

UNIVERSITY OF CALIFORNIA
SANTA CRUZ

**EDUCATIONAL APPLET'S FOR ACTIVE LEARNING IN PROPERTIES OF
MATERIALS**

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requirements for the degree of

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Jessica Masters

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The thesis of Jessica Masters
is approved:

Professor Tara Madhyastha, Co-chair

Professor Ali Shakouri, Co-chair

Professor Emily Allen

Professor Luca DeAlfaro

Frank Talamantes
Vice Provost and Dean of Graduate Studies

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Chapter 1

Introduction

Technology has forever changed the face of education. With simulations and on-line materials, it has become increasingly possible for students to take a more active role in learning. We created several on-line materials for a course in electrical engineering. We then used these materials in an on-line lab and evaluated student responses to the material.

1.1 Motivation

The traditional classroom approach of students passively absorbing information from a lecturer has given way to a new, more active approach, where students have access to a variety of multimedia course materials. Every student will learn best from a different combination of materials. But how are students to know what materials suit them best? Given prior knowledge about a student, is there a way to predict what materials are best suited to that student?

Instructors and publishers have devoted much time and energy to the development

of individual course content. Every tool that presents information in a new and different way is a contribution to education. The more forms of information that exist, the better the chance that each student can find a form that will help him or her learn in the best possible manner.

But while the development of course content has flourished, the existence of a system to organize and evaluate this content has not yet been created. A learning system would be a framework that any instructor could use to plug in their own choice of course materials. This framework would use information about a student to create a personalized information domain that is tailored to that student. Thus, students could have control over the path they take in their own learning process. The framework explicitly turns control over to the student allowing them to determine which learning materials are best suited to them.

1.2 Approach

Before we can predict different preferences of a student, we must first understand what information would serve as the best predictors. Keeping our long-term goal in mind, we decided to create several course content modules that differed in both style and content. We then used these modules in a classroom setting. We were able to record personal data about the students as well as how useful and enjoyable they found the course content modules. We then analyzed this data to identify which student characteristics are correlated to preferences.

Engineering students are traditionally active, sensing, visual and sequential learners[20]. Despite this, engineering courses are most often taught in a manner that is “heavily biased toward intuitive, verbal, reflective, and sequential learners[7].” Because of this discrepancy, we

chose Properties of Materials, in the Electrical Engineering department (Electronic Properties of Materials, in the Materials Engineering department at San Jose State University), as the forum to develop new course content and evaluate the effectiveness of that content. Besides the intuitive, verbal nature of the course, Properties of Materials was also chosen because it is offered at both the University of California at Santa Cruz and San Jose State University. We created several applets for this class that display physical concepts and information that is often difficult for students to visualize. We fine-tuned the applets with feedback from the smaller class at Santa Cruz (roughly 30 students) and analyzed the applets with the students at San Jose, a class of roughly 150 students.

We wanted to create applets that would appeal to students with different learning preferences. We decided to have two types of applets: simulation and tutorial. The simulation applets are interactive and “hands-on.” These applets allow students to change different parameters and observe the effects. Different combinations of parameters may yield different results. For example, students can observe electrons in a metal at a high temperature, and then add an electric field. Students could also first add an electric field and then raise the temperature. The effects the students observe may be varied based on which parameters they choose to adjust, and the order in which they do so. On the other hand, the tutorials are more passive and “hands-off.” Information is presented in slide-show form. The tutorial contains both pictorial and textual explanations of concepts. The simulation is only visual, with no words interpreting what the students see. We felt these two forms of applets complimented each other: one passive with written explanations, the other active with only graphical explanations. By choosing two polarized styles to present information, we created a scale to place students on. On one

end of the scale was students with strong preferences for interactive and visual presentation of information, and on the other was students who preferred the tutorial-type presentation. Because the applets had such different styles, we felt most students would fall somewhere in between. Thus, we hoped to capture most of the students' preferences.

We first chose the way to categorize students' learning preferences. We identified a learning style index with which to categorize this information, and then hoped to use these categories to draw correlations between learning preferences, and other student information, and student preferences. Because of the small amount of resulting data we obtained, we could not obtain distinct correlations. Instead, we analyzed the data by deciphering populations trends and general preferences of the students.

