The use of interactive lecture demonstrations to improve students' understanding of operational amplifiers in a tertiary introductory electronics course

A. Mazzolini[1], T. Edwards[1], W. Rachinger[1], S. Nopparatjamjomras[1,2], O. Shepherd[1]
[1]*Engineering and Science Education Research group, Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, PO Box 218, Hawthorn, 3122, Australia.*
[2]*Institute for Innovative Learning, Mahidol University, 999 Phuthamonthon 4 Rd., Salaya, Nakhonpathom, 73170, Thailand.*

E-mail: amazzolini@swin.edu.au

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Abstract

Students often have difficulty in understanding fundamental concepts in introductory electronics. For example, some of our students at Swinburne University have particular difficulty understanding operational amplifier (OPAMP) concepts. Many of these students try to memorize basic OPAMP circuit layouts and their associated "voltage gain" equations without developing any deep understanding of how these circuits work. These students have difficulty analyzing circuits that are only slightly different from the basic circuits they have memorized. We have developed a sequence of interactive lecture demonstrations (ILDs) to help address these issues. These ILD activities foster a deeper understanding of OPAMP circuits through interpreting fundamental electronics principles (such as Ohm's Law and Kirchoff's Laws) and basic OPAMP characteristics (such as high input resistance and high intrinsic OPAMP gain). We have also developed an OPAMP conceptual test to gauge the efficacy of our approach. Testing of our students has indicated learning gains when students are taught using our "blended active learning" approach rather than just a traditional passive learning approach. Focus groups indicate that students perceive this approach to be beneficial to their learning experience.

Keywords: Active Learning, Electronics, Interactive Lecture Demonstration, Operational Amplifier.

Resumen

Los estudiantes suelen tener dificultades en la comprensión de conceptos fundamentales de la electrónica de introducción. Por ejemplo, algunos de nuestros estudiantes en la Universidad de Swinburne tienen especial dificultad para la comprensión de los conceptos del amplificador operacional (OP AMP). Muchos de estos estudiantes tratan de memorizar los diseños básicos de circuitos OPAMP y sus correspondientes ecuaciones de "ganancia de tensión", sin desarrollar una comprensión profunda de cómo funcionan estos circuitos. Estos estudiantes tienen dificultades para el análisis de circuitos que son sólo ligeramente diferente de los circuitos básicos que han memorizado. Hemos desarrollado una serie de manifestaciones conferencia interactiva (EPI) para ayudar a abordar estas cuestiones. Estas actividades ILD fomentar una mayor comprensión de los circuitos OPAMP a través de la interpretación de los principios fundamentales de la electrónica (como la Ley de Ohm y Leyes de Kirchoff) y características básicas OPAMP (como la resistencia de entrada alta y alta ganancia intrínseca OPAMP). También hemos desarrollado una prueba de OPAMP conceptuales para evaluar la eficacia de nuestro enfoque. Pruebas de nuestros estudiantes ha indicado que aprenden ganancias cuando los estudiantes se les enseña con nuestro "aprendizaje combinado activo" enfoque en lugar de un enfoque tradicional de aprendizaje pasivo. Los grupos focales indican que los estudiantes perciben que este enfoque es beneficioso para su experiencia de aprendizaje

Palabras clave: El aprendizaje activo, Electrónica, Manifestación Charla interactiva, amplificador operacional.

