PHYSICS EDUCATION RESEARCH GROUP

Curriculum Development to Address Student Difficulties with Models of Conductivity

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Presented at the American Association of Physics Teachers National conference, 99 august, in San Antonio.

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A New Model Course in Quantum Mechanics for Scientists and Engineers

supported in part by:
The National Science Foundation
Department of Education, “FIPSE”

Research Setting

Physics 420: Junior-level QM for Engineers

- Primarily electrical engineers (2/3 of the class)
- Typically between 10 and 25 students per course

Classroom format:

- Professor led lecture instruction.
- No recitation or discussion section scheduled.
- In the modified class, one hour of lecture is replaced by a UW-style tutorial.*

* L.C. McDermott, P.S. Shaffer, and the Physics Education Group at the University of Washington, *Tutorials in Introductory Physics*, Prentice Hall, Upper Saddle River, NJ, 1998.

Research Methods

- **Informal observations:**

  To get a general idea of student reasoning.
  Office hours, classroom discussions.

- **Interviews - The “State Space” of Difficulties:**

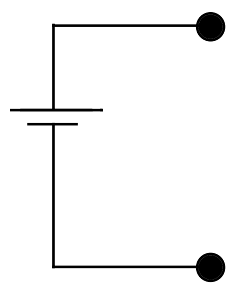
  To probe student understanding more deeply.
  Individual demonstration interviews.

- **Written tests - “Weighting Factors”:**

  To describe the distribution of student difficulties.
  Pretests, exam questions, diagnostic tests.

Interview Protocol

Present students with:



- battery
- wires
- steel wire
- copper wire
- aluminum
- rubber band
- wood
- Styrofoam
- and more...

Ask students to:

- describe what happens when circuit closed
- compare different substances
- discuss effect of higher (or lower) temperature
- and more...

In all instances,
"how do you know?"

Preliminary Model of Free Electrons

First comments:

Inter.: *When I connect the steel wire to the two leads here, what happens?*

Thomas: *There's going to be a current flowing through the wire.*

Inter.: *What do you mean by current flow?*

Thomas: *Electrons are going to move from the plus to the minus.*

Inter.: *Where are the electrons moving?*

Thomas: *They're coming from the battery so they'd move through the wires…*

Inter.: *Are there any electrons in the wire before you plug it in?*

Thomas: *Yeah, but they're not moving.*

Origin of Conducting Electrons

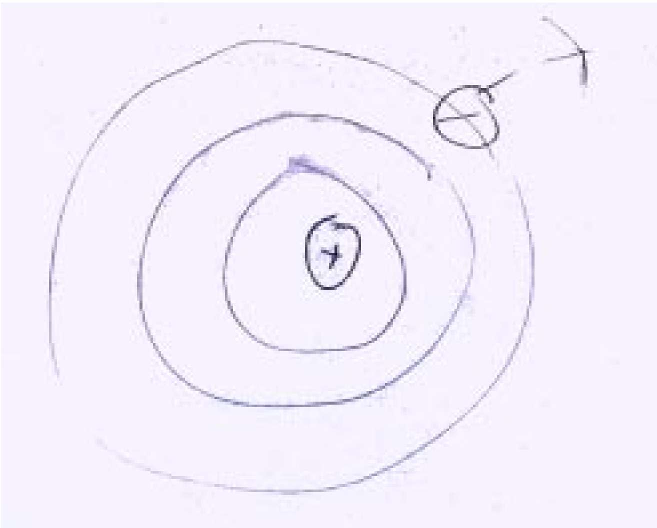
Once the battery is attached:

Inter.: *How do [electrons in the steel wire] move?*

Thomas: *… Just the ones on the most outer shell would move. They'd get pulled off the atom.*

Inter.: *And how do they get pulled off the atom?*

Thomas: *By the electric field. It attracts them and pulls them away from the positive nucleus of the atom.*



(5 of 9 students)

Free Electrons in Other Materials?

Conduction in lead vs. conduction in steel or copper wire:

Inter.: *How does density play a role?*

Thomas: *[It determines] how easily it [an electron] can be removed from the atom. Because it's packed in very tightly, so they're very close to each other, so the attraction is very high, so it would take a lot of power - a lot of energy - to remove [the electron] from the atom.*

Conduction in undoped vs. doped semiconductors:

Inter.: *What is the difference between silicon and the doped silicon?*

Thomas: *I think the doped ones are better conductors because I think it takes a lot of energy to remove the silicon electrons, but if you add electrons from a different metal, like aluminum, which require less energy to be removed, then you'd get more current using less energy.*

Does Ohm's Law Hold?

