A testing system for diagnosing misconceptions in DC electric circuits

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Abstract

A testing-based diagnosing system is implemented. The system has a problem library that collects some suitable problems and associated answers. The answers of each problem are related to misconceptions. Problem selector in the system provides some problems to test student. Based on the student’s answers, the diagnoser in the system will discriminate the student’s misconceptions. The problem selector and the diagnoser are implemented with matrix operations. For evaluating the performance of the system, the topic of basic DC electricity is used as the subject domain. There are nine types of misconceptions found in basic electricity. Based on the experimental results, the system has the satisfactory diagnosis. © 1998 Elsevier Science Ltd. All rights reserved.

1. Introduction

Throughout the learning progress, students may not perform as expected due to many reasons and therefore some deficiencies in knowledge are formed. These deficiencies can be categorized into three types: discrepancy, uncertainty, and incompleteness. While uncertainties and incompleteness in knowledge can be addressed by remedial instruction, basic discrepancies must be corrected. Otherwise such discrepancies in knowledge will result in misconceptions that may form a serious barrier to the student’s learning progress. Once misconceptions in a certain knowledge domain are formed, how to diagnose these misconceptions is important to a student’s learning. The program to diagnose the student’s current state of knowledge is called the student model (VanLehn, 1988). In the past decades, many systems had been developed in order to diagnose students’ misconceptions. Based on previous research, the four types of student model are as follows:
1. Performance measure (Stansfield, Carr & Goldstein, 1976). This records the student’s test scores. It does not point out what knowledge has been acquired, only an assessment of “how much” knowledge has been acquired.

2. Overlay models (Carbonell, 1970; Brown, Burton & Zdydel, 1973; Carr, 1977; Burton & Brown, 1979; Brown & VanLehn, 1982; White & Frederiksen, 1985). This type of student model assumes the student’s knowledge is a subset of expert’s. The overlay models have to address a representation of difference between the student’s and the expert’s knowledge.

3. Buggy models (Stevens & Collins, 1977; Brown & Burton, 1978; Sleeman & Smith, 1981; Burton, 1982; VanLehn, 1987). In this model, student knowledge is represented as a set of bugs or misconceptions. The findings of bugs or misconceptions have to be considered in the design of buggy models.

4. Model tracing (Stevens, Roberts & Stead, 1983; Wenger, 1987; VanLehn, 1988). By analyzing the student’s behavior, an executable model is constructed to imitate student knowledge. The approach has to major the analysis of the correct rules and incorrect rules that students may use in the process of problem solving.

Although, there are different concerning problems for each model, two general difficulties must be dealt with in any of the above student models. The difficulties are as follows:

1. Rules construction. Most student models are built with rules using an artificial intelligence technique. Because of the problem of verifying rule correctness and completeness, construction of rules is difficult.

2. Efforts toward ideal student models. It is difficult to build an ideal student model using the current techniques. Self (Self, 1990) has suggested that an ideal student model may be overwhelmed by difficult problems.

Several approaches to making student modeling more tractable have been developed in recent years. Examples of less precision-oriented modeling approaches include bounded student models (Elsom-Cook, 1989) and granularity-based recognition of students’ problem-solving plans and strategies (Greer, McCalla & Mark, 1989). Baffes and Mooney (Baffes & Mooney, 1996) also suggested that modeling a student should be made both practical and effective. The above approaches demonstrate that student models need not be precise and accurate. After consulting these methods, a “practical student model” has to be implemented to record the student’s learning process, and to infer his or her knowledge state so as to provide information about what concepts must be enhanced. In this paper, we propose a testing system with matrix representation for diagnosing misconceptions in the subject matter of basic electricity. The testing system is one of practical student models used in a computer-assisted instruction or learning system for adapting the instruction to the student’s needs.

In the following, we first outline the proposed testing system, and misconception discrimination and diagnosis theories are discussed. Then, we implement the testing system with matrix representations. Finally, the experiments were finished to show the diagnosing performance of our system, and conclusions are presented.
2. Outline of testing system

The system structure is shown in Fig. 1. At first, we collect problems designed by teachers into problem library. A misconception candidate set, denoted as $S_c$, is defined to record the possible misconceptions in the diagnosing process. Our approach assumes that the student may have all misconceptions at the initial time and then diagnoser deduces the misconceptions he/she really exists. Initially, all misconceptions are in the misconception candidate set. In order to record the misconceptions that a student really has, we define a misconception set, denoted as $S_m$. The misconception set is initially empty.