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I. INTRODUCTION

Active learning techniques (where students are encouraged to engage in the learning experience) have been used for many years to improve students' conceptual understanding of introductory physics at the university and high school levels. The efficacy of using active learning is now well established [1, 2, 3, 4, 5, 6, 7, 8]. There have been many physics education research (PER) studies that have demonstrated that student hold deeply-rooted misconceptions in the areas of physics (including mechanics, basic electric circuits, optics, heat etc) and that these misconceptions often are not corrected by traditional passive learning techniques (e.g., in optics, students have many deep misconceptions regarding reflection [9] and refraction [10] of light). Active learning can be used to expose and correct student misconceptions through the observation and discussion of real phenomena in lecture-, tutorial- or laboratory-based activities. Through a learning cycle (for example PODS- Predict Observe, Discuss and Synthesize) students can confront their misconceptions, correct them via discussions with peers and facilitators [11], and then construct their own understanding of the correct physical concepts underpinning the particular observation, and how these concepts fit into their "network of understanding" in the particular topic being studied [12]. PODS is simply a variation [13] of the familiar Predict-Observe-Explain learning cycle.

Over the past few years, we have been involved with the renewal of three first year study units at Swinburne University of Technology (in Melbourne, Australia). These units (Electronics Systems, Energy & Motion and Materials & Processes) all have large numbers of engineering and science students (200 to 450). The units are taught via large lecture groups (around 50-200 students), and smaller tutorial and laboratory groups (24 students); the lecture, laboratory and tutorial sizes are dictated by space and timetable constraints at the university. Nevertheless, within these constraints, we have been incorporating various active learning activities into the existing traditional teaching programs of these three units. These student-centered activities involve the development of collaborative-style tutorial sessions, discovery-style laboratory sessions and a number of interactive lecture demonstration (ILD) activities that replace some of the traditional-style lectures. We call this mix of traditional lectures and ILDs a "blended" teaching approach. In this paper we focus on the lecture-based active learning activities for one topic (operational amplifiers) in the Electronic Systems unit.

Operational amplifiers (OPAMPs) are often poorly understood by students, especially those at the first year university level. Perhaps because they are unfamiliar with operational amplifier devices (ie the OPAMP's inherent properties such as high gain, high input impedance, low output impedance etc.) and operational amplifier circuit design (ie use of negative feedback to trade off gain for stability), students tend to memorize a small number of specific OPAMP circuit configurations (such as the inverting and non-inverting amplifier). This "shallow learning" approach usually involves memorizing the circuit configurations and the gain formulas that apply to these particular configurations. These students generally have little idea of how OPAMP circuits actually work and the role that negative feedback plays in determining why the circuit operates the way it does. This becomes quite apparent if the labels of the input and feedback resistors (say R_1 and R_2) in the inverting OPAMP circuit shown in figure 1 are interchanged (i.e. R_1 is labeled R_2 and vice versa). In this situation, many students still plug the wrong values into the original (but now incorrect) inverting amplifier gain formula $V_{out}/V_{in} = -R_2/R_1$. Also if the circuit layout of a non-inverting OPAMP circuit is changed so that it functions the same way but looks a little different, students become completely confused. These and other observations of our students over the years have lead us to conclude that a "passive learning" approach to the teaching of OPAMPs leads to shallow learning involving simple memorization rather than true understanding of the concepts.

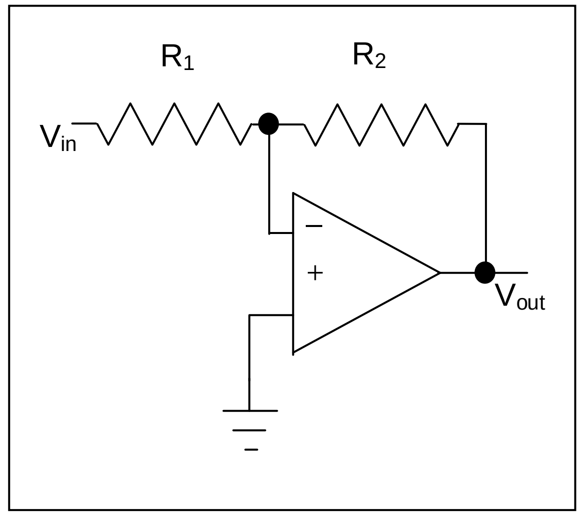

FIGURE 1. Circuit for inverting amplifier.

