitive to us as teachers.

4˙1. *Many hours of traditional lectures do little to improve students' conceptual understanding.* – In our electronics course, we have routinely assessed students' levels of understanding of various topics. One of the diagnostic tools that we have used is *identical pre- and post-tests* consisting of multiple-choice questions that have been designed to probe students' understanding of specific key concepts. Typically, the average normalised gain $\langle g \rangle$ has been used to measure improvements from a pre-test to post-test (Hake, 1998). It is defined as

$$g = \frac{\text{Observed improvement}}{\text{Maximum possible improvement}}. \quad (1)$$

Table I. – *Student test performance on phase relationships between sinusoids.*

Diagnostic Test	Percentage correct	No. of participating students
Baseline test	66.7	81
Pre-test	65.4	52
Post-test	84.6	33

In the studies reported here, the pre-tests were administered to students after traditional instruction but before ILD instruction, and then the post-tests were administered after ILD instruction. Interestingly, students' pre-test scores (*i.e.* after about 8 hours of traditional instruction in Operational Amplifiers) were typically around 25%, which given that these multiple-choice questions usually have only 5 or 6 alternatives is not much better than chance.

In 2011, while assessing students' understanding of AC circuits, we selected three questions from the relevant diagnostic test and collected student responses *before* traditional instruction to establish a baseline of student understanding. These questions assessed how well students could interpret the phase relationship between two sinusoidal waveforms. This is a critical concept for AC circuit analysis that students would have had some limited exposure to at high school and in their introductory mathematics and physics courses at university. As can be seen in table I, there was *no* significant difference in students' average test score between this baseline test (before traditional instruction) and the pre-test (after 8 hours of traditional instruction). On the other hand, there was a significant improvement ($\langle g \rangle = 0.55$) in students' performance on these particular questions between the pre-test (after the 8 hours of traditional instruction) and the post-test (after an additional 2 hours of ILD instruction).

4˙2. *A few additional hours of ILDs significantly improves students' conceptual understanding.* – In the last section, 2 hours of ILD instruction in interpreting AC waveforms and their vector (phasor) representation significantly improved ($\langle g \rangle = 0.55$) students' understanding of the phase relationship between sinusoidal waveforms.

We have also observed significant improvement after our OA ILDs. For example in 2013, the 13 students that attended all OA ILD instruction showed an average normalised gain of $\langle g \rangle = 0.21$ when comparing their OA pre-test scores (after 8 hours of traditional instruction) and post-test scores (after an additional 2 hours of ILD instruction), as shown in table II. This gain is more significant than it first appears because it represents the improvement *after* traditional instruction from only 2 hours of additional ILD active learning instruction covering the same material.

However, this simple measure of learning gains masks a large degree of learning complexity. As can be seen in table II, there is a large variation in how many students correctly answered each question in the pre- and post-test. More than this, there is also a large variation in the gains for each question: there was a substantial improvement on question 6, whereas on question 2 students actually did worse on the post-test. Such variations in a set of questions designed to assess understanding of OA concepts that are closely linked (at least in the teacher's mind) indicate that the path from confusion to clarity is indirect for many students.

The path from confusion to clarity does not appear to be straightforward for many students. Our results suggest that it is *not* like a switch that turns "understanding" on (*i.e.* like an incandescent light bulb that is off and then switches on). Instead we suspect

TABLE II. – *Diagnostic test results for a pre- and post-test (7 multiple-choice questions on OA concepts). These results show the number of students who correctly answered each question (as a percentage), the average of the 7 questions, and the corresponding normalised gains between pre- and post-tests. Only data from the 13 students who participated in all OA ILD activities have been included.*

Diagnostic Test	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Average
Pre-test (Score after traditional lectures)	15.4%	23.1%	38.5%	53.9%	0.0%	7.7%	46.2%	26.4%
Post-test (Score after ILDs)	30.8%	7.7%	61.5%	61.5%	7.7%	61.5%	61.5%	41.8%
Normalised gain $\langle g \rangle$	0.18	−0.20	0.38	0.17	0.08	0.58	0.29	0.21

that students gain partial understanding of concepts within certain contexts, and that deep conceptual understanding only develops after much trial and error (a little like the way a fluorescent light flickers several times before finally switching on) (Orlin, 2013). This idea is demonstrated by the following example.