Is there a threshold voltage for current to flow?

Inter.: *For the steel wire, if we put in a small voltage versus a larger voltage, is there a difference?*

Thomas: *Yeah, there would be a difference. Because even though the steel wire is not a resistor, it'd still have its own internal impedance of how much energy it takes to remove the electron and then get it to move around.*

Inter.: *Is there a possibility if I put in only some level of small voltage that I wouldn't get any current at all?*

Thomas: *Yeah, there is a possibility.*

Inter.: *Why?*

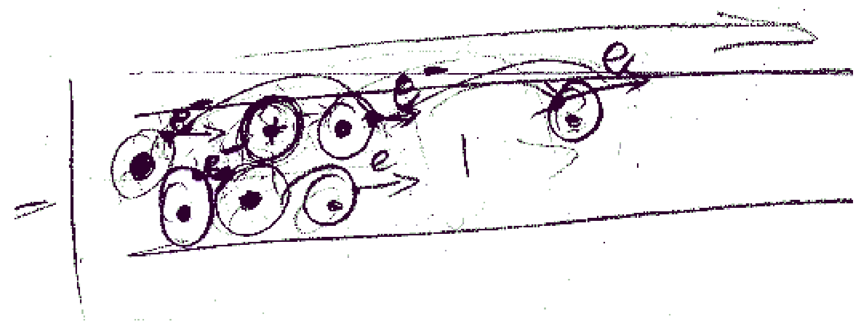
Thomas: *Just because it wouldn't be enough energy to remove the electron from its orbit.*

Inter.: *And how do you determine the energy that's needed to remove the electron from its orbit?*

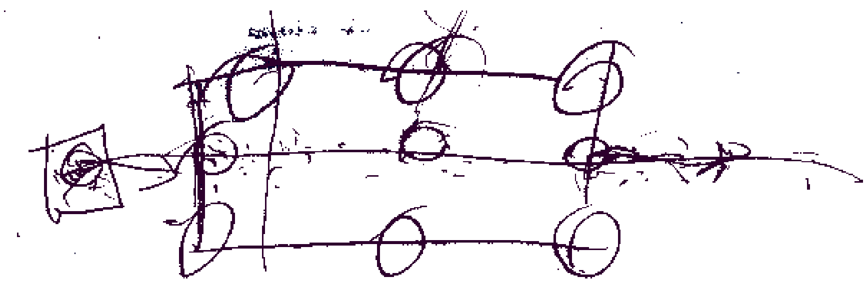
Thomas: *You'd use the Bohr model for that… you'd have that equation. … The first object, goal, is to remove the electron from the atom. That's where most of the energy is probably going to be used up anyway.*

Preliminary Model of Conduction

DAVID: "Electrons get out from one atom. There's a force on the electron. An electron gets out from here, let's say, it's moving, electrons get out from here. This electron takes the place of this electron here, this one takes the place of this one, and then this one, … It comes again out of the atom and it moves to the next one."



KARL: "The electron is going in, attaching itself somehow, there are too many, so one jumps, attaches itself, and so on… The electron going in is not the one coming out. It causes a shift which causes another to pop out… There's a need, it gets it, there's a need it gets it…



Other students make similar sketches (in total, 4 of 9 used gave this description):

Curriculum Development to Address Student Difficulties

Tutorials:

students work in groups on specially designed worksheets.

Active learning:

Observe - *Discuss* - *Build*

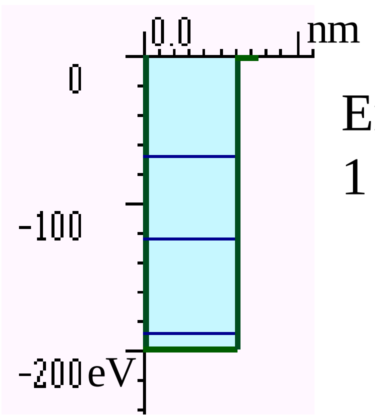
Students:

- verbalize their models
- discuss models with their colleagues
- distinguish between the multiple possibly useful models
- compare model implications with expected results
- revise and restructure their thinking as needed.

The Source of Free Electrons...