On the other hand, if students can grasp the basic concepts of how the OPAMP operates under negative feedback, and if they learn how to analyze OPAMP circuits using the basic principles of electronics circuit analysis (Kirchoff's Laws, Ohm's Law or Voltage Divider Rule) then hopefully they have all the skills needed to understand *any* OPAMP circuit no matter how complex. This sort of conceptual understanding is difficult to teach via a passive learning approach, where students are simply trying to memorize what the lecturer has said. Instead, we believe students need to be actively engaged in the learning process so they are thinking about the concepts needed to understand how operational amplifier circuits work, and are constructing their knowledge from their own quantitative observations. This active engagement approach is well established both for the study of basic electric circuits [14, 15, 16] and for more advanced topics such as digital design [17] and AC & transient response [18].

We have decided to modify the traditional OPAMP lecture program by substituting three of the six traditional OPAMP lectures with a sequence of interactive lecture demonstrations (ILDs) designed to engage students to explore the operation of the OPAMP in a deep rather than shallow manner. The technique of substituting ILDs for some traditional lectures has proved successful in some other studies [19].

II. MATERIALS AND METHODS

The active learning activities associated with the OPAMP lectures in our Electronics Systems study unit are designed around a series of ILDs and a Predict-Observe-Discuss-Synthesize (PODS) learning cycle. The ILDs cover topics in the OPAMP course such as the comparator, inverting and non-inverting OPAMP circuits. These topics are now covered mainly via the ILD activities, although students still have access to the old passive learning material (ie old lecture notes, power point material etc.). The learning cycle used with the ILDs elicits engagement by allowing all students in the lecture hall to individually predict what voltages and currents exist at certain points in a particular OPAMP circuit under a set of conditions. These predictions are recorded on a "prediction sheet". Students are then given the opportunity to discuss ideas with their class-mate neighbors, record their thoughts and then amend their predictions if they wish. The facilitator then performs the experiment on a *real* OPAMP circuit at the front of the class. The experiment, which is videoed in real-time, is displayed via a data projector so all students (even in large classes) can see what is happening. Students record the observed results on a "results sheet". They then discuss with their neighbors and facilitator any discrepancy between their predictions and observations. The students are encouraged to analyze their understanding of why the OPAMP circuit behaved the way it did, and whether this is consistent with their model of the OPAMP; these reflections are also written into the results sheet. The prediction sheets are collected by the facilitator and analyzed to determine the various models students use to make their predictions. This analysis can then be used to improve the teaching plan for the following year. The results sheets are kept by the students to help them with their study revision. Figure 2 shows a small part of a prediction sheet used in one of the ILD activities.

The OPAMP board that we use to demonstrate the observations during the ILDs is shown in Figure 3. The layout of the board is very simple, and closely resembles the circuit shown in the prediction sheets so students can clearly interpret the circuit that is being constructed. Feedback from our students indicates that many would like the OPAMP board to be even simpler, and we are currently working on a redesign that will remove all elements that are not essential to the circuit shown on the prediction sheet. The actual OPAMP IC is clearly visible on the front of the board so students can appreciate what the physical IC looks like; this also means that the IC can be easily changed during the ILD should it fail. The various circuits used in the ILDs are constructed by using a number of 2 mm H-plug connectors configured as either resistors or shorting links. Currents and voltages at various points around the board are measured with color-coded digital millimeters.

To evaluate the efficacy of the OPAMP ILDs, seven questions (see Appendix) have been developed to test key OPAMP concepts. While we acknowledge that these questions are far from perfect, and that we need to interview our students to gauge how effectively the questions probe key concepts, we believe the questions do give us an indication of whether ILDs are more effective than traditional lectures in improving the students' conceptual understanding of OPAMPs. We have also run several focus groups and a survey to gauge students' perceptions of how helpful the ILDs are in improving their understanding of OPAMPs.

