location of the cavity. Most of the students who gave incorrect answers correctly determined that negative charges would accumulate on the inside surface of the cavity. However, when finding the charge distribution on the outside of the sphere, students tended to ignore either the point charge or the charge distribution on the inside of the cavity.

The second pretest question (Fig. 4b) was significantly harder for students than the first. Only 18% of students correctly stated that the charge distribution would be asymmetrical on the inside surface of the shell and uniformly distributed on the outside surface if the positive charge were off-center. Only when the charge was centered did most students find the correct charge distribution.

2. *Tutorial homework*

One of the questions on the tutorial homework used in the junior level course is based on an experiment similar to one used in the tutorial. (See Fig. 1.) Students are told that a metal ball is suspended inside a metal cylinder, and a charged object is placed outside the cylinder. Out of 81 students, 65% correctly stated that there would be no induced charge distribution on the ball. These students all correctly reasoned that charges in the cylinder would spontaneously redistribute to cancel the external field, which is precisely the model introduced in the tutorial. This is an improvement over the result of Bilak and Singh, who found that only one-third of first-year graduate students correctly answered a similar question after traditional instruction. Instructional strategies based on model-building seem to be clearly beneficial to students' understanding of this topic.

3. *After tutorial: Post-test on field in a conducting shell*

A variant of the situation shown in Fig. 4b was used on a post-test in the junior level course. Students were asked to sketch the charge densities on the inner and outer surfaces of the conducting shell, as well as the electric fields inside and outside. Out of 94 students, 68% found the correct charge distribution and fields, and 50% used the logical structure provided by the tutorial to determine their answers. This is a significant improvement from the pretest, on which only 18% of the students gave the correct answers.

In both the introductory and advanced versions of the tutorial, spontaneous use of model-based reasoning after tutorial is significantly enhanced. However since the introductory class has around 5% of physics majors and the junior class is entirely physics majors, direct comparison across classes is difficult.

V. CONCLUSIONS AND IMPLICATIONS FOR INSTRUCTION

The findings from this research indicate that instruction that focuses on explicit model-building to create a causal model of conductors can strengthen the ability of students to reason about charge distributions, electric fields, and potential differences in conductors. It also seems to help students transition from using rule-based reasoning, which is often incorrectly applied, to using model-based reasoning. This strategy can be effective in introductory service courses as well as in courses for upper-division physics majors.

This particular study used a tutorial implementation, but that this technique is similar to that used by Eylon et al suggests that it can be effective in many contexts, not only with classes using tutorial-based instruction. In our view the major significance of this study is that guiding students to construct a model for charges in a conductor leads to more complex reasoning about this topic. This guidance could be implemented via other methods as well, for instance through an appropriate set of clicker questions and discussion, or in a 'flipped' classroom setting.

Having students construct a causal model for circuits has previously been shown to be effective in helping students reason about the behavior of circuits. We think it likely that engaging students in model-building at an earlier stage, starting with conductors, and then continuing the model development with instruction about circuits, could be even more productive than using a causal model only for circuits. We will explore this in future work.

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