Assessing student understanding in upper-division analog electronics courses*

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Abstract

While there are many important goals of laboratory instruction, particularly in upper-division courses, relatively little work has been done to assess the impact of such courses on students. As part of an ongoing, in-depth investigation of student learning in upper-division laboratory courses on analog electronics, we have been examining the extent to which students enrolled in these courses develop a robust conceptual understanding of analog electronics (one of many course goals). We will highlight the development and use of written questions on op-amp circuits that have been instrumental in probing student understanding in sufficient depth to identify specific conceptual and reasoning difficulties. We will also illustrate the role such questions may play in revealing weaknesses in the traditional treatment of certain electronics topics and in informing modifications to instruction.

Overview of investigation

This ongoing, multi-institutional investigation is focused on exploring and documenting, in a systematic manner, student understanding of:

- Fundamental electric circuits concepts (*e.g.,* Kirchhoff's junction rule)

  Examine the effectiveness of electronics instruction on addressing basic conceptual difficulties

  Investigate student ability to apply basic concepts in more advanced contexts (e.g., diode circuits)

- Canonical topics in analog electronics (*e.g.,* operational amplifiers)

  Examine student learning of topics emphasized in laboratory and therefore probe the impact of hands-on laboratory instruction on student conceptual understanding

Data sources:

- Student responses to written pretest and post-test questions
- Transcripts from interviews involving tasks similar to those used in written questions

Context for investigation

Our investigation of student understanding of analog electronics has been conducted in the context of junior-level courses on the topic at three different institutions: University of Washington (UW), University of Athens (UA), and University of Maine (UMaine). The courses at all three institutions are required for all physics majors.

Course	Physics 334 UW	Electronics I UA	Physics 441 UMaine
Enrollment	30-80	~250	10-15
Text	*Horowitz & Hill*[1]	*Tombras*[2]	*Diefenderfer & Holton*[3]
Lecture	2 hours/week	4 hours/week	1 hour/week
Laboratory	3 hours/week (in-class reports)	2 hours/2 weeks (no lab reports)	3 hours/week (formal lab reports)
Homework	weekly	none	occasional/pre-labs
Exams	2 exams	1 final exam	1 final exam

Example: Operational amplifier circuits

In the courses, students are introduced to the operational amplifier (op-amp), which is a high-gain differential amplifier. During instruction at UW and UMaine, it is emphasized that there are two *Golden Rules* for op-amp behavior (when there is proper feedback, as in the circuit in Fig. 1):

I. The op-amp output attempts to do whatever is necessary to make the voltage difference zero between the inverting (–) and non-inverting (+) inputs.

II. The inverting and non-inverting inputs draw no current.

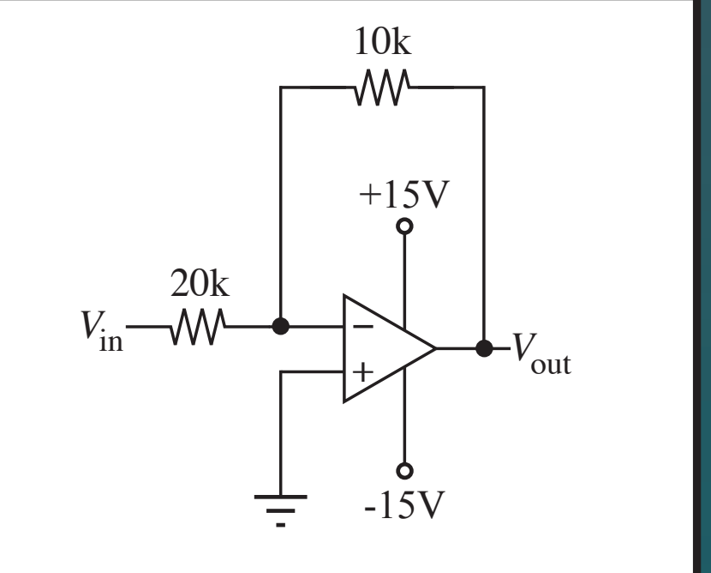


FIGURE 1. Basic op-amp circuit: Inverting amplifier.