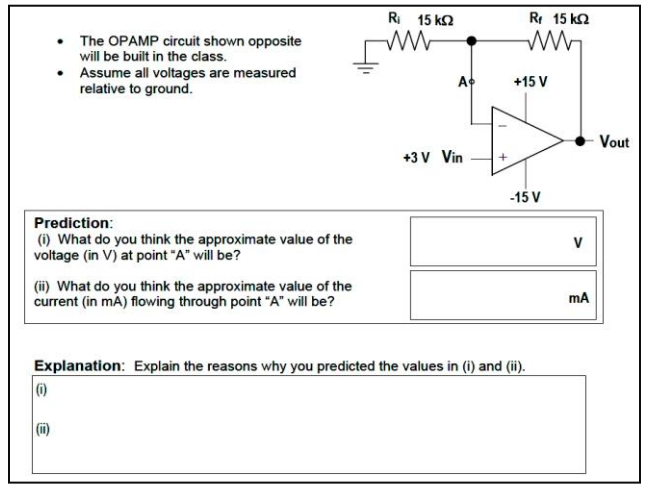

FIGURE 2. Part of a prediction sheet used for the non-inverting OPAMP circuit ILD activity. By understanding why the voltage and current at point A are as they are, students go on to develop a deeper understanding of how the circuit functions and how the circuit gain can be determined from simple electronics principles and OPAMP characteristics.

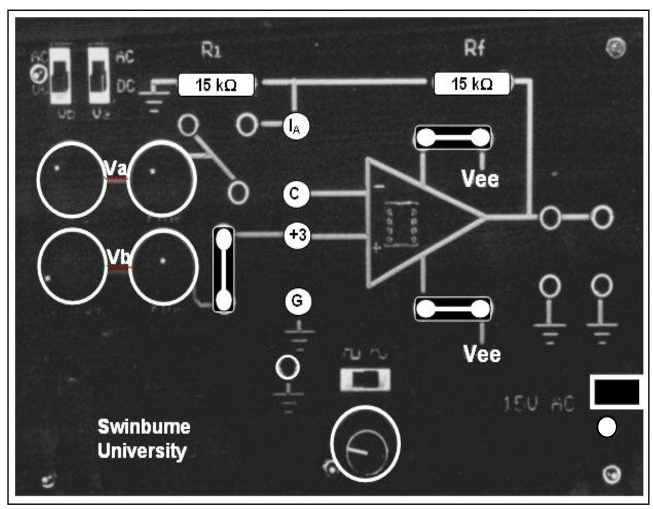

FIGURE 3. The board used for the OPAMP ILDs. The board has been set up for the activity shown for the prediction sheet in Fig. 2.

The Electronics Systems study unit has a large number of students and is therefore split into smaller lecture groups of between 50 and 100 students. The data (pre and post- tests) presented in this paper come from a study conducted over two years. In the first year (2006) one lecture group had the OPAMP section of the course taught via some traditional lectures *and* some ILDs (that is, "blended instruction"), while the other group was taught via traditional lectures only. In the second year (2007) data were collected only from one group where the OPAMP section of the course was taught via both traditional lectures and ILDs (blended instruction). Each of the groups had between 40-80 students participating in the pre- and post-tests. The pre-tests were administered immediately after the first few introductory OPAMP traditional lectures (and before any ILDs). The post-tests were administered shortly after the end of the OPAMP section of the course.

III. RESULTS AND DISCUSSIONS

Our study suggests that the lecture groups had comparable levels of understanding at the start of the OPAMP topic (pre-test results). The summary of results (presented in figure 4) shows the change, from pre-test to post-test, in the percentage of students choosing the correct answer for each particular question (i.e. Q1-Q7). As can be seen, the percentage difference between pre- and post-test results for the traditional only lectures (white columns) is quite small

