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WIP: Standards-Based Grading for Electric Circuits

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Abstract

The study of electric circuits is a common course (or courses) in most electrical and computer engineering programs. Several ECE courses depend on the fundamentals introduced and hopefully learned in the electric circuits course(s). Because mastery of each of these fundamental concepts is essential for future courses, the use of standards-based grading (SBG) is appealing, as it measures proficiency on an objective-by-objective basis.

SBG has been implemented in several fundamental undergraduate engineering courses, including fluid mechanics [2], thermodynamics [3], signals and systems [4, 5], and software verification [6]. In electric circuits, other grading strategies and interventions have been used, such as using team-based learning [7], reflection and metacognition [8], and mastery-based grading [9]. It should be noted that, while SBG and mastery-based grading are quite similar approaches, one major difference in the author's approach to SBG is that all-or-nothing mastery is not required on any assignment.

This paper studies the use of SBG in the author's freshman- and sophomore-level electric circuits courses at the Milwaukee School of Engineering (MSOE). In these electric circuits courses, course learning objectives have been identified based on program-approved course learning outcomes. An assessment schedule was created so that each CLO would be assessed multiple times throughout the course. Rubrics were developed for each CLO, and these were used to grade all assessment problems for the CLO. Proficiency on each CLO was assessed using these rubrics, and the final course grade was calculated from a weighted average of the objective assessment scores, combined with other assessments, such as homework and laboratory assignments.

This paper analyzes the effectiveness of the introduction of SBG in the introductory circuits course. The study consists of a comparison of course objective assessment between students who were enrolled in the author's Circuits I courses before and since the implementation of SBG. Although assessment of final exam data show a decrease in final exam objective performance after the implementation of SBG, course grades are unaffected by the change, and students are more aware of strengths and weaknesses in essential course objectives.

Comparison to similar works

Standards-based grading (SBG) is an assessment approach that has grown in use since its introduction in the early 1980s and subsequent implementations in the 1990s and early 2000s. In the 2010s its use extended into university-level engineering curricula. In 2016 several early adopters hosted a SBG workshop at the ASEE Annual Conference [1]. Some engineering instructors have documented the use of SBG in fundamental engineering courses, such as fluid mechanics [2], thermodynamics [3], signals and systems [4, 5], and software verification [6]. This paper extends from the author's efforts to implement SBG in introductory electric circuits courses for biomedical, computer, and electrical engineering students.

There have been many interventions to improve students' performance and concept retention in electric circuits courses. Narrowing the focus to papers that are concerned with strategies involving grading: using team-based learning [7] to motivate self-learning, using reflection and metacognition [8] to learn from early mistakes, and applying mastery-based grading [9] to motivate students to master course topics. It should be noted that the SBG approach described in this paper is quite similar to mastery-based grading, but there are some differences that distinguish the two approaches.

The end goals of SBG and mastery-based grading are similar: that students can identify which course topics need strengthening, and multiple attempts are given to demonstrate improved performance. In both approaches, major course topics are identified as course learning objectives (CLOs). Similarly, both approaches use homework, quizzes, and exams for formative and summative assessments.

Where the approaches differ is in the details. The mastery-based approach in [9] requires a student to demonstrate all-or-nothing mastery in each of ten fundamental topics on basic-level problems to pass the course. The quality of the passing grade is based on accumulation of points through regular homework submission as well as demonstration of extended topical knowledge on advanced-level exam problems.

In contrast, the author's SBG approach does not require all-or-nothing mastery on each course topic. Instead, each assessment (quiz or exam question) is scored based on the extent to which the student demonstrates mastery on the objective. For each objective, a student will have between two and four attempts to demonstrate improved performance. For objectives introduced early in the course, there will be one initial quiz, one make-up quiz for students needing to improve their initial quiz score, one midterm exam question, and one final exam question. For objectives which require synthesis of earlier course concepts and are introduced in the last two to three weeks of the term, there may be only one quiz and one final exam question. Quizzes typically consist of one or two basic- to moderate-level problems, whereas midterm and final exam questions involve moderate- to advanced-level problems.

Motivation for standards-based grading

The analysis of electric circuits is a fundamental topic to subsequent electrical and computer engineering courses. SBG is an attractive approach to grading fundamentals courses because it focuses on the assessment of individual course objectives rather than to focus on an overall grade for each assignment.