The proposed system first uses problem selector to select appropriate problems from the problem library and presents them to students. When students have answered them, the diagnoser will collect the student’s answers. On the basis of the student’s answers, the diagnoser will infer which candidate’s misconceptions in $S_c$ are proven to exist in the student. The identified misconceptions will be put into the misconception set $S_m$. If diagnoser cannot identify the misconceptions the student really has, then the problem selector selects next appropriate problem to test student for discriminating the candidates. The process will continue until the student’s misconceptions are detected.

The diagnoser discriminates the candidate’s misconceptions based on the student’s answers. The problem selector gives the student additional problems to distinguish among student candidate’s misconceptions. By adding more problems, the test increases the effectiveness of the diagnosis. The problem library stores the testing problems. Each problem has related diagnostic meaning. The possible wrong answers of each problem are associated with some misconceptions. In other words, the student has a wrong answer for a problem, the diagnoser can clarify the candidate’s misconceptions related to the answer.
In order to evaluate the effectiveness of the testing system, we use the subject of basic DC electric circuits. At first, we survey misconceptions in the DC electric circuits by gleaning the previous literature as shown in Appendix A. There are nine misconceptions found in the surveying. Then, some problems and corresponding answers with diagnosing meaning are designed, based on the nine misconceptions. Finally, the testing system is implemented using matrix representations according to diagnosis theories that will be discussed in the following sections.

3. Misconception diagnosis

In order to diagnose a student’s misconceptions, the system has to collect a series of misconceptions from a subject domain. Then many test problems related to all misconceptions are designed. The relationships between test problems and misconceptions are established by a problem designer. Every wrong answer for any test problem has some corresponding misconceptions. In other words, if a student has answered “a” for the problem \( i \) and the answer is formed due to the misconception \( M_j \), the relation between answer \( PR_{ia} \) (answer “a” of problem \( i \)) and misconception \( M_j \) exists. Table 1 shows an instance of relationship of answers and misconceptions. Table 1 has six test problems and four types of misconceptions. There are two possible answers for Problem 1 and three possible answers for the rest of the problems. The relationship between answer and misconception is also shown in Table 1. For example, when a student answers \( PR_{1a} \) for problem 1, the student may have misconceptions \( M_1, M_3, \) or \( M_4 \). The relationships in Table 1 can be represented by equivalence classes as shown in Table 2. For instance, the equivalence class of \( PR_{1a} \) is a set of \( M_1, M_3, \) and \( M_4 \), denoted as \( C(PR_{1a}) = (M_1, M_3, M_4) \).

| Problem 1 | PR_{1a}: (M_1, M_3, M_4) | PR_{1b}: (M_2, C) |
| Problem 2 | PR_{2a}: (M_1, M_2) | PR_{2b}: (M_4) | PR_{2c}: (M_3, C) |
| Problem 3 | PR_{3a}: (M_1, M_3) | PR_{3b}: (M_2, M_4) | PR_{3c}: (C) |
| Problem 4 | PR_{4a}: (M_1, M_2, M_3) | PR_{4b}: (M_4) | PR_{4c}: (C) |
| Problem 5 | PR_{5a}: (M_1, M_2) | PR_{5b}: (M_3) | PR_{5c}: (M_4, C) |
| Problem 6 | PR_{6a}: (M_1, M_4) | PR_{6b}: (M_2, C) | PR_{6c}: (M_3) |
M4). The equivalence class $C(PR1a)$ indicates that the student has possible misconceptions $M1$, $M3$, or $M4$ if he/she answered $PR1a$ for problem 1.

Lee (Lee, 1988) used the set-intersection method to discriminate some student’s misconceptions. For example, a student has possible misconception $M1$, $M3$, or $M4$ as he/she chooses answer “a” for problem 1. In this case $C(PR1a) = \{M1, M3, M4\}$. Forthwith, having the student solve problem 2, if his/her answer is $PR2a$, he/she may have misconception $M1$ or $M2$, or $C(PR2a) = \{M1, M2\}$. The intersection of $C(PR1a)$ and $C(PR2a)$ is $\{M1\}$. So it deduces that the student has possible misconception $M1$ but has not $M2$ and $M3$. However, if a student answers “$PR1a$” and “$PR2c$” for problem 1 and problem 2, he/she might have possible misconception $M1$, $M3$, or $M4$ for $PR1a$ and possible misconception $M3$ for $PR2c$. The intersection of $C(PR1a)$ and $C(PR2c)$ is $\{M3\}$. That is to say, the student has misconception $M3$ to be diagnosed. Under this situation, to do any further problem about misconception $M3$ is not needed since the misconception has been diagnosed.