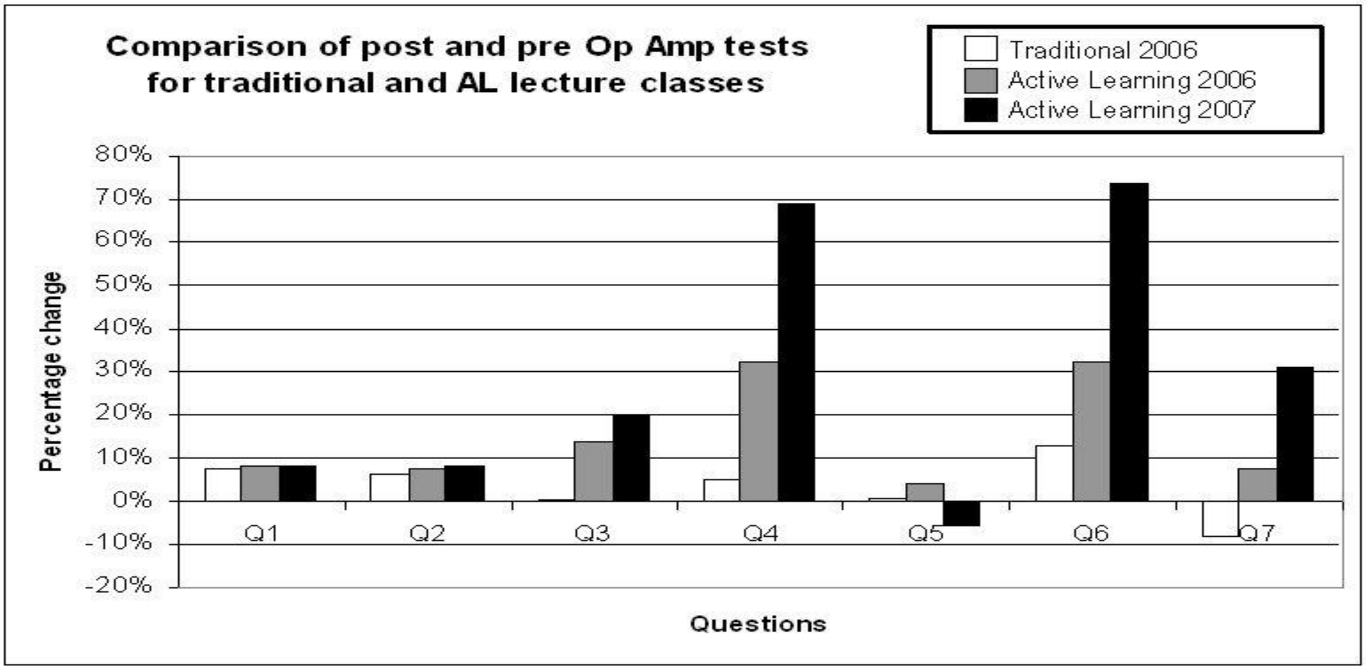

FIGURE 4. Change in the percentage of students getting each particular question (1-7) correct from pre-test to post-test. Q1 tests the concept of open loop gain; Q2 tests whether negative feedback reduces overall gain; Q3 & Q5 test the concept of zero voltage difference across the inputs of an OPAMP with negative feedback; Q4 tests the concept of zero current flowing into the inputs of an OPAMP; Q6 & Q7 test OPAMP gain without feedback and the concept of clipping.

(on average around 3.4%). Assuming binomial distributions and that the seven questions can be treated as independent items none of the observed differences in the traditional only lectures were significant at the 5% level. For the 2006 traditional lectures *plus* active learning ILDs (grey columns) the percentage difference is higher (on average around 15.1%). For the 2007 traditional lectures *plus* active learning ILDs (black columns), the percentage difference is higher again (on average around 29.1%) and shows a dramatic improvement (30 to 75%) for questions 4, 6, and 7 (which are statistically highly significant).