Chapter 2

Related Work

There have been many contributions to the field of educational technology. A complete survey of this technology is beyond the scope of this thesis. However there have been many on-line course content modules developed for classes akin to Properties of Materials. This chapter discusses some of the existing content most similar to the applets we created. Also of interest is the wealth of research on student's learning preferences, especially as these preferences apply to engineering students in particular. We describe existing models of learning preferences as they relate to our work. Finally, we describe briefly information filtering as it applies to this research.

2.1 Course Materials

Several on-line applets and much educational course content have been created in the area of Properties of Materials. We focused on creating applets that were different from

existing demonstrations.

2.1.1 SUNY Buffalo

The State University of New York at Buffalo department of Electrical Engineering has created several on-line Java applets in areas that include crystal structure, metal-oxide semiconductors, digital circuits, and semiconductor devices[25]. They created the applets for use “in conjunction with traditional lectures to approach an ideal teaching style... one that calls for active student participation with live demonstrations, practical laboratory exercises with lots of scope for experimentation and reflective observation[1].” It is very important to note that course content modules are never meant as a replacement of traditional lectures, but rather as a supplement to them. A list of the applets created by SUNY Buffalo can be found at [25].

SUNY Buffalo chose to use animated applets written in Java for several reasons. Applets can provide pictorial examples of abstract and often difficult concepts [1]. This type of presentation appeals to learners with sensing preferences. Applets are a visual mechanism to present information. Applets often appeal to active learners since their graphical user interface allows the user not only to view the demonstration, but also take part in and interact with that demonstration. [1]. Applets can provide both a bird’s eye view of a large system as well as including information about the details, thus appealing to both sequential and global learners [1]. It was for these reasons, in addition to Java’s portability, that we chose to use Java applets to create our on-line simulations and tutorials.

2.1.2 On-Line Demonstrations of Quantum Concepts

The Quantum Science Across Disciplines project has created several on-line materials to develop high schoolers' understanding of quantum science concepts. In addition to creating this content, the project is evaluating the impact of the material both on student learning as well as on instructional methods [9].

At the University of Maryland, a new course in applied quantum physics has been developed. This course continually investigates the way that students learn physics. They have developed materials to supplement traditional lectures. These materials allow a student to become more actively involved with the concepts. The professors have based the new course on the philosophy that “to teach our students more effectively, we must listen to how they think and how they approach the physics[19].” Instructors can obtain this information informally through observation, but also through quizzes and assignments designed to record how students learn. The other fundamental idea behind the new course is that students must become more engaged in their own learning for that learning to be effective[19].

The Visual Quantum Mechanics project at Kansas State University has developed on-line materials in the area of quantum physics at both a high school and college level. The materials are designed to create a more “activity-based” environment [26]. The goal of the project is to promote a general understanding of the concepts among students with different backgrounds and experience levels, rather than a comprehensive ability to perform mathematical calculations. Currently, the project focuses on determining the concepts that create the most difficulty for students and developing additional materials addressing those concepts

[18].

2.2 Learning Preferences

Many psychologists have tried to develop scales to categorize the way students learn. This includes describing how both students take in and process information. Each student has some set of preferences that defines the best way and most conducive environment for that student to learn. This does not mean, however, that students cannot learn by other methods. Rather, it means that students must work harder to develop their ability to learn by other means. Ideally, a student's education would contain information presented both according to and different from their learning preferences [7].

2.2.1 Learning Style Models

There are many existing models of learning preferences. These models include the Myers-Briggs Type Indicator, Kolb's Learning Style Model, Herrmann Brain Dominance Instrument, and the Felder-Silverman Learning Style Model. Each of these models attempt to categorize different methods of learning and use those categories to help ensure that each learning preference is satisfied, at least some of the time[7].

The Myers-Briggs Type Indicator is based on the psychology theories of Carl Jung. Students are classified as either extroverts or introverts. Beyond this category, students can be either sensors, who are more practical, or intuitors, who are more imaginative. Students can have analytical tendencies, and base their decisions on logic, or have feeling tendencies, and

base their decisions on the human factor. Finally, students can be judges, who seek to complete tasks and draw conclusions, or perceivers, who attempt to obtain as much information as possible, even if that means forgoing conclusions. Students are classified as having one dominant trait in each of the four categories, and the combination of these four characteristics makes up their Myers-Briggs Type. There are 16 possible types [15].