The set-intersection method can be simulated by a misconception discrimination tree. In a misconception discrimination tree as shown in Fig. 2, there is a problem at each non-terminal node, and there is a misconception (or a correct conception) at each terminal node. The directed edges connect answers and problems, answers and misconceptions, or answers and correct conceptions. The undirected edges connect answers and problems. For instance in Fig. 2, problem 4 is the first problem to be posed. If a student answers “$PR4a$”, he/she may have misconceptions $M1$, $M2$, or $M3$. Then, problem 6 would be chosen as the next problem to examine what misconceptions the student has. If “$PR6a$” is his/her answer on problem 6, then the only intersection is $M1$ that is what the student has.

Lee’s approach (Lee, 1988) assumed that a student initially did not have any misconception, then the system tried to find out whether his/her thought was correct or not. But, if some misconceptions are not included in the problem library, that is, without any adequate problems to diagnose these misconceptions, then the system may consider that the student does not have these misconceptions. The cause of this mistake is very serious, because the student may have
these misconceptions that are left undiagnosed. If the test problems are not exhausting, many
of the misconceptions might not be found. Each missed misconception could cause an
irretrievable result.

On the contrary, we suppose that a student has all misconceptions at the initial time, and
then delete the misconceptions that are identified to be non-existent in the student. Even if the
problem library is not ideal, that is, some misconceptions are not included in the problem
system, the worst of the diagnostic result is that the student has more apparent misconceptions
than he really has. The unfair treatment for the student is doing further corrections, and it is
not a loss for the student.

There is another disadvantage in Lee’s approach. Lee (Lee, 1988) considered that all
misconceptions have related answers in each problem. It is very difficult to design a problem
library where each problem has answers related to all misconceptions. Therefore, our approach
is to let a teacher design the relations between answers and misconceptions as possible, but not
involving all misconceptions into answers on a problem.

4. Theory of discrimination

In order to diagnose the exact misconceptions a student has, there must be a set of problems
to test the student. Based on the student’s answers to these problems, a diagnoser is used to
find the student’s misconceptions. The problems are collected as a misconception
discrimination set that is a set of problems able to diagnose which misconceptions the student
really has. Generally speaking, it is not necessary to have a student solve all problems but only
to find the misconception discrimination set. This way not only can a student avoid the
unnecessary problems, but the misconception discrimination set can show the most appropriate
problems to examine what misconceptions a student has.

The problem selector tries to find the misconception discrimination set. The first problem to
test a student is selected randomly. The next appropriate problem is the one where its answers
should cover as many misconceptions in $S_c$ as possible. If many problems are related to these
misconceptions, we must choose the best one among them. If these misconceptions are all
related to only one answer, the problem cannot aid discrimination of these misconceptions.
Thus, we hope the candidate’s misconceptions can be distributed over the answers of a
problem on average. For formulating the rules of problem selection, each problem will be
weighted a degree when it may be used to discriminate the misconceptions in $S_c$. The weight of
problem $i$ indicates the degree of distribution of candidate misconceptions over the answers for
problem $i$. For instance in Table 2, the distribution degree of problem 6 is larger than the
degree of problem 4 for candidate misconceptions (M2, M3, M4) because the candidates M2,
M3, and M4 are related to answers PR6a, PR6b, and PR6c respectively in problem 6, but
these candidates are only distributed over two answers for problem 4. The better selection of
test problems is the problem with the highest distribution degree. The distribution degree
(denoted as $d_i$) of problem $i$ for $S_c$ is defined as follows:
$d_i = \frac{1}{|p_i|} \sum_{j=1}^{|p_i|} R_{ij}$

(1)

where $|p_i|$ is the number of answers for problem $i$, and $R_{ij}$ is the relation function of $j$-th answer for problem $i$. $R_{ij}$ can be set in the following way:

$$R_{ij} = \begin{cases} 
1, & \text{if anyone in } S_e \text{ is related to the answer } j \text{ for problem } i. \\
0, & \text{otherwise}
\end{cases}$$

(2)

The $R_{ij}$ is recalculated at each time $S_e$ changed.