To date, very little research has been conducted on student understanding of op-amps and basic op-amp circuits. Engineering education researchers at Swinburne University of Technology recently developed a multiple-choice op-amp conceptual test in order to examine the impact of interactive lecture demonstrations on students' understanding of op-amp circuits.[4]

A. Non-inverting amplifier post-tests

After examining student responses to a variety of less-targeted op-amp questions, we developed the following free-response question in order to investigate student ability to predict how, if at all, a small perturbation (in this case, the addition of a resistor between V_{in} and the non-inverting input) would impact the behavior of a non-inverting amplifier. This free-response question (Fig. 2) was administered to students at UW ($N = 54$) on a final exam after all instruction. Results are presented in Table 1.

In the circuits at right, the op-amps are identical and ideal. The input voltages V_{in} are constant and identical.

Is the absolute value of V_A *greater than, less than,* or *equal to* that of V_B? $\boldsymbol{V_A = V_B}$

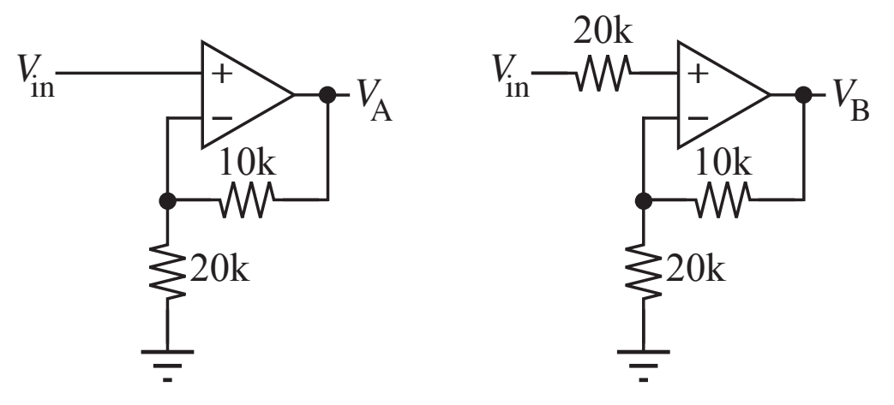


FIGURE 2. Two non-inverting amplifiers post-test question and correct answer.

An illustrative student justification for $V_A > V_B$:

"These circuits are non-inverting amplifiers that multiply the voltage at the + terminal by 3/2 so $V_A > V_B$ because the voltage at the + terminal in B has already lost voltage because of the resistor."

Approximately 20% of all students argued that $V_A > V_B$ because there will be a voltage drop across the 20k input resistor.

Table 1. Output voltage comparison (Fig. 2)	***% of responses*** **UW (N=54)**
$V_A = V_B$ (correct)	**70%**
$V_A > V_B$	30%

In order to explore such reasoning in greater detail, we developed the following question involving three non-inverting amplifiers. It was administered after all relevant op-amp instruction.

At right are three op-amp circuits with identifical positive input voltages V_{in} (from ideal voltage sources).

Rank, from largest to smallest, the absolute values of the ouput voltages $V_A – V_C$. $\boldsymbol{V_A = V_B = V_C}$

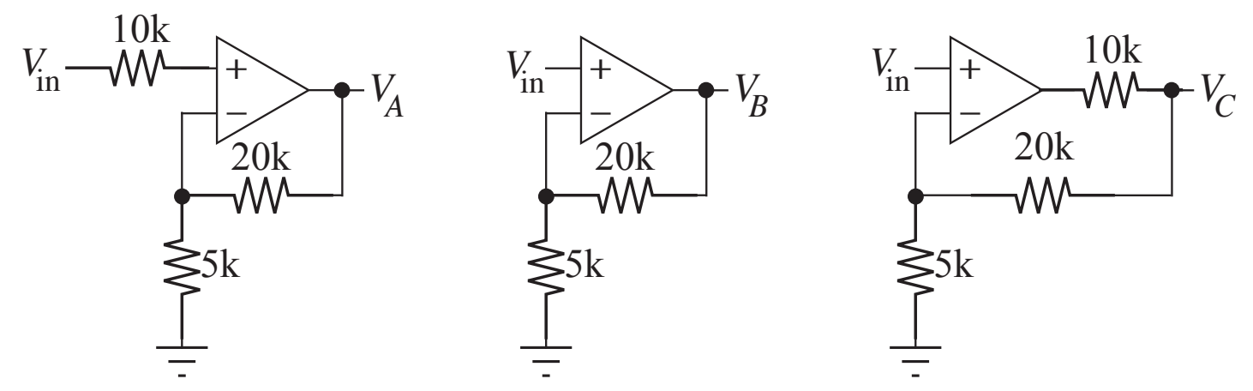
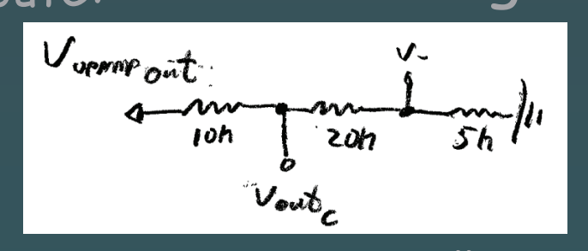


