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Comparing problem solving performance of physics students in inquiry-based and traditional introductory physics courses

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Performance of students in an introductory inquiry-based physics class is compared with that of students in three other introductory physics courses on two different examination problems. One problem is a qualitative problem, typical of those used in inquiry-based physics. The second problem is a quantitative problem, similar to those found in a standard introductory physics text. The students in the inquiry-based physics course were all elementary education majors. They performed significantly better than the engineering students and as well as the honors physics students on the two problems used.

I. INTRODUCTION

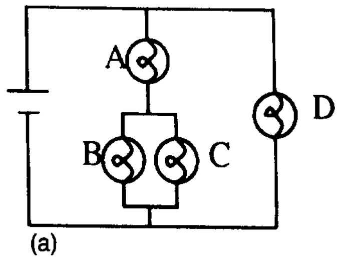
Research has shown that many students taught introductory physics in the standard lecture-recitation format learn to solve quantitative problems well (as indicated by good course grades) but do not develop an understanding of physics concepts different from their initial common sense (mis)conceptions.[1–6] If the goal of introductory physics is both teaching students to solve quantitative problems and inducing a correct conceptual understanding, then our courses are not successful.

Courses have been designed which explicitly focus on changing the conceptual understanding of students.[7–12] However, comparing physics courses taught in the traditional format with nontraditional courses is difficult because often the goals, the emphasis, and, therefore, the problems used to assess understanding and knowledge in the two types of courses differ significantly. It is not possible to assess a student's qualitative understanding of physics by examinations which contain only problems requiring quantitative solutions. In order to compare traditionally taught students with those taught nontraditionally, it is desirable to use both quantitative and qualitative problems in assessing both groups of students.

This type of assessment has been done in the context of the calculus-based introductory course at the University of Washington, as part of the evaluation of a lecture-based course with tutorials.[8,13] The course differed from a traditional course only by the replacement of one of the lectures with a tutorial session each week. Unlike traditional recitation sessions, which emphasize quantitative problem solving, the tutorials focus on deepening student conceptual understanding. Students in the course with tutorials performed markedly better than students in a traditional lecture-based course (without tutorials) on both qualitative and quantitative problems.

Previous studies[4,12,13] have compared courses which emphasize quantitative problem solving but are taught in ways designed to improve conceptual understanding as well. Our study compares traditional courses with an inquiry-based course which differs completely from other courses in format, content, and design. *Physics by Inquiry*,[7] a laboratory-based set of modules, uses research on student understanding of physics to guide curriculum design[14] and emphasizes con-

1a) All of the bulbs in Figure 1 have the same resistance R. If bulb B is removed from the circuit, what happens to the current through (brightness of) bulb A, bulb D and the battery? Indicate whether it increases, decreases or remains the same. Explain your reasoning.



1b) A wire is added to the circuit as in Figure 2. What happens to the current through (brightness of) bulb A, bulb D and the battery? Indicate whether it increases, decreases or remains the same. Explain your reasoning.

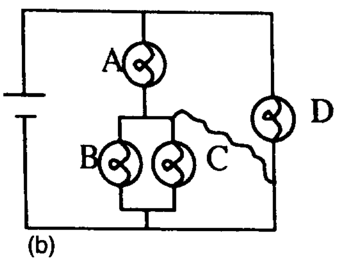
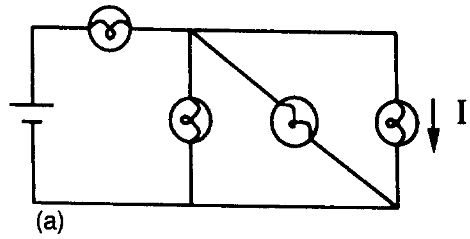


Fig. 1. (a) Synthesis (qualitative) problem, part A. (b) Synthesis (qualitative) problem, part B.

2a) What is the total resistance of the network shown in Figure 3? (All of the bulbs have the same resistance R.) Show your work.



2b) What is the current through (brightness of) each bulb and through the battery? (All of the bulbs have resistance R and the current through the bulb on the right is I as indicated.) Show your work.