5. System design

The system structure of our test-based knowledge diagnosing system is shown in Fig. 1. The diagnoser and the problem selector are two major tasks, and their embedded theories are implemented with matrix representations.

5.1. Diagnoser

The diagnoser’s role is to determine the candidates in $S_e$ based on the student’s answer. The input to diagnoser is the student’s answer for a problem and its output is $S_e$. The diagnoser is designed as $m$ inputs and $n$ outputs, where $m$ is the number of all answers for all problems and $n$ is the number of misconceptions and correct conception. The operation in diagnoser is modeled by a weight matrix $H$ defined as below.

$$H_{ij} = \begin{cases} 
1, & \text{if answer } i \text{ is related to misconception } M_j, \\
-1, & \text{if answer } i \text{ is correct and misconception } M_j \text{ is related to the other answers of the same problem that answer } i \text{ belongs to.} \\
0, & \text{if answer } i \text{ is not related to misconception } M_j.
\end{cases}$$

(3)

The input to the diagnoser is represented as a unitary row vector $PR$. Any time, only one entry in $PR$ is 1 and the others are 0. For example, $PR_i = 1$ means the student chooses $i$-th answer. The output of the diagnoser is denoted as a row vector $MS$. The $MS$ is a simulation of $S_e$ and defined as follows:

$$MS_j = \begin{cases} 
-1, & \text{if misconception } M_j \text{ does not exist,} \\
1, & \text{if misconception } M_j \text{ may exist,} \\
0, & \text{if misconception } M_j \text{ is indeterministic.}
\end{cases}$$

(4)

Based on the input $PR$, the diagnoser will calculate the output $MS$ by the following formula.

$$MS = PR \times H.$$  

(5)

During the diagnosing process, some misconceptions are proved to be non-existent for the student. In this case, these misconceptions should not be involved in the following diagnosis.
Hence, these misconceptions have to be masked out in the following diagnosis. The mask-out is completed in the adaptive algorithm as below.

**ALGORITHM ADAPTATION**

FOR all outputs $j$ in the diagnoser DO

IF $MS_j = 1$ THEN $H_j = 0$ for all $i$

END ALGORITHM

At the end of the diagnosis, the misconception set $S_m$ is found by the decoding of weight matrix $H$. $S_m(j) = 1$, indicates that the student possess misconception $M_j$, if $\sum H_{ij} > 0$ for all $i$. $S_m(j) = 0$, means the student has not misconception $M_j$, if $\sum H_{ij} = 0$ for all $i$.

6. Problem selector

The problem selector accepts the data of candidates in $S_c$ and outputs an index to the next problem for discriminating these candidates. The selection principle of problem selector is based on the formula of Eq. (1). The degree of Eq. (1) is calculated each time $S_C$ changes. The dynamic calculation of Eq. (1) or operations in problem selector can be achieved by two matrices of $V$ and $W$ represented as follows.

$V_{ij} = \begin{cases} 1, & \text{if answer } j \text{ is related to misconception } M_i, \\ 0, & \text{otherwise}. \end{cases}$

$W_{jk} = \begin{cases} \frac{1}{|p_k|}, & \text{if the problem } k \text{ has the answer } j, \\ 0, & \text{otherwise}. \end{cases}$

where $|p_k|$ is the number of answers for problem $k$.

The operations of problem selector are described in the following formulas:

$A = MS \times V$

$P = A \times W.$

The outputs in $P$ are the distribution degree of problems for $S_c$ as the formula in Eq. (1). The problem with maximal degree is the one to be selected for next testing.

7. Experiment

We implemented our system in PC with Visual Basic language under the Windows environment. The system includes a problem selector, diagnoser, and problem library. The topic of basic DC electricity is selected for the subject domain. Nine types of misconceptions are derived after surveying the results of previous research (Dupin & Johsua, 1987; Shipstone,
These misconceptions are given in Appendix A. We also designed 20 basic electricity problems for diagnosing testing. But the number of key testing problems is only nine, as given in Appendix B. Table 3 shows the equivalence classes for these problems. The remaining problems have similar diagnostic meanings to the key problems. Based on our experiments, the number of problems selected for student testing is about 8–14.