A variety of computer tools are used to introduce the band diagrams.
Example: Kansas State University *Visual Quantum Mechanics*

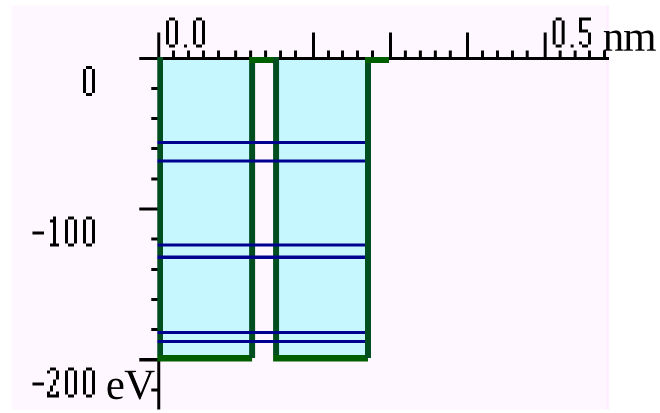
I.



Energy levels in
1 potential well

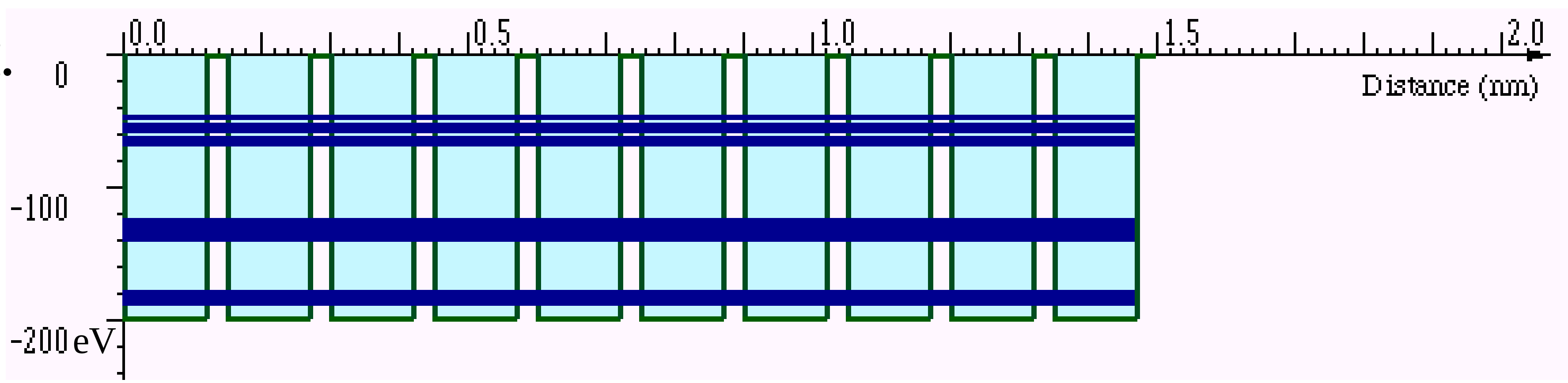
then with 2:

II.