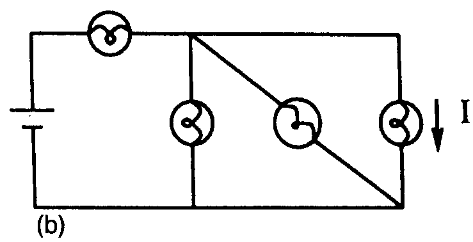


Fig. 2. (a) Analysis (quantitative) problem, part A. (b) Analysis (quantitative) problem, part B.

ceptual understanding rather than quantitative problem solving. For the past three years, *Physics by Inquiry* modules have been taught to elementary education majors at The Ohio State University (OSU). As part of the assessment of this inquiry-based course, we have designed two examination problems to be included on midterm or final examinations in four different introductory physics courses. One problem is qualitative and the other is quantitative. This procedure allowed us to do a rigorous comparison of the problem solving skills of students taught by inquiry in a laboratory-based course with those of students taught traditionally in lecture-based courses.

The qualitative problem, which we will also refer to as the synthesis problem, is a typical examination problem in the *Physics by Inquiry* course. It can be solved without any calculation using reasoning based on a model of current flow in dc electric circuits. The problem can, however, also be done quantitatively. The quantitative problem, which we will also refer to as the analysis problem, is similar to typical examination problems in traditional courses. Simple calculations must be done to obtain the correct answer. Both problems were placed on examinations in four courses: *Physics by Inquiry* (202), Honors Physics (H132), the standard calculus-based physics course for engineering students (132), and another introductory physics course for nonscience majors (102). The instructors for all courses were asked to review the problems to ensure they were appropriate to the material covered in their course. All of the instructors considered the problems appropriate.

In Sec. II we describe the two problems. In Sec. III we

Table I. Time spent in lecture, laboratory, and recitation each week.

Class	Hours lecture per week	Hours laboratory per week	Hours recitation per week	Hours total per week
H132 (honors)	5	2	0	7
202 (inquiry)	0	6	0	6
132 (engineers)	3	2	2	7
102 (nonscience)	3	2	0	5

Table II. Information on exams given in different classes.

Class	Time spent on dc circuits before exam	Length of exam	Total number problems on exam
H132 (honors)	1 week	2 h	6+2 bonus
202 (inquiry)	2 1/2 weeks	75 min	4
132 (engineers)	2 weeks	1 h	4
102 (nonscience)	1 week	55 min	10

describe the students and the courses. In Sec. IV we present the results, and in Sec. V we state our conclusions.

II. DESCRIPTION OF THE PROBLEMS

The synthesis problem is shown in Fig. 1 and a solution is given in the Appendix. The problem can be done completely qualitatively; no quantitative calculations are necessary. However, the correct solution can also be obtained quantitatively using Ohm's Law. An answer was considered completely correct only if it contained a correct equation and/or a correct explanation indicating *why* the current increased, decreased, or remained the same through bulbs A and D and through the battery. For example, in part A, the statement, "Bulb D is unaffected," was counted as incomplete because the statement does not address *why* bulb D was unaffected. As is customary, the batteries were assumed to be ideal and the bulbs were assumed to be ideal resistors.

The analysis problem is shown in Fig. 2 and a solution is given in the Appendix. Some quantitative calculation is necessary for solution. Again, an answer was considered completely correct only if a correct equation and/or a correct explanation was used to obtain the solution. In part B, the question asked for the current through the battery and for the current through three of the four bulbs. An answer which omitted the current through the battery or through one of the bulbs was counted as incomplete and therefore not completely correct. In part A, $4R/3$, $R+R/3$, and $R+(1/R+1/R+1/R)^{-1}$ were accepted as correct, but $R_A+(1/R_B+1/R_C+1/R_D)^{-1}$ was not accepted as correct, because in this case the student failed to recognize that the bulbs all had the same resistance. Again, the batteries were assumed to be ideal and the bulbs were assumed to be ideal resistors.

III. DESCRIPTION OF THE STUDENTS AND THE COURSES

A comparison of class time, time spent on dc electric circuits, exam length, and other general statistics for each class are given in Tables I and II.