The aim of the experiment is to find the diagnosing performance of our system in the physical testing environment. In the physical environment, the teachers are allowed to design the testing problems without the concerns of validity and reliability. Therefore, the proposed testing problems in the experiment are designed by concern with the relationship between answers and misconceptions only.

The experiment is done by interviewing and testing students. There are 28 low-achievement students in senior high school joining the interviewing and testing. After a student had completed the test, he/she must explain each piece of knowledge of basic electronics that corresponds to each misconception. If he/she can explain some piece of knowledge correctly, then he/she does not have this misconception; otherwise, he/she may have this misconception. According to the interview results, we make a comparison with the results of our system. The results of 28 students’ tests are summarized in Table 4. There are five students having no misconceptions that both results of interview and system testing are equal. However, in the interview process we find that nine students have only one misconception, but the system testing of two of them are not matched to the interview’s results. Table 4 shows the results of both the interview and system testing for 28 students.

The success rate of our diagnosing system is defined as

\[
\text{No. of students (Interviewing results } = \text{ Diagnosing results) / Total number of students}
\]

The experimental results in Table 4 show that the success rate of diagnosis is \((5 + 7 + 4 + 4 + 1)/28 = 0.75\).

The success rate of diagnosis in our proposed system cannot always achieve 100%. For example, in our experiment there are seven students in whom the diagnosing misconceptions are more than the actual misconceptions. The unfair treatment for these students is to let them do further corrections and it is no loss for the students.

During the experiment process, we found that the success rate of diagnosis may be affected by the following factors:

<table>
<thead>
<tr>
<th>Problem 1</th>
<th>PR1a: (M1)</th>
<th>PR1b: (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem 2</td>
<td>PR2a: (M2)</td>
<td>PR2b: (C)</td>
</tr>
<tr>
<td>Problem 3</td>
<td>PR3a: (M5, M6, M7)</td>
<td>PR3b: (C)</td>
</tr>
<tr>
<td>Problem 4</td>
<td>PR4a: (M5, C)</td>
<td>PR4b: (M8)</td>
</tr>
<tr>
<td>Problem 5</td>
<td>PR5a: (M5)</td>
<td>PR5b: (C)</td>
</tr>
<tr>
<td>Problem 6</td>
<td>PR6a: (M5, M6)</td>
<td>PR6b: (C)</td>
</tr>
<tr>
<td>Problem 7</td>
<td>PR7a: (M5, C)</td>
<td>PR7b: (M8)</td>
</tr>
<tr>
<td>Problem 8</td>
<td>PR8a: (M7)</td>
<td>PR8b: (M3)</td>
</tr>
<tr>
<td>Problem 9</td>
<td>PR9a: (C)</td>
<td>PR9b: (M3, M9)</td>
</tr>
</tbody>
</table>
1. A complete set of misconceptions for a specific domain is acquired.

Based on basic electricity, we got nine misconceptions. But the misconceptions, which we found by surveying the previous research, are not complete. That is, the diagnosis is based on an inaccurate set of misconceptions. In our experiment, the results showed that a student gave a wrong answer PR4b for problem 4 when we proved the student does not have misconception M8. In the interview with the student, we found the student had a new type of misconception. The student thought the resistance of bulb L1 was larger than the total resistance of bulbs L2 and L3, and he also thought the light of a bulb was proportional to its resistance. So the student answered that L1 > L2 = L3.

2. The test problems.

Students usually solve problems by analogy. We should avoid a problem with several comparable answers where the student can easily figure out the correct answer by guess. In fact, it is not easy to design an ideal problem system which includes the tests to all misconceptions of a specific domain.

3. The reaction of the students.

Twenty-eight students were chosen in this experiment. Seven of them were approved that they had more misconceptions than they actually had. We tried to ask them why they still chose the wrong answers when the misconception did not exist on their minds. They did not know why they chose incorrect answers. The conclusion may be that the partial knowledge of the student is always in a puzzle or the student did not pay attention in the experiments.

8. Conclusions

This paper proposed a test-based diagnosis system for misconceptions in DC electric circuits. The system is mainly divided into three parts: problem library, problem selector and diagnoser. The system provides some test problems. Based on the students’ answers, the system will again provide other appropriate problems to discriminate and diagnose misconceptions the student really has. The principle of discrimination is derived from the Lee’s approach (Lee, 1988). The
Lee’s approach is modified to meet more requirements at the practical diagnosis. With our diagnosis rules, the diagnoser and the problem selector are implemented with matrix operations.