There was very little or no improvement in pre- and post-testing results for questions 1, 2 and 5. We suspect that the lack of change (pre- and post-tests) or differentiation (traditional or active learning) in these results is due to problems with the questions themselves. In particular-

(a) Question 1 tested students understanding of the concept of “open loop gain”. Only traditional lectures were used to teach this particular concept, so this question may not assist in determining whether the active learning activities were more/less effective than traditional lectures.

(b) Questions 2 and 5 were very difficult questions for students to interpret, and required an understanding of several different concepts to determine the correct answer. Each question had a complex circuit variation that was *not* covered during instruction. At the time we thought that good students, who really understood OPAMPs well, would be able to answer these questions correctly. In retrospect it seems the questions were too complex for students to answer correctly even after instruction.

Questions 6 and 7 referred to a comparator circuit that was familiar to most students and either tested the relatively simple concept of saturation (Q6) or the more difficult concept of voltage switching around an input reference voltage (Q7). Traditionally, the key concept covered in Q7 has been poorly understood by students, so it is encouraging that the ILDs seemed to improve this situation. Question 4 used the same complex and unfamiliar circuit as in question 5 but required students to understand only one concept (zero current into OPAMP inputs), which seemed to be well understood in the blended learning groups. Question 3 again used an unfamiliar circuit and required some complex and detailed reasoning. While the blended learning results were encouraging, most of the students could not apply key concepts to solve this complex problem.

It is also interesting to note that students (in the traditional lecture plus active learning ILDs) generally performed better in the OPAMP tests in 2007 compared to 2006. We believe that this improvement is primarily due to the lecturer/facilitator becoming more comfortable with presenting the ILDs, with using the equipment and with following the PODS learning cycle more precisely. These factors may also contribute to the discrepancy between the exceptionally high learning gains experienced by the originators of ILDs [7] and the more moderate learning gains of "new adopters" who may have been (at the time) a little less familiar with ILD facilitation [e.g. 20,21].

In 2006, two student focus groups (total of 15 students) were interviewed to gauge their perceptions in regard to the Electronic Systems unit in general and the active learning activities in particular. The responses from the students were generally very positive, and some of their comments concerning the OPAMP ILDs were as follows-

"With our lecturer, he… …actually set up an experiment to show us how it works and there was a sheet to fill in our predicted answer, like what we think it's going to look like, and then we conduct the experiment and get the actual answer and get that and compare it. And then on the bottom of it you have to explain why you think the answer will be like that, then why the result is the same or different. So you kind of know where you went wrong."

"It's more interesting, it engages you, it makes you wake up and you know, look at the board, look at the experiment, how they set up the experiment and all that."

"I guess with the experiment it actually proves to you, it convinces you that that's the real answer whereas you can't just give a formula and say "oh, that actually proves the formula is right" so it makes you better understand."

"It is good when we have to work with the people around us and he'll like give us a question and we have to find the answer and explain it to each other so then we get different ways of hearing how other people do it and understand it."

"not just knowledge in a book… visualise it, see it in action, picture it in action."

We also administered a student survey to one of the Electronic Systems lecture groups that were taught via traditional lectures plus active learning ILDs (including the OPAMP ILDs). Thirty-six students responded to the survey questionnaire, which probed the students' perceived effectiveness of the ILDs. Student responses to the survey questions were gauged using a 5-point Likert scale (ranging from strongly disagree to strongly agree). Students' responses to the questions were generally very positive. For example, 91.7% of students agreed or strongly agreed that the ILDs were more helpful in explaining concepts that the traditional lectures; similarly 83.3% thought that ILDs *did* help them learn by discussions with their peers. Finally the survey showed that 83.3% of students wanted more ILDs in the Electronic Systems course.