For students, SBG offers several advantages over traditional grading on a 0-100 scale. On the first day of class, students are given the list of CLOs, a grading table which shows how their grade connects to CLO assessment, and a schedule of homework, quizzes, and exams for assessing each CLO. Throughout the course, students can access and track their assessment scores for each objective. Students are given multiple opportunities to show improvement on each objective through quizzes, midterm examinations, and the final examination. Final grades are then computed as a weighted average of the objective assessment scores, as is described in the Grading section.

Changes from previous teaching methodology

Before the introduction of SBG, the course was taught using a traditional "chalk-and-talk" lecture style. The course was traditionally graded based on a weighted average of homework scores, laboratory scores, midterm exam scores, and the final exam score. Students would have only been aware of their performance on a course concept by identifying the concept(s) involved with a homework or exam problem and comparing their score to the standard institutional grading scale.

After the introduction of SBG in Spring 2020, the lecture style was intentionally not changed, except for adaptations due to the COVID pandemic. The course grading was changed to a weighted combination of objective assessment scores and homework and laboratory assignments. No major changes were made to homework and laboratory assignment grading. However, a schedule was created to assess each CLO two to four times throughout the course. For each CLO, a grading rubric was developed and used for grading quiz and exam questions. [An example rubric is included in Figure A3 in the Appendix.] Grades in the learning management system were arranged by objective scores so that students would be aware of their performance on each CLO.

For the instructor, the initial development of objectives, grading rubrics, assessment problems, and schedule requires prep work typically conducted during breaks between terms. However, grading time during the term is greatly reduced because less time is spent developing rubrics for each problem. Rubrics for each CLO can be updated and reused the next time the course is taught.

Implementation of SBG in electric circuits courses

This study was conducted by an electrical engineering faculty member at a medium-sized, teaching-focused university. The electric circuits courses at this institution form a three-trimester, one-year sequence: the first focuses on DC steady-state analysis; the second, AC steady-state analysis; and the third, transient circuit analysis. The author regularly teaches the first course and occasionally teaches the second and third courses. Enrollments in a single section range from the mid-teens to the mid-twenties. These three circuits courses are currently required for all biomedical engineering, computer engineering, and electrical engineering students. The first two courses have three hours of lecture and two hours of lab per week, whereas the third course has three hours of lecture and no lab.

The course learning objectives (CLOs) for the first circuits course, Circuits I, are listed in Table 1 on the following page. The CLOs for the other two circuits courses are included in the Appendix. These CLOs have been approved by EE program faculty.

A schedule was created for the introduction and assessment of these CLOs. Table 2 on the following page shows the homework and quiz assessment schedule for Spring 2021. For each week shown in the table, the corresponding homework assignment was due the end of the prior week. Homework solutions were then published for students to review over the weekend, and quizzes were given at the beginning of the subsequent week.

Table 1: CLOs for Circuits I

Learning objective	**SBG abbreviation**
Write and solve KCL and KVL equations using standard methods of circuit analysis for DC circuits, including symbolic DC circuits.	(Covered by multiple CLOs)
Demonstrate a standard of expertise in the understanding of circuit laws and in the analysis of electrical circuits.	(Covered by multiple CLOs)
Compute power calculations for a DC circuit.	Power
Analyze DC circuits that include ideal operational amplifiers.	Op amps
Use an organized process, strategy, or template in solving problems.	Organization*
Simplify electrical circuits using series/parallel resistance combinations, source transformations, and Thevenin's/Norton's theorems, including symbolic DC circuits.	Simplify
Solve a DC circuit problem using the superposition principle	Superposition
Demonstrate the use of nodal analysis in the solution of circuit problems	Nodal
Demonstrate the use of branch currents in the solution of circuit problems	Branch
Demonstrate calculator skills in solving simultaneous equations representing n-node circuit problems	Calculator*
Demonstrate the ability to analyze DC circuits using circuit simulation software	Simulation**
Demonstrate circuit laboratory skills and perform DC measurements	Lab skills**

* CLO was not assessed on the final exam.

** These CLOs were assessed using laboratory assignments.

Table 2: CLO assessment schedule for Spring 2021.