Table III. Results for the synthesis (qualitative) problem.

Class	Completely correct	Part A correct	Part B correct	Number of students
H132 (honors)	1 (4%)	4 (14%)	2 (7%)	28
202 (inquiry)	7 (29%)	18 (75%)	8 (33%)	24
132 (engineers)	5 (2%)	9 (3%)	5 (2%)	239
102 (nonscience)	0 (0%)	0 (0%)	0 (0%)	40

Table IV. Results for the analysis (quantitive) problem.

Class	Completely correct	Part A correct	Part B correct	Number of students
H132 (honors)	16 (57%)	27 (96%)	16 (57%)	28
202 (inquiry)	4 (17%)	13 (54%)	7 (29%)	24
132 (engineers)	15 (6%)	71 (30%)	18 (8%)	239
102 (nonscience)	1 (3%)	1 (3%)	1 (3%)	40

A. Inquiry-based physics

The inquiry-based course had 24 students, all of whom were elementary education majors. Three of them (12%) had taken a physics course before this one. The "hands-on, minds-on" laboratory course covers electric circuits (about 3/5 of the course) and optics (about 2/5 of the course). The students, working in cooperative groups of four or five, learn to develop their own conceptual models based on their own experiments. They are assisted by a set of *Physics by Inquiry* modules,[7] an inquiry-trained instructor, and their peers. Groups work at their own pace. The role of the instructor and the materials is to guide the students by asking questions to help them learn to think critically and develop concepts on their own. A more detailed description of an inquiry-based physics course has been presented by Arons,[15,16] McDermott *et al.*,[17,18] Quattrone and Courville,[19] and Kahn and Strassenburg.[20]

The course meets twice a week for 3 h. The inquiry course examination was given about three weeks into the course. It

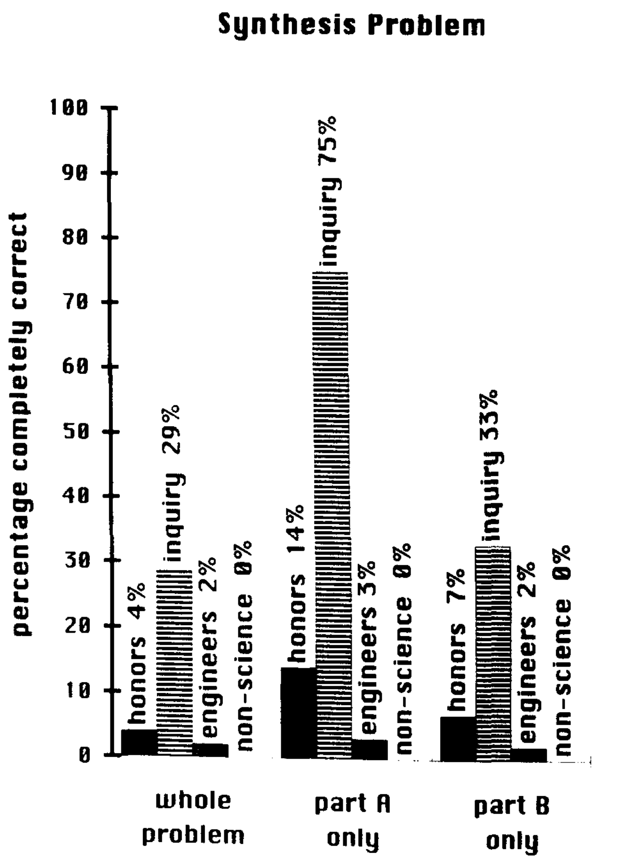


Fig. 3. Percentage of students providing completely correct answers for the synthesis problem and for parts A and B separately.

consisted of four problems. The other two were of roughly the same difficulty as the two discussed here. The students were given 75 min to complete the examination. All students finished the exam and did not feel rushed.

The students had not yet done any quantitative problems and had not studied Ohm's Law at the time of the examination. They had developed the inverse relation between current and resistance and qualitatively studied resistances in series and in parallel. They had not studied the concept of voltage, which would be needed to solve the problem using Ohm's Law. Their solutions to the problems are based on a model of current flow in dc electric circuits built on the assumption that the brightness of a bulb is proportional to the current flow through that bulb. The course staff expected them to do well on the synthesis problem and not very well on the analysis problem.