The Kolb Learning Style Model classifies students on two separate axes: how they take in information, and how they internalize that information [12]. One axis spans concrete experience to abstract conceptualization. The other axis spans active experimentation to reflective observation. These axes leave us with four quadrants, or categories: concrete/reflective, abstract/reflective, concrete/active, reflective/active. Each of these four types is associated with a characteristic question that explains what motivates students who fit that description. The concrete/reflective students will focus on the “why.” Abstract/reflective students are motivated by the question “what.” Students who are classified as concrete/active students will be motivated by the question “what if.” Finally, abstract/active students will focus on the “how.” Students can fall anywhere on the plane of these two axes, which will be in one of the four categories [12].

The Herrmann Brain Dominance Instrument classifies students based on the functions of the physical brain. Students are considered either left brain or right brain, and cerebral or limbic. A left brain/cerebral student will be logical and factual. A left brain/limbic student will be structured and detailed. A right brain/cerebral student is more visual and innovative. Finally, a right brain/limbic student is emotional and symbolic [10].

2.2.2 Felder-Silverman Learning Style Model

We chose to use the Felder-Silverman Learning Style Model. This model classifies students along four axes: sensing/intuitive, visual/verbal, active/reflexive, and sequential/global. Students will fall somewhere on the scale between the two extremes in each of these four categories[7].

Sensing learners are “concrete, practical and oriented toward facts and procedures,” while intuitive learners are more “conceptual, innovative, and oriented toward theories and meanings[7].” No matter what the context, the surrounding environment presents us with more information that can possibly be processed. People must somehow sift through this information and retain what they find useful. Sensing individuals are more likely to retain information that is obtained through their senses, while intuitive individuals are more likely to retain the information obtained through their own “memory, reflection, and imagination[6].” Sensors are practical and prefer facts and observations. Intuitors are more imaginative and prefer concepts and interpretations[6].

Visual learners prefer “visual representations of presented material, including pictures, diagrams, and flow charts,” while verbal learners prefer “written and spoken explanations[7].” Visual learners virtually require some sort of schematic or demonstration to retain information. In contrast, verbal learners will learn from spoken or written words and formulas[6].

Active learners learn “by trying things out, and working with others” while reflective learners learn “by thinking things through and working alone[7].” An active learner will prefer to exchange ideas with a group and try those ideas out. A reflective learner will prefer to think

a solution through thoroughly rather than first trying it out[6].

Students with a preference for sequential learning learn “linearly, orderly, in small incremental steps,” while those with a preference for global learning learn more “holistically, as system thinkers, learning in large leaps[7].” Sequential learners can often provide a detailed step-by-step explanation of a solution, but fail to see where that solution fits into the larger, broader context of the subject. A global learner will often be unable to provide the incremental steps until he or she has a strong understanding of the big picture[6].

We chose the Felder-Silverman model because it was the most accessible and practical. The Felder-Silverman model is presented as an on-line, easy to use quiz of multiple choice questions, the Index of Learning Styles (ILS), which was developed by Felder and Soloman[23]. It is easily scored. The results are instantaneous and are accompanied with links to a website for additional information on the student’s dominant preferences[8]. The Felder-Silverman model records both student preferences and the strength of those preferences [5]. Because we were only trying to draw correlations from our data, it was not necessary to use a validated model of learning preferences[21]. In addition to this, it has been found by several other studies, most notably the one at The University of Western Ontario, discussed below, that engineering students have strong preferences for the categories in this model. Therefore we were confident we would be able to draw correlations from our experiment [20].

2.2.3 Learning Preferences in Engineering Education

Much work has been done to assess the typical learning styles of engineering students and teaching styles in those same disciplines. Felder has found that instruction in en-

engineering courses is biased toward learners with intuitive, verbal, reflective and sequential preferences, as is discussed below[7]. Despite this, most engineering students do not fit these categories. According to a study at San Jose State University, 43% of students in engineering show strong sensing preference, and 60% of students have strong preferences for learning by visual methods[3]. In general, most engineering students are active, sensing, visual and sequential in their learning preferences[20]. Another study at the University of Western Ontario supports this idea. This study found that 69% of engineering students surveyed had active preferences, 59% had sensing preferences, 80% had visual preferences, and 67% had sequential preferences. This data was collected from over 800 engineering students at that institution[21][20]. Being constantly taught in a manner that is not conducive to your learning preference can hinder your ability to retain information and advance in the engineering field.