Week	CLOs assessed
3	Power
4	Simplify (emphasis on series/parallel)
5	Branch, calculator
6	Nodal, calculator
7	Superposition
8	Simplify (emphasis on Thevenin); make-up quiz for branch, nodal, or superposition
9	Make-up quiz for power, branch, nodal, or superposition
10	Op amp

Grading

For each of the three circuits courses taught using SBG, all assignments – homework and laboratory assignments, quizzes, and exams – are graded on a five-point scale. An example rubric with associated quiz and exam questions is included in the Appendix. The following table describes the general grading rubric used for each CLO assessment.

Table 3: General SBG rubric for circuits courses

Score	Label	Description
5	Exemplary	No errors
4	Advanced	One small error or two very small errors
3	Intermediate	One intermediate error or two small errors
2	Novice	One major error or two intermediate errors
1	Unacceptable	More than one major error
0	Incomplete	Student did not complete the assignment on time

Types of errors – major, intermediate, small, and very small – are judged at the instructor's discretion. Theoretical and conceptual errors are classified as major or intermediate, depending on how they impact the solution, whereas clerical and computational errors are typically classified as small or very small. Typical errors of each type are described in the grading rubric for each CLO, such as in Figure A3 in the Appendix. These rubrics are provided to students after the first quiz on each CLO.

The overall course score in Circuits I is computed by weighting each objective or assignment score as shown in Table 4. Grades are assigned according to the threshold levels shown in Table 5. Objective weightings for Circuits II and Circuits III are included in the Appendix.

Table 4: Objective weighting for Circuits I in Spring 2021

Objective or assignment	Assignments/quizzes/midterms*	Final exam*	Objective weighting*
Homework/participation	16%	-	16%
Laboratory assignments	18%	-	18%
Organization	3%	-	3%
Calculator	3%	-	3%
Power	5%	5%	10%
Simplify	5%	5%	10%
Branch	5%	5%	10%
Nodal	5%	5%	10%
Superposition	5%	5%	10%
Op amps	5%	5%	10%

*These percentages are based on the most recent offering of Circuits I.

Table 5: Grade assignment based on overall course score

Range	Grade
4.50-5.00	A
4.00-4.49	AB
3.50-3.99	B
3.00-3.49	BC
2.50-2.99	C
< 2.50	F

It is the author's experience that students who receive lower than a C in Circuits I rarely pass Circuits II on the first attempt; many often change majors or choose not to return the next term. Therefore, the CD and D categories were removed from the grading table, so that students with significant lack of understanding would be forced to repeat this course before proceeding to Circuits II.

COVID adaptations

Several adjustments were made to adapt to the COVID pandemic, which forced a sudden pivot to online instruction in Spring 2020 and hybrid instruction in Spring 2021.

In Spring 2020, after the COVID pandemic shut down in-person learning throughout the US, lectures were given synchronously in Microsoft Teams and OneNote and recorded for students who could not attend. Individual quizzes and exams were created for each student to limit and detect the possibility of academic misconduct. A common problem structure was used for each problem, but numbers and desired quantities varied for each student. The mail merge feature in Microsoft Office 365 was used to facilitate these individualized assessments. Lab assignments were modified to be largely simulation-based. Instructors collected experimental data, which were given to students to analyze and compare to theoretical expectations.

In Spring 2021, students were required to attend labs in person or use long-term checkout to complete the lab assignments remotely. However, due to social distancing requirements, not all students could attend in-person lectures simultaneously, and the practice of recording synchronous lectures continued. Individualized assessments were not used this term, but multiple versions of each assessment were created to hinder academic misconduct.

Comparison of student objective assessment pre- and post-SBG

The study consists of a comparison of final exam results between groups who took the course before and after the introduction of SBG during the Spring 2020 term. The hypothesis of this study is that the introduction of SBG will have improved students' awareness of deficiencies in their knowledge and application of each CLO in the first circuits course. To attempt to measure this change in awareness, final exam scores for each CLO are aggregated for each cohort in the control and experimental groups.

The control group consists of students who completed the Circuits I course with the author as instructor in Spring 2015, Spring 2016, and Spring 2017. Out of 88 students in this set, all but one student majored in electrical or computer engineering. Their final exams were retained and reassessed using current rubrics.

The experimental group consists of students who completed the Circuits I course with the author as instructor in Spring 2020 and Spring 2021. Out of these 51 students, 28 were electrical or computer engineering majors; the other 23 were biomedical engineering majors.

Figure 1 on the following page displays the average CLO assessment score with error bars marking 95% confidence intervals for each group – control (pre-SBG) and experimental (post-SBG).