Two critical points emerged from our system. The first is that it is not necessary to consider all misconceptions in the related answers. The second point is that we suppose a student has all misconceptions at the initial time, and then delete the misconceptions that do not exist. The two points are not considered in Lee’s approach.

The performance of the proposed system has been evaluated by experiments. For the achievement of the experiment, basic DC electricity is used as the subject domain. Nine types of misconceptions and testing problems are found in the basic electricity. The experimental results show the system can support satisfactory diagnosis and conclude some factors affected to the performance of diagnosis.

Acknowledgements

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Appendix A. Analysis of misconceptions in DC electric circuits

Over the past decades, various studies on misconceptions of basic electricity have been made focusing on many aspects and generating numerous results. In the area of series circuits, Carlsen and Andre (Carlsen & Andre, 1992) have shown a developmental sequence of misconceptions about electric circuits. In addition to simple series circuits, a more general consideration of basic DC circuit configurations, including parallel circuits, was adopted in Dupin and Johsua’s study (Dupin & Johsua, 1987). Shipstone et al. (Shipstone, 1988) made a study of the understanding of basic electrical concepts by 15–17-year-old students in five European countries. According to these studies, we conclude all the results and reorganize as nine primitive misconceptions in the following:

(M1) **Current existence**: the student believes that a single wire connection between a battery and a bulb will light up the bulb. But the student does not know that the existence of current is associated with the condition of closed circuit.

(M2) **Voltage existence**: a large number of pupils know that current only exists in a closed circuit, but they also believe it is the same for voltage.

(M3) **Weakening of current**: the student believes that current flows around the circuit in one direction and becomes weakened as it goes so that the later circuit elements receive less current.

(M4) **Division of current**: the student believes that current flows around the circuit in one
direction and is shared equally by the circuit components, but is partially or completely used up in the circuit components.

(M5) **Battery role:** the student believes that the battery is a “current reservoir” delivering a constant current whatever the circuit attached.

(M6) **Current in series circuit:** many students believe that currents are the same in two contrasting circuits while ignoring the doubled resistance in the series circuit.

(M7) **Voltage in series circuit:** the student regards voltage the same as the current in the series circuit and guesses that all voltages crossing components in the series circuit are the same.

(M8) **Current in parallel circuit:** a large number of pupils believe that bulbs in parallel would shine less than a single identical bulb.

(M9) **Voltage in parallel circuit:** the student believes that branch voltages in the parallel circuit are different.

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**Appendix B. The key testing problems of basic electricity**

Q1: Will this bulb be lightened? (a) Yes, (b) No.

![Diagram of a series circuit with a battery and a bulb.]

Q2: Does a voltage exist? (a) Yes, (b) No.

![Diagram of a parallel circuit with a bulb and a resistor.]

Q3: Compare the brightness of L1, L2, and L3. (a) L1 = L2 = L3, (b) L1 > L2 = L3, (c) L1 > L2 > L3.
Q4: Compare the brightness of L1, L2, and L3. (a) L1 = L2 = L3, (b) L1 > L2 = L3, (c) L1 = L2 > L3, (d) L1 = L3 > L2.

Q5: Compare the brightness of L1 and L2. (a) L1 = L2, (b) L1 < L2.

Q6: Compare the current amount of I1, I2, and I3. (a) I1 = I2 = I3, (b) I1 > I2 = I3, (c) I1 > I2 > I3.
Q7: Compare the current amount of $I_1$, $I_2$, and $I_3$. (a) $I_1 = I_2 = I_3$, (b) $I_1 > I_2 = I_3$, (c) $I_1 = I_3 > I_2$.

Q8: Compare the voltage amount of $V_1$, $V_2$, and $V_3$. (a) $V_1 = V_2 = V_3$, (b) $V_1 > V_2 > V_3$, (c) $V_1 > V_2 = V_3$.

Q9: Compare the voltage amount of $V_1$, $V_2$, and $V_3$. (a) $V_1 = V_2 = V_3$, (b) $V_1 > V_3 > V_2$, (c) $V_1 > V_2 = V_3$. 
References