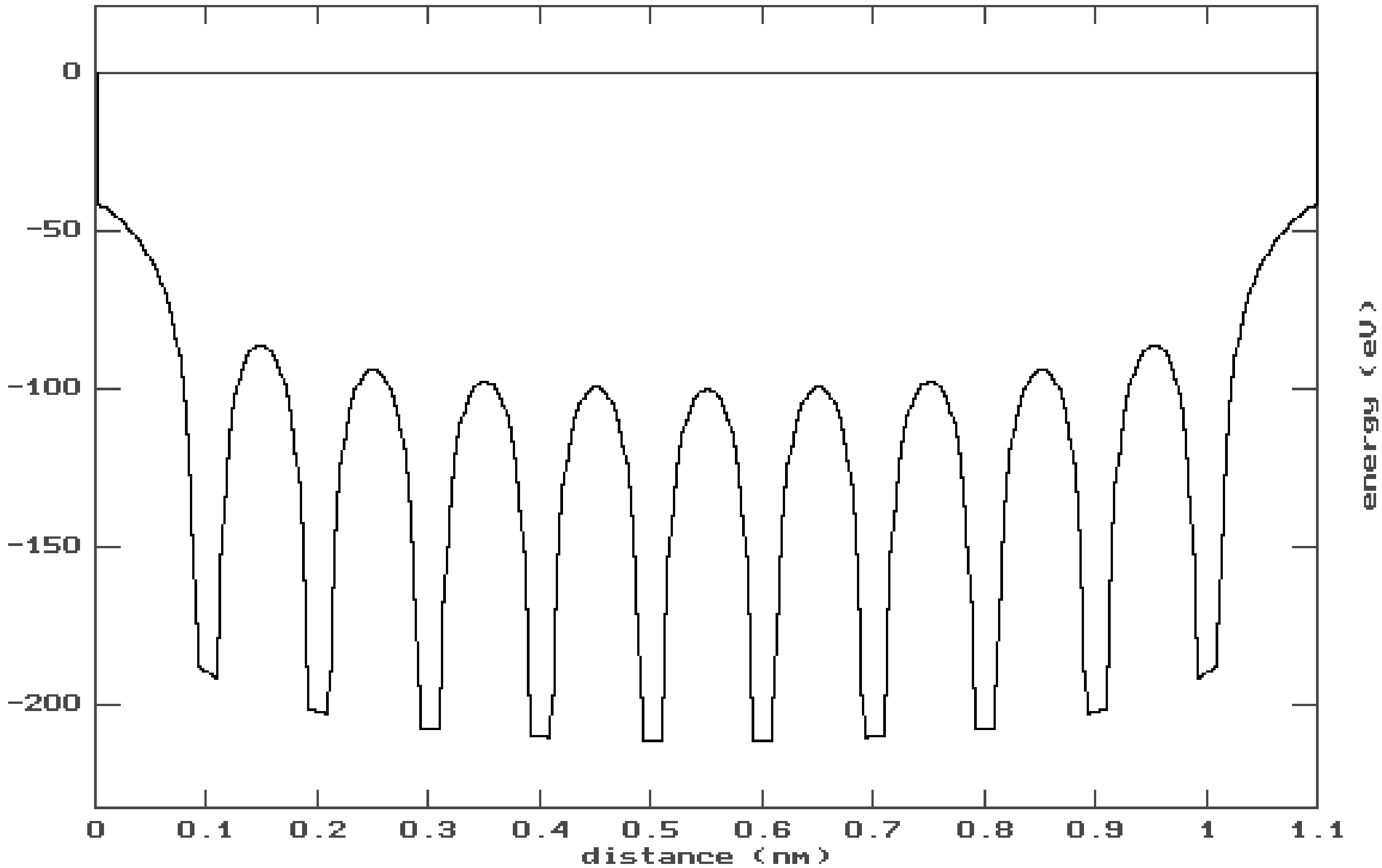
finally with 10:

III.



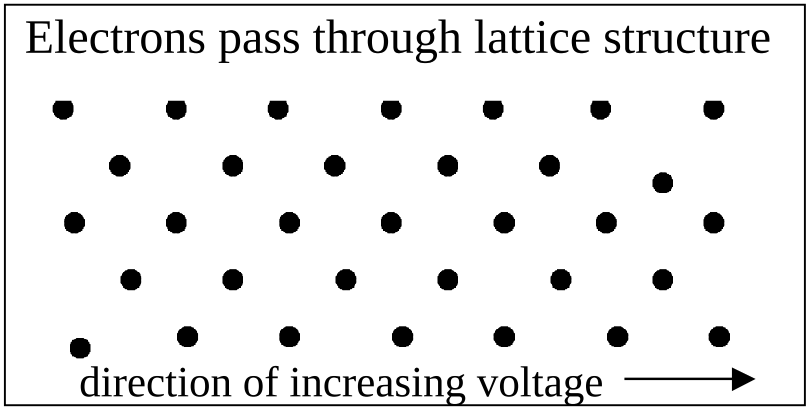
…In Simple Representations

Example: CUPS *Lattice 1-D*



Models of Electron Flow

Students are introduced to the Drude model of conduction through a lattice of atoms.