A majority of the material in any engineering class involves theories, concepts, and symbols. Drawings are sometimes used, but they are often based on “abstract” parameters. Intuitive learners deal well with these forms of presentation, but sensing learners can have a difficult time translating these abstract forms into “concrete mental images[6]”. Engineering courses are taught with words and formulas. Traditionally courses have been taught with blackboard lectures to scale the lessons to large numbers of students. This form of presentation is almost exclusively verbal, consisting of written words, spoken words and formulas, and will not reach visual learners. In this lecture environment, neither active nor reflective learners will thrive. Active learners do not get the chance to try out any concepts they learn, and reflective learners do not get time to mentally process these concepts[6]. Global learners often need time to contemplate the big picture before understanding the smaller details. In most engineering

courses, however, instructors do not have time to wait for global learners to catch up[6].

It is clear that with traditional lectures alone, instructors in any discipline will not reach students with varied learning styles. In engineering, however, the traditional methods may miss a *majority* of students, not just a small portion of them. Clearly, there is a need for information to be presented in other forms. These other methods of presentation can supplement traditional classroom lectures so that students can seek out a form that is most appropriately tailored to their own learning preference.

2.3 Tailoring Web Content

There has been much effort devoted to evaluating algorithms which attempt to predict a website user's future preferences based on past preferences or characteristics. A list of some currently available information filtering systems can be found at [17] and [24]. Some algorithms use explicit voting to determine the user's preferences while other algorithms use implicit usage patterns [4]. One of the goals of our experiment is to obtain a base data set which can provide initial preferences. In future projects, this initial data set could be used as the basis to form an algorithm to help predict new data sets for website users.

Chapter 3

Properties of Materials

Electrical Engineering 145 at the University of California at Santa Cruz and Materials Engineering 153 at San Jose University are two courses in Properties of Materials. These courses use the same textbook[11] and deal with the “fundamental electrical, optical, and magnetic properties of materials, with emphasis on semiconductors: chemical bonds, crystal structures, energy bands, electrical and thermal conduction, optical and magnetic properties[22].”

3.1 Course Overview

Properties of Materials courses contain content that can be difficult for students to visualize. Many engineering students could benefit from a more interactive and visual presentation of information as opposed to just lectures and textbook readings. It is important to note that the applets we developed are intended to be used as a supplement to classroom lectures and traditional labs.

The courses at both universities involve lectures in addition to laboratory exercises. There is assigned reading, homework, quizzes and midterms. An emphasis is put on problem solving both in the lecture as well as in labs[22][2].

3.2 Metals

Electron movement in metals is a key concept that describes many physical properties such as electrical and thermal conduction. Both classical and quantum mechanics play an important role in understanding electron motion in metals. If not acted on by an external force, electrons in a metal will have random motion at any finite temperature. If an electric field is applied, electrons will be accelerated in the direction opposite to the field. Along with electrons, there are atoms, which form a lattice-like structure in the metal. If the temperature of a metal is increased, vibration of the atoms increases. Electrons may collide with the vibrating atoms, obstructing the motion of the electrons. At the temperature of absolute zero, where there is no atom vibration, electrons can flow without resistance inside a perfect metal. Impurities and imperfections in the metal can further increase the resistivity of the metal.

It is important for students to grasp the concept of electrical conduction intuitively to understand more complicated concepts such as thermoelectric effects. The key conduction concepts are drift, diffusion, resistivity, conductivity, and electron mobility.

Drift refers to when electrons are drawn in the direction of an outside applied force, for instance an electric field. Even without an outside force, electrons can have a net current due to their random motion and concentration variations. This concept is called diffusion,

which tends to make electron concentration more uniform everywhere.

Related to electron drift and diffusion is the difference between the average and net number of electrons crossing an arbitrary plane in the material. Suppose we draw an arbitrary plane through the metal. The average number of electrons crossing this plane is the average of the number of electrons crossing from left to right plus the number of electrons crossing from right to left. The net number of electrons crossing a plane is the absolute value of the difference between these two values.

Resistivity is related to electron motion. When increasing the temperature of the metal, we increase the amplitude of atomic vibrations, as stated above. Because electrons can't move as freely when they collide with vibrating atoms, the resistivity of the metal is increased.

Conductivity is the inverse of resistivity. The more resistive a metal is, the less conductive it is. From this fact, when we increase the temperature of a metal, we decrease the metal's conductivity.

A final concept addressed by the applets is electron mobility. Electron mobility determines how much electrons will move on the average in a given electric field.