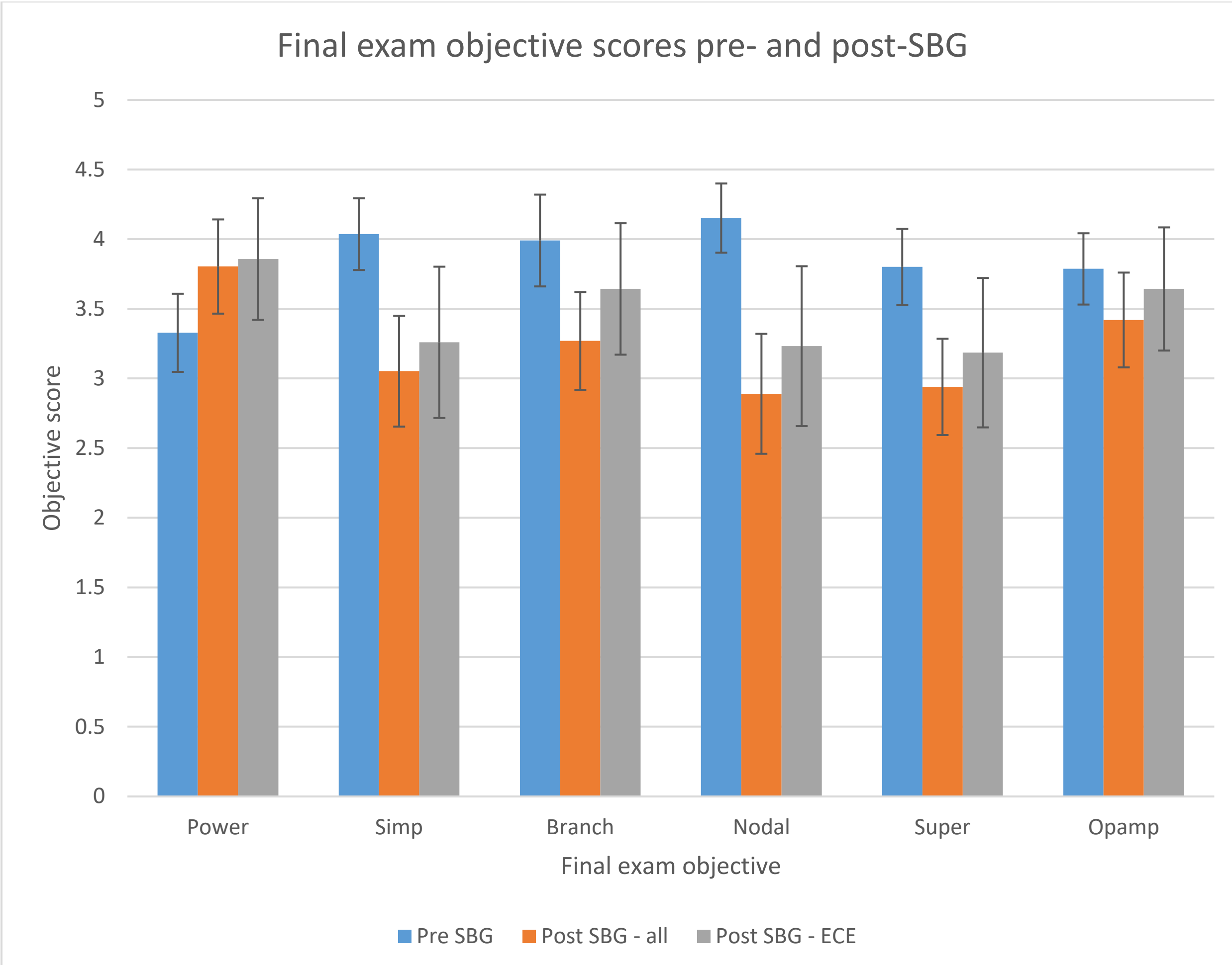

Figure 1: Aggregated final exam objective assessment scores for Circuits I.

There is a clear improvement in the power CLO, whereas the other CLOs show significant decline in scores. If the experimental group is restricted to electrical and computer engineering (ECE) students, there are still declines in each CLO except the power CLO, but the declines are not significant except for the Nodal CLO, as indicated by the non-overlapping error bars.