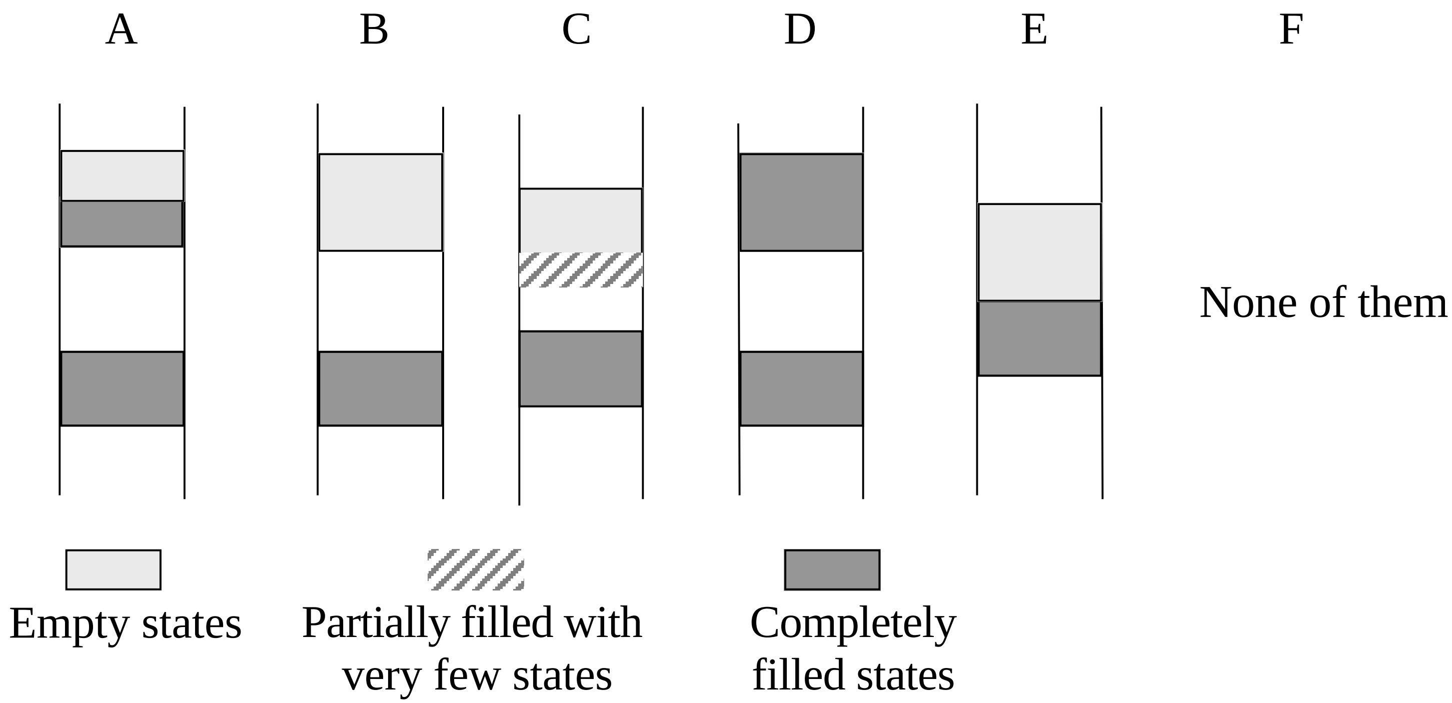


Students have the opportunity to discuss the realms of validity of the different models.

We expect our students to be able to interpret the different representations and models presented.

Post-test of Student Learning

Final examination question:



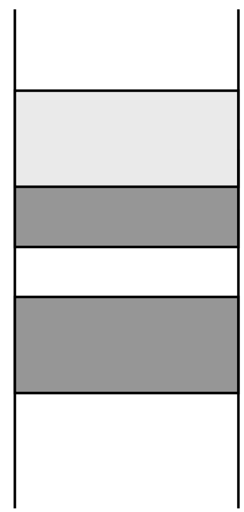
Consider the following band diagrams. For the different materials, select one of the diagrams that can best represent the band structure of the corresponding material . (If you choose "F", please sketch your own diagram). Explain your reasoning.

a) Conductor
b) Insulator
c) Semiconductor
d) Resistor

Student Performance, part (a)

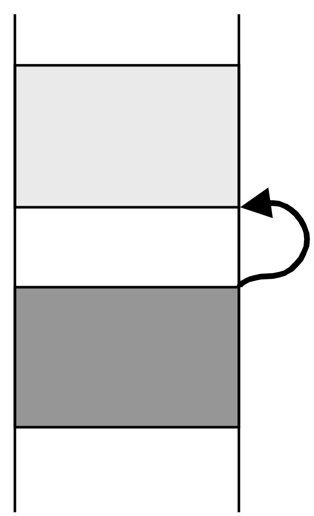
Origin of free electrons in a conductor:

11 of 25 (44%) gave correct answer:



"Electrons only need to move to next energy level in same band, which is small amount of energy and makes moving electrons easy."

12 of 25 (48%) gave "modified Bohr" answer:



"Similar to semi-conductor … It takes very small energy to excite the electrons into the upper band."

Conclusions

- Students have fundamental difficulties with many of the prerequisites concepts of quantum mechanics.
- Students often apply prerequisite ideas inappropriately to QM
  - Circuits and conductivity
  - QM tunneling
  - Energy graphs and probability
  - etc.
- In other areas of QM, an iterative process of curriculum development has been effective.
- Our tutorials are presently in “alpha;” further iterations are necessary to help our students learn the physics more effectively.