B. Honors physics

The physics honors students are students who have applied for admission to honors physics. If necessary, enrollment is limited, with cuts made based on mathematics background, ACT/SAT scores, grade point average (high school), and physics background. In the year of the sample, no cuts were made. The difference between the honors course and the standard calculus-based course is the level of mathematics used and the depth of the course. The same topics are covered in both courses, so that a student can switch from one to another if necessary. The course content includes electric potential, current, resistances in series and parallel, power, and L,R,C combinations. The text is Halliday and Resnick.[21] There are five lectures and one laboratory each week. There are no recitations.

In the honors course the two problems were given as bonus questions on the final examination, after students had completed their study of dc circuits. Two out of 30 students did not work the problems. The data include only the 28 students who did work the problems. The instructor teaching the course said he did not teach the material explicitly, because he assumed that the students already understood it.

C. Engineering physics

The calculus-based engineering physics course had 239 students. Most of the students are engineering students, but some are medical students or physics majors. The content is the same as for the honors course. The text is also Halliday and Resnick.[21] The course meets for three lectures and two recitation sections each week. The recitation sections each have about 20 students. There is also a weekly laboratory session.

The questions were administered on the midterm examination after the students had studied dc circuits. The examination consisted of four problems, approximately equal in length and difficulty, including these two problems. The students were given 1 h to complete the examination. Most students finished in the allotted time. The instructor felt that the problems were appropriate to the material covered.

D. Physics for nonscience majors

The 102 course was designed to teach physics to students with little mathematics background. Sixty-five percent had taken a high school physics course. There were 20 different majors among the 40 students. The course met for three lectures and one 2 h laboratory each week.

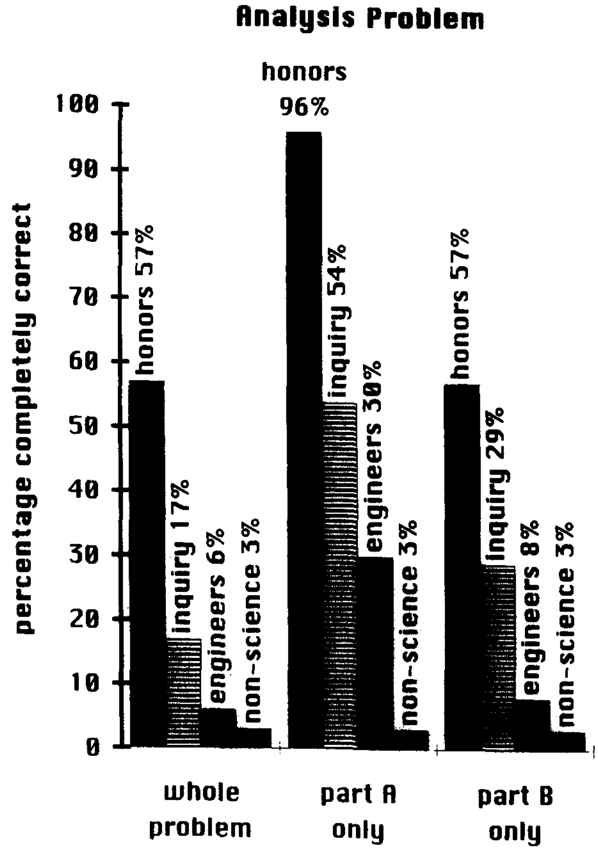


Fig. 4. Percentage of students providing completely correct answers for the analysis problem and for parts A and B separately.

The midterm examination, administered after coverage of dc circuits, consisted of 10 problems including these two problems. The other problems were shorter than these two. The students were given 55 min to complete the examination. Most of the students finished in the allotted time. The course staff thought that the problems were above the knowledge level of the students, even though Ohm's Law and resistors in series and in parallel had been discussed in class.

IV. RESULTS

Tables III and IV give the number of students in each class and the number who solved the problems correctly. Data are

Table V. Chi-squared comparison for the synthesis (qualitative) problem.