3.3 Semiconductors

Students are expected to understand the same basic concepts of drift, diffusion, resistivity, conductivity, and electron mobility as they apply to semiconductors. Semiconductors are separated into two categories: intrinsic and extrinsic.

3.3.1 Intrinsic Semiconductors

An intrinsic semiconductor is a “pure” semiconductor with no impurities. Like a metal, an intrinsic semiconductor has a crystal-like lattice structure made up of atoms. At high temperatures, each atom can be ionized and give up free electrons. In an intrinsic semiconductor, the electrons from these ions are the only carriers contributing to the electrical conduction of the semiconductor.

In an intrinsic semiconductor, the number of electrons present is related to the temperature of the material. At absolute zero, the crystal-like lattice structure is made up of atoms with no free electrons. As the temperature rises, the atoms become ionized. When this occurs, an electron is released from the ion. Thus, as the temperature rises, the number of free electrons in the semiconductor increases. This is the main difference from metals, where the number of electrons does not change with temperature. Like metals, the vibration of the atoms, and ions, also increases with temperature, and this can affect electron motion. The effects of an applied electric field are also similar to a metal: electrons are drawn in the opposite direction of the applied field.

3.3.2 Extrinsic Semiconductors

An extrinsic semiconductor is also called a “dopant” semiconductor and contains impurities, “dopants.” Like the intrinsic semiconductor, there are electrons that can be freed from ions at high temperatures and contribute to the electrical conduction. In addition, however, there are impurities (dopants) that also give off free electrons at lower temperatures.

The effects of temperature are different for extrinsic semiconductors. There are three

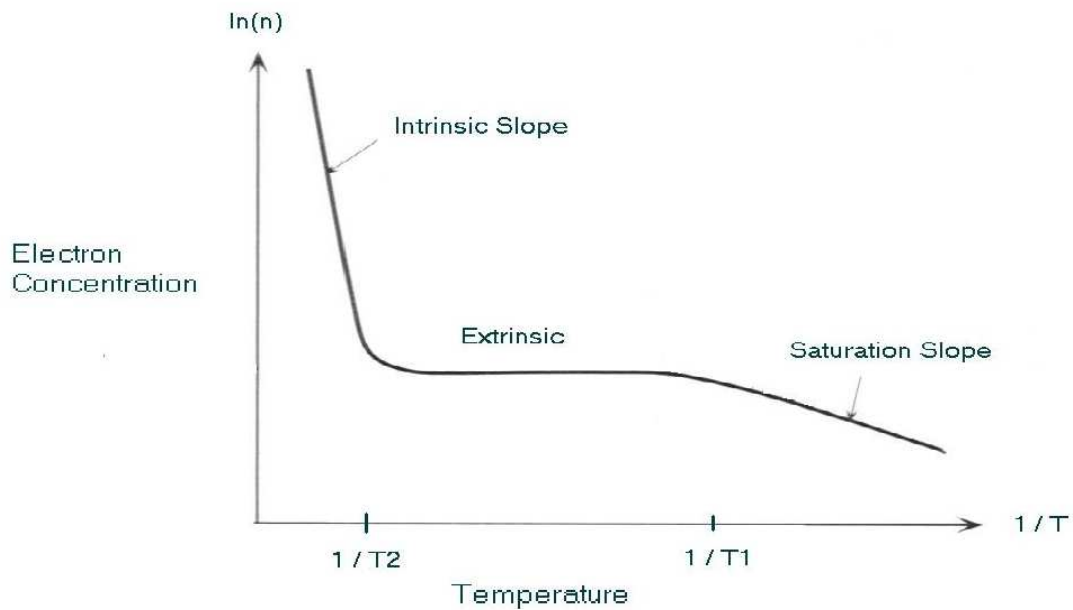


Figure 3.1: Temperature Dependence of Electron Concentration for Extrinsic Semiconductors [11]

ranges of temperature: the saturation regime, the extrinsic regime and the intrinsic regime. The saturation regime is at low temperatures. In this range, the only electrons in the semiconductor are those given off by the impurities, or dopant ions. At absolute zero temperature these electrons are not free, however, and remain in orbit around the doped ions. Within this range, these electrons are released from the dopant ions and then contribute to the electrical conduction. In the extrinsic regime, at medium temperatures, the only free electrons are still those released from dopant ions. In the highest temperature range, the intrinsic regime, the other atoms in the material can become ionized and release their own electrons. This distribution can be seen in Figure 3.1. As in metals and intrinsic semiconductors, vibration of atoms increases with

temperature. Also, with the addition of an electric field, electrons are drawn in the direction opposite to the field.