FIGURE 3. Three non-inverting amplifiers post-test question and correct answer.

40% (UA) to 45% (UW) of all students indicated that there was a voltage drop due to the resistor when claiming $V_B > V_A$. Current is almost never mentioned in these responses.

Reasoning for the ranking $V_C > V_B$ included the following:

"Circuit C is similar to B, but the input resistor from A has taken up residence between the op-amp output and V_{outC}, thus creating a voltage divider:



where $V_{opamp\ out} = V_B$."

Table 2. Output voltage ranking (Fig. 3)	***% of responses*** **UW (N=160)**	 **UA (N=181)**	 **UMaine (N=8)**
$V_A = V_B = V_C$ (correct)	**25%**	**10%**	**25%**
Specific comparisons			
$V_B > V_A$	55%	50%	50%
$V_C < V_B$	45%	40%	65%

20% (UA) to 35% (UW) of all students appeared to treat the op-amps in circuits B and C as having the same outputs, possibly due to similarities in the circuits.

Approximately one-half of students gave responses for each comparison on the three amplifiers question that are inconsistent with *Golden Rules I* and/or *II*.

B. Inverting amplifier post-test

In order to probe student understanding of the currents and voltages in a standard inverting amplifier circuit, versions of the question shown in Fig. 4 were administered after all relevant lecture and laboratory instruction.

In the circuit at right, the op-amp is ideal and there is no load connected to the circuit's output. $V_{in} = –5\text{V}$.

- What is V_{out}? **+2.5 V.**
- For points A–G, indicate the direction of current. If there is no current, state so explicitly. **See diagram.**
- Rank the currents through points *A–C* according to absolute value. **A = B = C**

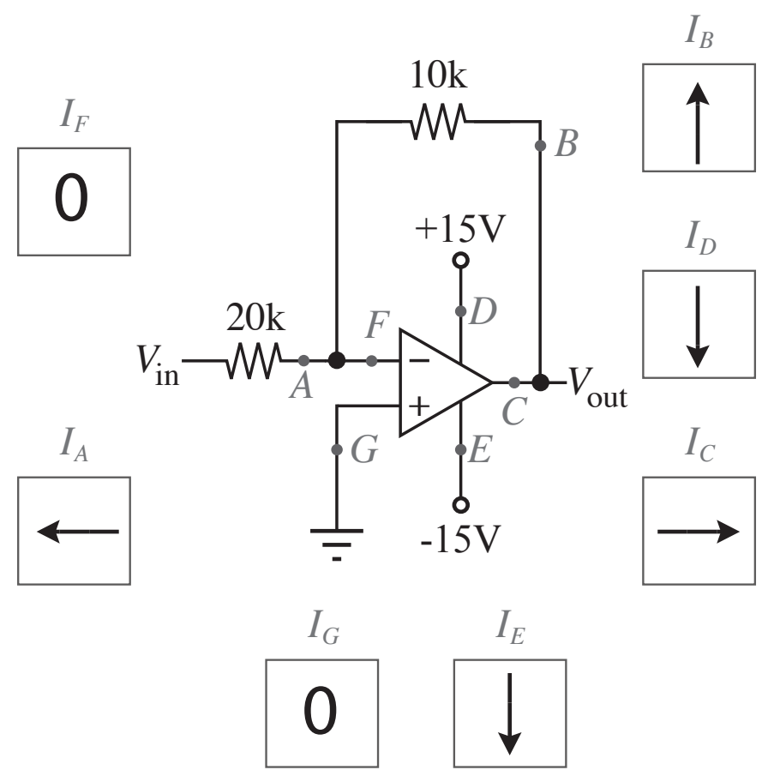


FIGURE 4. Original version of the inverting amplifier post-test question and correct answers.