In our "AC circuits and resonance" diagnostic test, there were two questions that to the expert represented different manifestations of the same underlying phenomenon, so-called *expert-equivalent* questions (Bao and Redish, 2006). These two questions investigated students' understanding of the same concept in resonance via i) a word description question and ii) a visual description question. A superficial analysis of the pre- and post-test results for these two questions from the combined data from 2010 to 2012 indicated that the average score went from 28% (pre-test, after traditional instruction) to 52% (post-test, after additional ILDs), which showed a respectable normalised gain of $\langle g \rangle = 0.33$. However, we went further than this: not only checking whether students answered the questions correctly or not, but also evaluating whether their two answers were conceptually consistent with each other, and tracking how their responses changed from the pre-test to the post-test (Daniel and Mazzolini, 2014). Although there was a general shift towards answering more questions correctly in the post-test (shown in fig. 1 by the trend to the right), the map of transitions is clearly complex. Most students answered inconsistently and, in particular, the largest category in the post-test was "inconsistent right" —that is, they answered only one of the questions correctly. They seem to have understood the phenomenon in one context, but not transferred their understanding to the other context. This may be an example of the "specificity effect" (Brookes, Ross, and Mestre, 2011) where students have not yet generalised their understanding of a principle beyond the example used to present it.

4·3. *Few students attend lectures consistently (either traditional or ILDs).* – When we run our traditional lectures or ILDs at Swinburne University, we see about 35–40% of the enrolled cohort attending any particular class. Previously we had assumed that these students were the conscientious ones that attended *all* classes. (Consistent attendance is important in STEM disciplines where the concepts developed in one class build on those developed in the previous class.) But the analysis of our ILD data revealed that i) in 2012, of the possible 154 students who attempted the exam, only 26 attended all 3 consecutive ILD sessions, and ii) in 2013, of the possible 135 students who attempted the

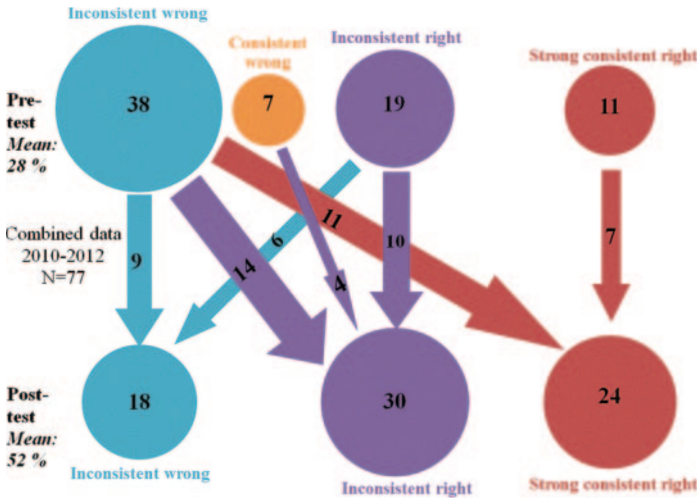

Fig. 1. – Changes in consistency from pre-test to post-test (transitions of less than four people excluded).

exam, only 31 attended 3 or all 4 ILD sessions. Clearly our students did not consistently attend ILD classes in a sequential manner in 2012–13, even though they appeared to be interacting well and enjoying the classes. We wondered if one reason for the poor consecutive attendance at our ILD classes was that the ILDs came near the end of semester and perhaps many students had become disillusioned or "burnt out" by then, or that they were under severe time pressure to meet end of semester deadlines for assignments etc. However, when we examined attendance in several other courses at our university, we found that attendance was sporadic for several traditional lecture classes and not just for our ILD classes. The attendance data was a good approximate fit to a binomial distribution, which meant that it was almost as if each student flipped a slightly weighted coin in deciding whether or not to attend any particular lecture or ILD (Daniel, Mazzolini and Schier, 2012). This is not a good sign for sequential STEM teaching!

4·4. *Although students find the concepts relating to Operational Amplifiers difficult, their exam marks on related questions improve significantly after OA ILDs.* – In 2011 we did not run any OA ILDs as in that year we concentrated on running new ILDs relating to AC circuits and resonance. With only traditional lectures on OAs that year, students performed comparatively poorly on the OA question, with an average score of 27% compared to the average score on all other exam questions of 55%. However, when we ran OA ILDs in 2012 and 2013, the exam performance on the OA question was much improved. The average exam score for the OA question (averaged over those two years) was 58%, comparable to the average exam score of 64% for all other topics. The OA questions each year were very similar in format, and designed to test concepts rather than students' ability to apply formulas.