IV. CONCLUSIONS

We are excited and encouraged by the results of our small study. The pre- & post-test results, the student survey and the focus group discussions seem to indicate that students are learning OPAMP concepts better using a blended learning approach of traditional lectures and ILDs rather than just traditional lectures alone. Our OPAMP conceptual evaluation test questions need some revision, and we will do this before the next phase of our study. We also want to extend the number of ILD activities in our Electronic Systems unit. We have now developed evaluation tests and ILD activities for the AC Resonance part of our course and will publish our analysis soon. As well as working on ILDs we have also revised our Electronic Systems tutorials (to make them more student centered) and our laboratory activities (to make them more exploratory). Again the student feedback we are getting concerning these activities is very positive. Finally, it is very encouraging to wander around the laboratory class and hear the students having animated discussions about why their observations do, or do not, agree with their predictions. To us, as teachers, this is a very positive sign.

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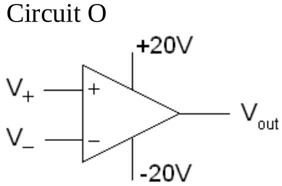
APPENDIX

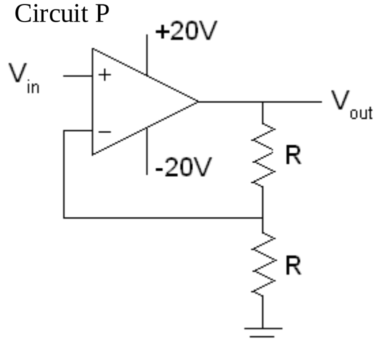
Questions used for pre- and post-testing of students' understanding of ideal OPAMPs

Question 1

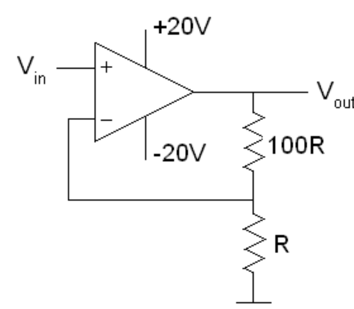
Circuit O



Circuit P

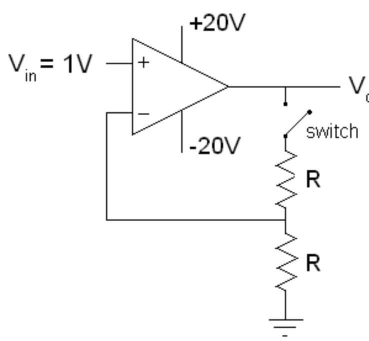


Circuit Q



In which of the three circuits shown does the op-amp have a very high open loop gain (approaching infinity)?
(a) Circuit O, (b) Circuit P, (c) Circuit Q,
(d) None of the circuits, (e) All of the circuits

Question 2

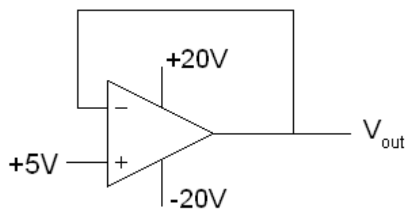


In the circuit shown, the input voltage V_{in} = 1V.

What happens to V_{out} when the switch is closed?

(a) decreases to zero, (b) decreases to a positive value,
(c) remains the same, (d) increases,
(e) decreases to a negative value

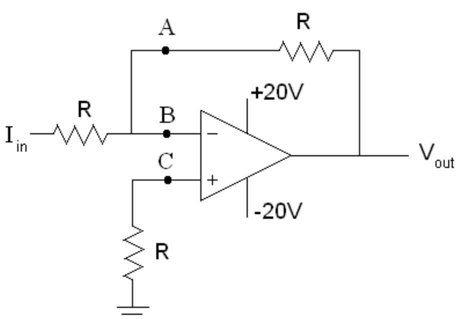
Question 3



In the circuit shown, what is the output voltage V_{out}?

(a) -20V, (b) -15V, (c) -5V, (d) 0V, (e) +5V, (f) +20V,
(g) +25V

Question 4



In the circuit shown, the resistance "R" of each of the resistors is 5 kΩ. The input current I_{in} is 5mA.