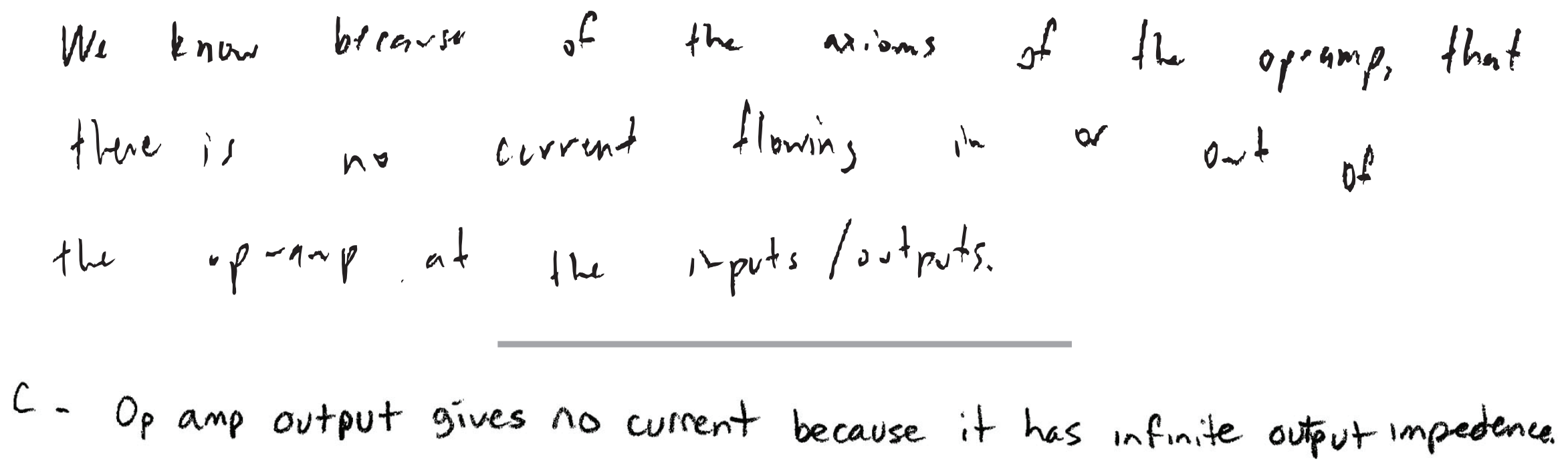
At all three institutions, approximately one-third of the students gave fundamentally incorrect responses for V_{out}. (See Table 3.)

Table 3. V_{out} (Fig. 4)	***% of responses*** **UW (N=183)**	 **UA (N=471)**	 **UMaine (N=8)**
Correct	**55%**	**55%**	**50%**
Sign error	15%	10%	15%

Roughly 40%-50% of all students: (1) correctly determined V_{out} and (2) indicated that $I_F = I_G = 0$ (consistent with *Golden Rule II*). Given that the responses from these students seemed to suggest at least a basic understanding of the behavior of the circuit, we report the performance of these students on the current ranking question in Table 4 below.

The most prevalent incorrect current ranking, A = B > C = 0, was given by approximately one-quarter of all students. (This ranking is inconsistent with Kirchhoff's junction rule.) A careful analysis of post-test responses suggests that students tended to use two different but related lines of reasoning to support this incorrect ranking. Examples of each are given below.