Classes compared	Degrees of freedom	Chi-squared value	Significance level
H132, 201, 132, 102	3	46.8	<0.000 01
H132, 132, 102	2	1.3	0.52
201 and H132	1	6.5	0.011
201 and 132	1	36.5	<0.000 01
201 and 102	1	13.3	0.000 27
H132 and 132	1	0.3	0.58
H132 and 102	1	1.5	0.22
132 and 102	1	0.8	0.37

Table VI. Chi-squared comparison for the analysis (quantitative) problem.

Classes compared	Degrees of freedom	Chi-squared value	Significance level
H132, 201, 132, 102	3	72.1	<0.000 01
201, 132, 102	2	5.0	0.08
201 and H132	1	8.8	0.003
201 and 132	1	3.7	0.05
201 and 102	1	4.1	0.04
H132 and 132	1	62.0	<0.000 01
H132 and 102	1	26.2	<0.000 01
132 and 102	1	0.9	0.34

Table VIII. Chi-squared comparison for the synthesis problem, part B.

Classes compared	Degrees of freedom	Chi-squared value	Significance level
H132, 201, 132, 102	3	51.6	<0.000 01
H132, 132, 102	2	3.9	0.14
201 and H132	1	5.7	0.02
201 and 132	1	45.3	<0.000 01
201 and 102	1	15.2	<0.000 01
H132 and 132	1	2.5	0.11
H132 and 102	1	2.9	0.09
132 and 102	1	0.9	0.34

also given for each problem part separately. Only students providing completely correct answers, as defined in Sec. II, are included in the columns for correct solutions. We did not attempt to award partial credit because of its subjectivity and dependence on the grader. A detailed analysis of student responses is in progress. However, some areas already analyzed relate to the validity of the problems. In the analysis problem, we checked to see whether students failed to realize that three of the bulbs were in parallel due to the way the circuit was drawn. None of the honors physics students, 2% of the engineers, 12% of the inquiry students, and 12% of the nonscience majors failed to recognized that three of the bulbs were in parallel. In addition, we checked to see whether students were answering correctly, but had no explanation or insufficient explanation. This was not the case. Students with incorrect answers backed those answers with incorrect explanations and students with correct answers backed their answers with correct explanations, in all classes. Student responses indicated that there was no misunderstanding of the wording of the problems and of the type of response requested. We reiterate that except for the 102 class, all the instructors agreed that the problems were appropriate for their students in length and level of difficulty.

In Figs. 3 and 4 we graph the percentage of students in each course with completely correct solutions. We also graph the two parts of each problem separately. On both problems a higher percentage of the students in all groups except 102 were able to do part A, while part B was significantly harder.

We used the chi-squared test to determine whether the performance of students in the different classes was significantly different on the two problems or on the individual parts of the problems. We considered groups to be significantly different when the chi-squared value was at or below the 0.01 significance level (at least 99% confidence that they are different) and to be the same above the 0.1 significance level. Values between 0.1 and 0.01 indicate a possible difference, but require more data to increase the certainty of the conclusion.

The classes were compared as a whole and in groups of two and three. The results are given in Tables V–X. The inquiry (202) students did significantly better on the synthesis problem than all of the other classes. The other classes were not significantly different from one another on that problem. The honors (H132) class did significantly better than all of the other classes on the analysis problem. The 102 (nonscience) students and the 132 (engineering) students were not significantly different on that problem. The inquiry (202) students did somewhat better than 102 and 132 students, but significantly below the honors class.

V. CONCLUSIONS

Clearly the inquiry-based students (202) did far better on these problems than the 102 students. Both groups are nonscience majors. More 102 students had taken a physics class previously. The 102 students were less prepared for the synthesis question, but more prepared for the analysis question than the 202 students. The much higher scores of the inquiry-based students indicate that the inquiry-based method of teaching may be superior to traditional methods for nonscience majors.

The comparison of the inquiry students (all elementary education majors) with the engineers is also significant. On all parts except part A of the analysis question the inquiry students did much better than the engineers. On part A of the analysis problem they were still somewhat better, although

Table VII. Chi-squared comparison for the synthesis problem, part A.