The current is zero at which of the points A, B and C?

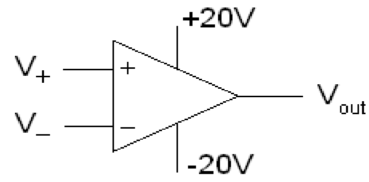
(a) A, B and C, (b) A and C only, (c) A and B only,
(d) B and C only, (e) C only. (f) None of A, B and C

Question 5

For the same circuit as shown in Question 4, the voltage is zero at which of the points A, B and C?

(a) A, B and C, (b) A and C only, (c) A and B only,
(d) B and C only, (e) C only, (f) None of A, B and C

Question 6



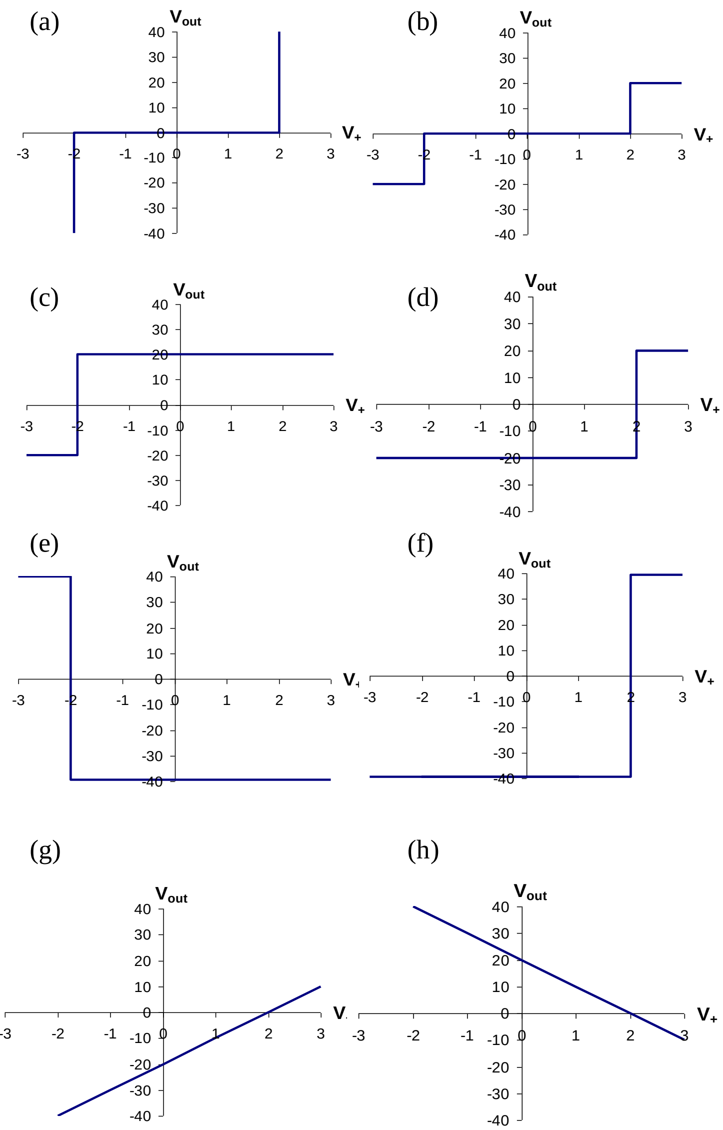
For the circuit shown, $V_+ >> V_-$.

The value of Vout is:

(a) 0V, (b) -20V, (c) +20V, (d) +40V, (e) -40V, (f) +infinity
(g) -infinity

Question 7

For the same circuit as shown in Question 6, if V_- = -2 V, which of the following graphs (a to h) best represents V_{out} as a function of V_+?



Note that the correct answers to the questions are as follows:

Q1 = (e), Q2 = (b), Q3 = (e), Q4 = (d), Q5 = (a)
Q6 = (c), Q7 = (c)