It should be noted that the final exams for each group differ, since the control group was not tested against SBG objectives. Students in the control group were given a six-problem final exam. Some of their problems mapped directly to one or two CLOs, such as the Op amp CLO or the Simplify (Thevenin) CLO, whereas other problems had an open-ended format, where students could choose their preferred analysis technique from among nodal, branch current, superposition, or Thevenin analysis techniques. In the experimental group, students were given a seven-problem final exam. Each final exam question mapped directly to one CLO; although not explicitly stated, it would have been obvious to each student by the wording of each problem which CLO was being tested.

It should be noted that the introduction of SBG did not significantly change the average overall class grade. The data in the following table (Table 5) show that 52% of students in the control group earned an A or AB, but 15% of the same group received grades of CD or lower. Conversely, only 33% of students in the experimental group earned an A or AB, but only 6% received an F (since CD and D grades were not given as noted in Table 5). It should be noted that students in Spring 2020 were given Pass or No Pass grades; the grades shown in the table are what they would have earned under normal circumstances.

Table 6: Final grades pre- and post-SBG.

Group	A	AB	B	BC	C	CD	D	F	GPA
Control: pre-SBG (n=88)	29	17	9	12	8	3	3	7	2.909
Experiment: post-SBG (n=51)	7	10	19	10	2	0	0	3	2.922

Conclusions

It is clear from the data in Figure 1 that the introduction of SBG did not improve, but in most cases worsened overall final exam performance except for the Power CLO. However, other factors may have contributed to this decline in final exam performance.

COVID pandemic: SBG was first implemented in the Spring 2020 term. All but the first week of classes (the term started in March) were conducted remotely only. All students were required to leave campus and return to their homes (some traveling out of the country) and resume instruction after a one-week pause. Students were not able to study and learn together as they had previously been able, and it is reasonable to assume that the added stress of studying remotely may have limited their ability to focus and perform to the best of their abilities.

Students in Spring 2021 were able to return to hybrid instruction. Several students were able to attend most lectures and labs in-person, whereas a few elected to work remotely for most of the lecture and lab periods. However, due to social distancing requirements and some of their other instructors electing to conduct classes remotely, these students had uncertain daily schedules, and it was challenging for students and instructors to fully engage when not all participants were present in person.

Addition of biomedical engineering students: Biomedical engineering students had previously taken the electric circuits courses for non-ECE majors before Spring 2020. The data in Figure 1 show that the mean CLO scores for the experimental (post-SBG) group are lower with the inclusion of BE students versus ECE students only. It should be noted that the post-SBG ECE students scored lower, on average, on most CLOs than the pre-SBG ECE students.

Final exams: The final exams for the control group were not structured for SBG assessment. Several problems were written as open-ended analysis problems, so that students could choose which analysis approach they understood best. Students in the experimental group were asked to answer each question using a specific analysis technique. Whereas this transparency was expected for students in the experimental group, they could not hide deficiencies in certain CLOs. Students in the control group might have had weaknesses that could have been masked by the open-ended approach questions.

Future work

To further improve the efficacy of the SBG approach, the following modifications are being proposed for the Spring 2022 term:

Mastery quizzes: Following the approach in [9], weekly quizzes testing each CLO would be assessed for mastery. Unlike the all-or-nothing approach, the author is considering allowing small errors, such as typographical and small calculation errors. Students who score less than a 4 (out of 5) would need to take another mastery quiz the following week in addition to the current week's mastery quiz.

Circuits concept inventory: Using a concept inventory such as the Electric Circuits Concept Inventory (ECCI) [10], measure students' conceptual knowledge at the beginning and at the end of the first circuits course to gauge their growth. Using other instructors' students as a control group, and the author's students learning under SBG as the experimental group, these concept inventory scores would be useful to show whether SBG is an effective intervention.

Restructuring the grading scale: It should be hard for a student to pass the course if they do not master each CLO at a basic level. Following the approach in [9], mastery quizzes testing conceptual knowledge at a basic level would be used to determine whether a student passes the class. Other assignments and moderate- to advanced-level problems on midterm and final exams would be used to determine the quality of the passing grade. The SBG rubrics will be maintained for grading basic level problems.

References

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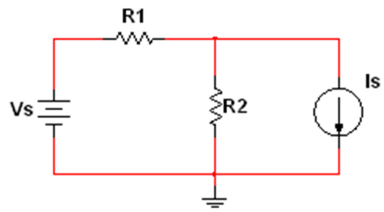
Appendix

Table A1: CLOs for Circuits II.