However, this improved performance on the OA exam question in 2012 and 2013, when the ILD activities were held, at the time was surprising because students had performed so poorly on the ILD post-tests. For students that attended all the ILD sessions, the average score on the post-test in 2012 was only 29% ($\langle g \rangle = 0.05$) and in 2013 not much better at 42% ($\langle g \rangle = 0.21$). During the ILD activities, we felt that students were having considerable difficulties in understanding the concepts associated with OAs and negative

TABLE III. – *Summarised questionnaire responses about OA ILDs (2012–2013).*

Statement	Year	SD	D	N	A	SA
ILDs are more *interesting* than normal lectures	2012	5.2%	5.2%	22.4%	51.7%	15.5%
ILDs clearly show me the *gaps* in my knowledge	2012	1.6%	0%	8.1%	54.8%	35.5%
ILD classes gave me good *feedback* on how well I understood OAs	2013	0%	0%	23.1%	23.1%	53.8%
I *learn* more from an ILD than I do from a normal lecture	2012	3.5%	7.0%	42.1%	36.9%	10.5%
ILDs were more effective than normal lectures in helping me *learn* about OAs	2013	0%	0%	41.7%	8.3%	50%
ILDs helped me *understand* OAs	2013	0%	0%	30.8%	23.1%	46.1%

feedback. It is clear that the ILDs did partially improve conceptual understanding, and we further speculate that the ILDs also gave students clear and unequivocal feedback on their level of understanding (much more than traditional lectures) and that this may have help drive good study practices for OAs prior to the examinations.

4·5. *Students appear to recognize the learning benefits of the ILDs.* – We have tried to gauge students' perceptions of the OA ILD sessions via questionnaires. In 2012, we ran an in-class survey (60 students participated) and in 2013, we ran a post-semester on-line survey (13 students participated). The results are shown in table III. As can be seen, the majority of students in both years had positive (*agree* and *strongly agree*) responses to the statements regarding the effectiveness, helpfulness and interest level of ILDs compared to traditional lectures. This is encouraging as we ask a lot of our students during the ILD sessions, and the level of interaction we expect is perhaps outside the comfort zone of some of our students who think that education is primarily about the transmission of information. The following comment about the OA ILDs, written by a student who participated in the 2013 on-line survey clearly articulates the reason why our on-going education research to refine and improve our ILD activities is so important.

> "*The Op-Amp lectures were by far the most useful lectures of the semester. If this method of lecture delivery was adapted to the rest of the course topics...... it* [would] *represent a huge step forward for both the delivery of the course and the intelligibility of the subject material.*"

5. – How has collecting, and reflecting on, PER data improved our students' learning?

Progress in science is often based on interpreting observational data. Should we not use the same criteria for guiding our progress in science education? The following are some examples of how reflecting on our PER has helped us improve the learning outcomes of our students.

5·1. *Importance of the "facilitator role" in active learning.* – To be effective, an active learning class needs a very well-trained facilitator, but unfortunately the role of facilitator does not come naturally to some academics. From a personal perspective, one of us (APM) recalled that in his early active learning classes he felt that he was an excellent AL facilitator. But one year, one of his colleagues videoed some of his ILD classes and it quickly became apparent that he was doing far too much lecturing and not enough facilitating. This has been a personal lesson that is still hard for him to learn today! Fortunately our electronics ILD classes are now taught by the two of us, and we constantly review and debrief with each other how well we are facilitating the active learning in our classes. We now believe, more than ever, that peer discussion, rather than direct instruction, is the key to student learning (Smith, Wood, Krauter and Knight, 2011).

5·2. *Lesson plans should use a learning cycle that is consistent with active learning pedagogy.* – We use a well-defined PODS (Predict Observe Discuss Synthesise) learning cycle with each ILD activity. This learning cycle is based on a well-established active learning pedagogy (Mazur, 1997). In recent years, using "clickers" in our ILD classes has enabled us to easily monitor *in real time* our students' predictions in regard to the outcomes of various ILD experiments. Our PER data has indicated that peer discussion in-between students' initial prediction and their revised prediction is extremely important in the learning process. Figure 2 shows the prediction and revised prediction data from a typical ILD session. In this example, only 29% of the class initially predicted the correct outcome for the ILD experiment, with 71% of the students choosing one of the 7 distractors. The students were then asked to try to convince a student nearby who had a different prediction to change their opinion. After only one or two minutes of discussion, 81% of the students had revised their predictions correctly.

5·3. *Assessment tools and learning activities should be reviewed frequently.* – Before we started using ILDs, we adopted the convention used commonly in electronic textbooks and referred to the voltage gain of an isolated OA as its *open-loop gain*, and to the gain of an OA circuit using negative feedback as its *closed-loop gain*. Once OA ILDs had commenced, it became apparent during the ILD activities and during the analysis of pre- and post-test data that there was considerable confusion about the concepts of open-loop gain and closed-loop gain. It appeared to us that some students were confusing a property of the OA (open-loop gain) with a property of the OA circuit (closed-loop