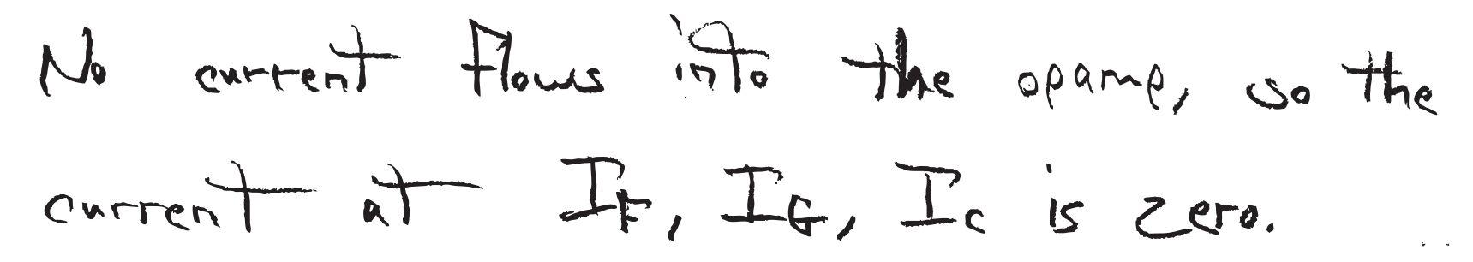
Table 4. Current ranking from inverting amplifier post-test (Fig. 4)	*Considering only those responses correct on V_{out} & $I_F = I_G = 0$* ***% of responses*** **UW (N=86)**	 **UA (N=181)**	 **UMaine (N=4)**
Correct (*A = B = C*)	**55%**	**20%**	**25%**
A = *B* > *C* = 0	20%	30%	25%
C > *A* = *B*	10%	10%	25%



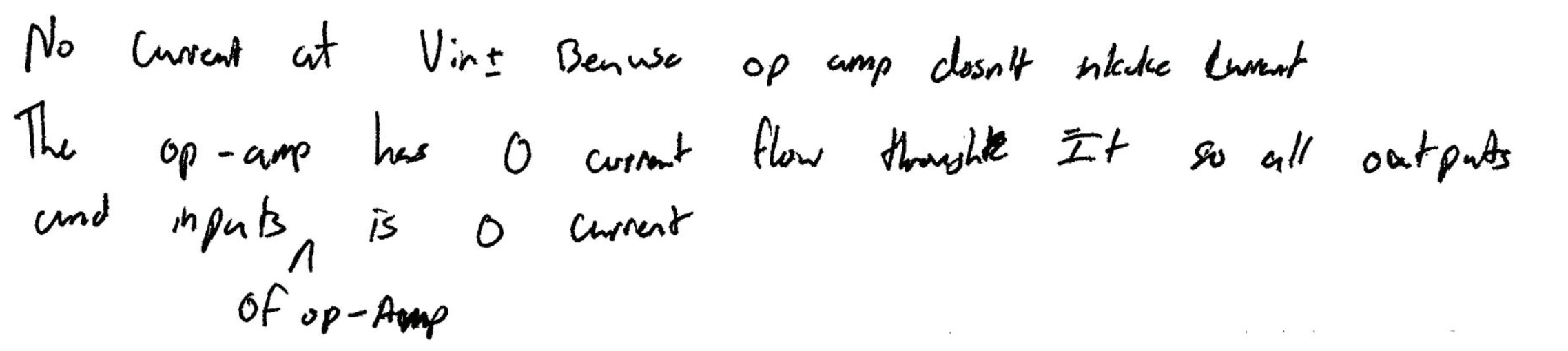
We know because of the axioms of the op-amp, that there is no current flowing in or out of the op-amp at the inputs/outputs.

C - Op amp output gives no current because it has infinite output impedence.

Tendency to generalize Golden Rule II inappropriately (i.e., no current into or out of any connection to op-amp)
~5% of all students



No current flows into the opamp, so the current at I_F, I_G, I_C is zero.



No Current at Vin± Becuse op amp dosn't intake Current The op-amp has 0 current flow throught It so all outputs and inputs of op-Amp is 0 current

Failure to recognize role of rails when applying Kirchhoff's junction rule (i.e., incorrectly assuming $I_F + I_G = I_C$)
~5% of all students

FIGURE 5. Reasoning used to support the idea that there is no current through point C.

Summary of findings

Results from op-amp post-tests administered at three different institutions suggest that, after lecture and hands-on laboratory instruction, many students:

- lack a functional understanding of the Golden Rules for op-amps
- fail to develop a robust understanding of the behavior of op-amp circuits (*e.g.,* currents)
- are not able to apply more basic circuits concepts productively in these contexts

References

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*This work has been supported in part by the National Science Foundation under Grant Nos. DUE-0618185 and DUE-0962805.