Classes compared	Degrees of freedom	Chi-squared value	Significance level
H132, 201, 132, 102	3	135.6	<0.000 01
H132, 132, 102	2	8.9	0.011
201 and H132	1	19.5	<0.000 01
201 and 132	1	120.1	<0.000 01
201 and 102	1	41.7	<0.000 01
H132 and 132	1	6.0	0.014
H132 and 102	1	6.1	0.014
132 and 102	1	1.6	0.21

Table IX. Chi-squared comparison for the analysis problem, part A.

Classes compared	Degrees of freedom	Chi-squared value	Significance level
H132, 201, 132, 102	3	72.8	<0.000 01
201, 132, 102	2	21.4	<0.000 01
201 and H132	1	13.0	0.000 31
201 and 132	1	6.0	0.014
201 and 102	1	23.4	<0.000 01
H132 and 132	1	48.0	<0.000 01
H132 and 102	1	60.0	<0.000 01
132 and 102	1	13.3	0.000 26

Table X. Chi-squared comparison for the analysis problem, part B.

Classes compared	Degrees of freedom	Chi-squared value	Significance level
H132, 201, 132, 102	3	65.3	<0.000 01
201, 132, 102	2	15.2	0.000 5
201 and H132	1	4.1	0.04
201 and 132	1	11.9	0.000 56
201 and 102	1	9.8	0.001 7
H132 and 132	1	55.5	<0.000 01
H132 and 102	1	26.2	<0.000 01
132 and 102	1	1.4	0.27

more data would increase the certainty of this conclusion. In short, the inquiry students outperformed the engineering students on both the traditional physics problem and the qualitative problem.

The inquiry students also did better than the honors students on the synthesis problem, while the honors students did better on the analysis problem. Here it is clear that each group of students did better on the type of problem they were accustomed to. The chi-squared value for these two classes with both problems combined indicates no significant difference between the performance of the two groups overall. That is, considering both problems together, the performance of the honors physics students is indistinguishable from that of the inquiry students.

The better performance of the inquiry students when compared to that of the engineering students raises the question of whether inquiry-based instruction is superior to traditional instruction for science and engineering majors. It is possible that the size of the classes (24 for inquiry, 239 for engineering) might affect the results in this case. However, the honors students and the inquiry students have comparable class sizes (respectively, 28 and 24). Although each group performed better on the type of problem they were accustomed to, overall their performances were indistinguishable.

Other differences in classes include the amount of time spent on electric circuits, the amount of time spent in laboratory, the amount of personal contact each student receives from the instructor, etc. It is true that all of these variables may contribute to the differences in scores and that further studies may isolate some factors as more important than others. We would like to emphasize, however, that the point of inquiry-based instruction is to allow students to spend more time on a topic, to allow more interaction time between students, to change the role of the instructor from lecturer to guide, and to give students a laboratory environment in which to develop their own conceptual understanding. It is designed to be radically different from traditional instruction. In this study, we considered the inquiry-based course as a whole, without isolating individual differences from the traditional course. Since the inquiry students, elementary education majors, initially have less knowledge of physics than the other students (in particular less than the honors students, with comparable class size), we are forced to consider the conclusion that inquiry-based instruction is superior to traditional instruction. We hope that further studies will continue to test the validity of this conclusion.

ACKNOWLEDGMENTS

We thank the instructors of the courses for generously including these questions on their examinations. We also thank Lillian C. McDermott and Leonard Jossem for their helpful comments on the manuscript. One of us, B. A. T., is grateful for a fellowship from the College of Mathematical and Physical Sciences at OSU.

APPENDIX: PROBLEM SOLUTIONS

We give both a more qualitative and a more quantitative solution to each problem.