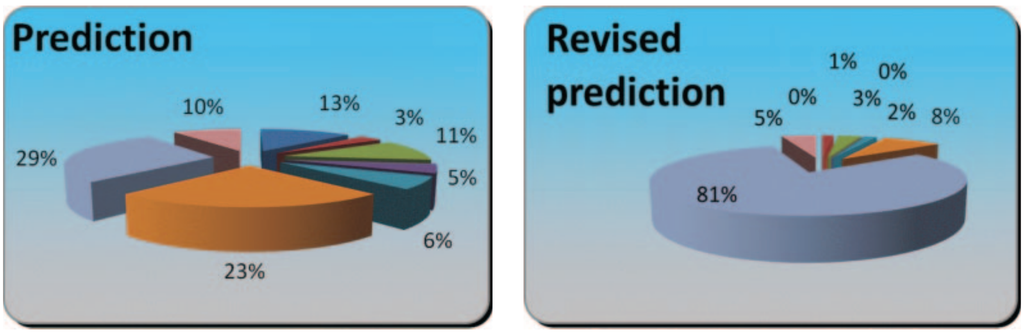

Fig. 2. – Initial prediction (29% of students predicted correctly) and revised prediction after peer discussions (81% of students predicted correctly) from a typical OA ILD session.

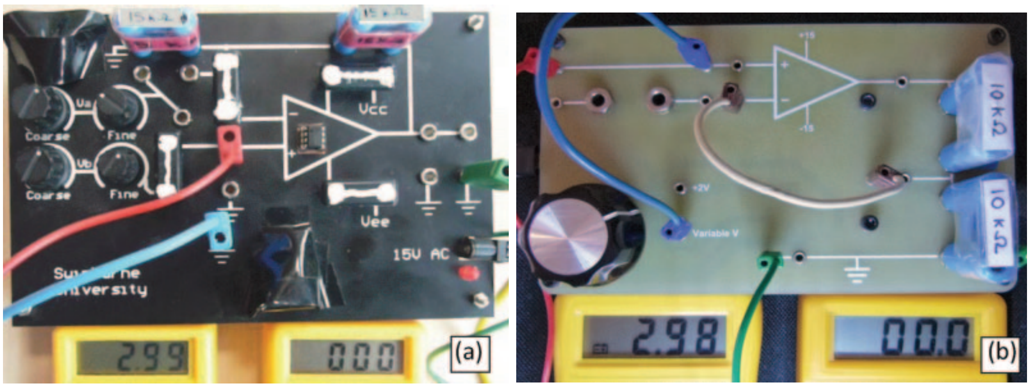

Fig. 3. – (a) Initial OA ILD equipment (2006–12) (b) Revised OA ILD equipment (2013).

gain). To help rectify this confusion we now use the terms *intrinsic gain* instead of open-loop gain, and *circuit feedback gain* instead of closed-loop gain. We have noticed that this simple name change has reduced students' confusion in OA pre- and post-test questions related to these concepts.

5˙4. *ILD equipment and activities should be reviewed and redesigned to make them simpler and clearer to understand.* – When we first started OA ILD instruction in 2006, we designed and built a very detailed and flexible OA board (see fig. 3(a)), which allowed us to construct a vast array of different OA circuits. The OA circuits were constructed at the front of the class, and a video image of the board was projected onto a large screen. Students could then look at the board while making predictions and observations from an *ILD activities* PowerPoint presentation displayed on a second screen. We used the OA board for many years, but some students told us that the board was too complicated (even when we covered up some of the functionality as shown in the figure) and that it often did not exactly match the circuits we were discussing in the PowerPoint presentations. Although it took much effort, the board was eventually redesigned (so that it more closely resembled the diagrams in the ILD activities) and simplified (see fig. 3(b)). The new board was used for the first time in the 2013. The average normalised gain in 2012 for the students that attended all the OA ILD sessions was only 0.05, whereas in 2013 the gain was 0.21. We attribute these improved learning gains in part to the better-designed OA circuit board.

5˙5. *ILD lesson plans should be reviewed to make them focused on simple key concepts.* – When we reviewed our OA ILD data each year, it became apparent to us that students were having considerable and on-going difficulties in understanding the key concepts about OAs and negative feedback. In 2013, we undertook a major review of our ILD lesson plans and rewrote them so that they focused only on key concepts that students were having difficulties with. With these revised ILDs, performance on the post-test increased from 29% in 2012 to 42% in 2013. That such poor statistics nevertheless represent some improvement in teaching and learning is an indication of how difficult these concepts are for students.

6. – Conclusion

Successful teaching requires humility: an acceptance of the difficulty of achieving a deep understanding of the concepts in question, and our limited ability to successfully challenge and overcome our students' strongly-held misconceptions. An on-going critical and rigorous evaluation of our own teaching practices and whether those practices do or do not positively influence student learning, is the key prerequisite for any improvements.

> "Let the long and the short of our didactic be to investigate and discover the means for teachers to teach less, and learners to learn more".
>
> John Amos Comenius, *Didactica Magna* (1628)

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