Learning objective	**Abbreviation**
Use an organized process, strategy, or template in solving problems	Organization*
Apply circuit laws and in the analysis of electrical circuits	(Covered by multiple CLOs)
Solve KCL and KVL systems of equations using standard methods of circuit analysis for AC circuits, including symbolic AC circuits	Standard analysis
Perform complex power calculations	Power
Analyze AC circuits with mutual inductors and transformers	Transformers
Demonstrate for simple filters the changing circuit performance as a function of frequency	Filters (assessed with Transfer function)
Derive frequency-domain transfer functions for passive and active circuits	Transfer function
Relate mathematical expressions of transfer functions to Bode plots	Bode
Represent a complex number in complex exponential form and convert complex numbers from polar to rectangular form, and vice versa, using Euler's identities	Euler*
Demonstrate calculator skills to solve circuit equations	Calculator*
Demonstrate the ability to analyze AC circuits using circuit simulation software	Simulation*
Demonstrate circuit laboratory skills and perform AC measurements	Lab skills*

Table A2: CLOs for Circuits III.

Learning objective	**SBG abbreviation**
Use an organized process, strategy, or template in solving problems	Organization*
Analyze and design series and parallel resonant circuits	Resonance
Determine the time-domain transient analysis response of a first-order circuit	1^{st} order
Determine the time-domain transient response of a second-order circuit	2^{nd} order
Graph the time-domain transient responses of first- and second-order circuits	Graphing*
Classify a second-order transient response as either underdamped, overdamped, or critically damped	(Combined with 2^{nd} order)
Use computer simulation tolls to do transient analysis	Simulation*
Determine Laplace transforms for simple time-based functions commonly used in the analysis of electrical and control systems	Transforms
Use Laplace methods to obtain voltages and currents in circuits having arbitrary input functions and initial conditions	Laplace
Derive s-domain transfer functions for simple RL, RC, and RLC circuits	Transfer functions



In the circuit to the left, use nodal analysis to determine

a. Voltage across R2 (with respect to ground)
b. Current to the right through R1

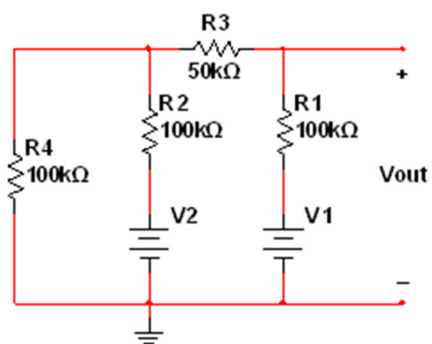
You must write at least one KCL equation in terms of unknown node voltages.

Use values as specified in the following table:

Vs	R1	R2	Is
5V	100Ω	400Ω	0.08A

Figure A1: Quiz question for Nodal CLO.

Consider the following 2-bit ladder digital-to-analog converter (DAC) circuit.



Use **nodal analysis** to determine the output voltage V_{out}

a. if V_1 and V_2 both represent logic-1; that is, if $V_1 = 5\ V$ and $V_2 = 5\ V$.
b. Repeat for $V_1 = 0\ V$ and $V_2 = 5\ V$.

Figure A2: Final exam question for Nodal CLO.

Exemplary solution:
- Correctly solved for the desired quantity or quantities with correct units
- Solution demonstrates correct use of nodal analysis
- No polarity errors can be found in the solution

VS errors (-0.5 point):
- Typo/scribal/math error that does not affect the sensibility of the final answer

S errors:
- Typo/scribal/math error that causes a noticeable KVL/KCL/Ohm error

I errors:
- Polarity error on a voltage or current
- Extra or missing current(s) in a KCL equation
- Simplification error changes part of the circuit

M errors:
- Simplification error drastically alters the circuit
- Voltage = current in a KVL or KCL equation
- Final answer does not make sense or has incorrect or missing units

Advanced (4): Two VS errors or one S error
Intermediate (3): Two S errors or one I error
Novice (2): One M error or two I errors or one I error and multiple S errors
Unacceptable (1): Solution does not use nodal analysis or more than one M error or more than two I errors

Figure A3: Rubric for assessing the Nodal CLO.