1. An acceptable qualitative solution to the synthesis problem

Part A [Fig. 1(a)]: Assume that the battery is ideal and that the bulbs are ideal resistors. Label the branch containing bulbs A, B, and C branch 1, and the branch containing bulb D branch 2. Since the two branches are connected in parallel across the battery, they are independent: a change in one branch will not affect the other. So removing bulb B has no effect on bulb D; the current through bulb D remains the same. In branch 1, removing bulb B decreases the number of pathways through which the current can flow and therefore increases the resistance of that branch. Since current and resistance are inversely related, the current through branch 1, and therefore the current through bulb A, decreases when bulb B is removed. Since the current through branch 1 decreased, the current through the battery also decreased, because the current through the battery is the sum of the currents through branch 1 and branch 2.

Part B [Fig. 1(b)]: When the wire is added in parallel with bulbs B and C, bulbs B and C are shorted out (assuming the wire has much less resistance than the bulbs). The resistance of branch 1 will decrease, and the current through that branch will increase. So the current through bulb A will increase. Branch 2 is unaffected because it is connected in parallel with branch 1 across the battery. So bulb D is unaffected by the short, and the current through bulb D remains the same. The current through the battery will increase, since it is the sum of the currents through branches 1 and 2, and the current through branch 1 increased.

2. An acceptable quantitative solution to the synthesis problem

Part A [Fig. 1(a)]: Assume that the battery is ideal and that the bulbs are ideal resistors. The voltage across bulb D does not change. Since its resistance remains the same, the current through bulb D remains the same by Ohm's Law, $V=IR$. The resistance of the B-C parallel network increases from $R/2$ (found by using $1/R_{\text{parallel}}=1/R+1/R=2/R$) to R when bulb B is removed. Since the resistance through the branch containing bulb A increases while the voltage across that branch remains the same, the current through the branch and therefore through bulb A decreases. The current through the battery decreases because the total resistance of the circuit increases while the voltage remains the same, since an ideal battery is a constant voltage source.

Part B [Fig. 1(b)]: When the wire is added in parallel with bulbs B and C, bulbs B and C are shorted out. The resistance of the branch containing bulb A decreases from $3R/2$ to R, increasing the current through that branch (since the voltage across the branch remains constant). So the current through bulb A increases. The current through the battery increases because the total resistance of the circuit decreases. The current through bulb D remains the same because the voltage across it remains the same.

3. An acceptable qualitative solution to the analysis problem

Part A [Fig. 2(a)]: Assume that the battery is ideal and that the bulbs are ideal resistors. When three resistors of the same resistance are in parallel, the current has three pathways, instead of one pathway for one resistor. So the network draws three times the current of one resistor. The resistance of the network of three resistors in parallel is then one-third the resistance of one resistor, $R/3$. Since the parallel network is in series with a single resistor, the total resistance of the circuit is $R+R/3=4R/3$.

Part B [Fig. 2(b)]: Label the bulbs in parallel B, C, and D, and the single bulb A. The current through bulbs B, C, and D must be the same: since they have the same resistance and are connected in parallel, an equal amount of current will flow through each path. Since the current through bulb D is I, the current through each of the bulbs B and C is also I. The current through bulb A and through the battery is $3I$, since it is the sum of the currents through bulbs B, C, and D, and the same current flows through bulb A and the battery because they are connected in series.

4. An acceptable quantitative solution to the analysis problem

Part A [Fig. 2(a)]: $R_{\text{total}}=R+(1/R+1/R+1/R)^{-1}=4R/3$

Part B [Fig. 2(b)]: The current through each of the bulbs in parallel must be the same, since the voltage across them is the same and they each have the same resistance. So each of the three bulbs in parallel has current I. The currents into and out of each node must sum to zero (Kirchhoff's first law), So the current through the battery and through bulb A must be $3I$.

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THERE IS NO SUCH THING AS A *SCIENTIFIC MIND*

Scientists are people of very dissimilar temperaments doing different things in very different ways. Among scientists are collectors, classifiers and compulsive tidiers-up; many are detectives by temperament and many are explorers; some are artists and others artisans. There are poet-scientists and philosopher-scientists and even a few mystics. What sort of mind or temperament can all these people be supposed to have in common? *Obligative* scientists must be very rare, and most people who are in fact scientists could easily have been something else instead.

Peter Medawar, *Pluto's Republic* (Oxford, New York, 1984), p. 116.