Chapter 4

Educational Materials

We have created applets to illustrate the principles described in Chapter 3. Here, we describe each of the applets. We discuss features of each applet as well as the concepts that should be learned from the applets.

The simulations are all hands-on, interactive applets. The idea is to allow students to understand concepts by manipulating an animated representation of the physical properties. The tutorial is hands-off, in the form of a slide show presentation. Each of the following applets can be viewed at the Collage (COLLaborative Approach to Global Education) Project website: <http://www.collage.soe.ucsc.edu/> [13].

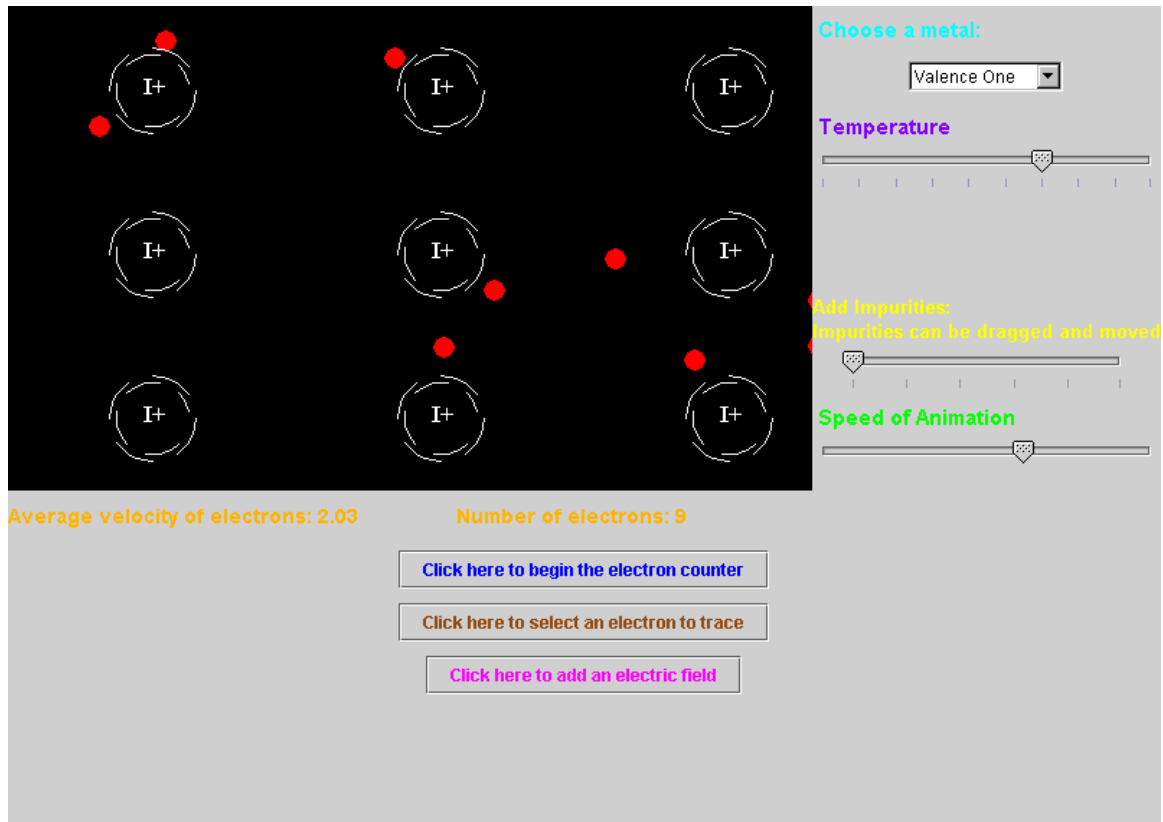


Figure 4.1: Electrons in Metal Simulation: no parameters selected

4.1 Electrons in Metal Simulation

4.1.1 Features

The “Electrons in Metal” Simulation was the first educational applet we developed. The idea was to illustrate electron motion by displaying electrons as red bouncing balls that move with random motion, bouncing off each other and ions, represented as larger white balls. The screen is divided in two different sections: a black rectangle that represents the metal and the rest of the screen, which contains the buttons and sliders for changing parameters. Figure 4.1 shows the simulation with no parameters selected.

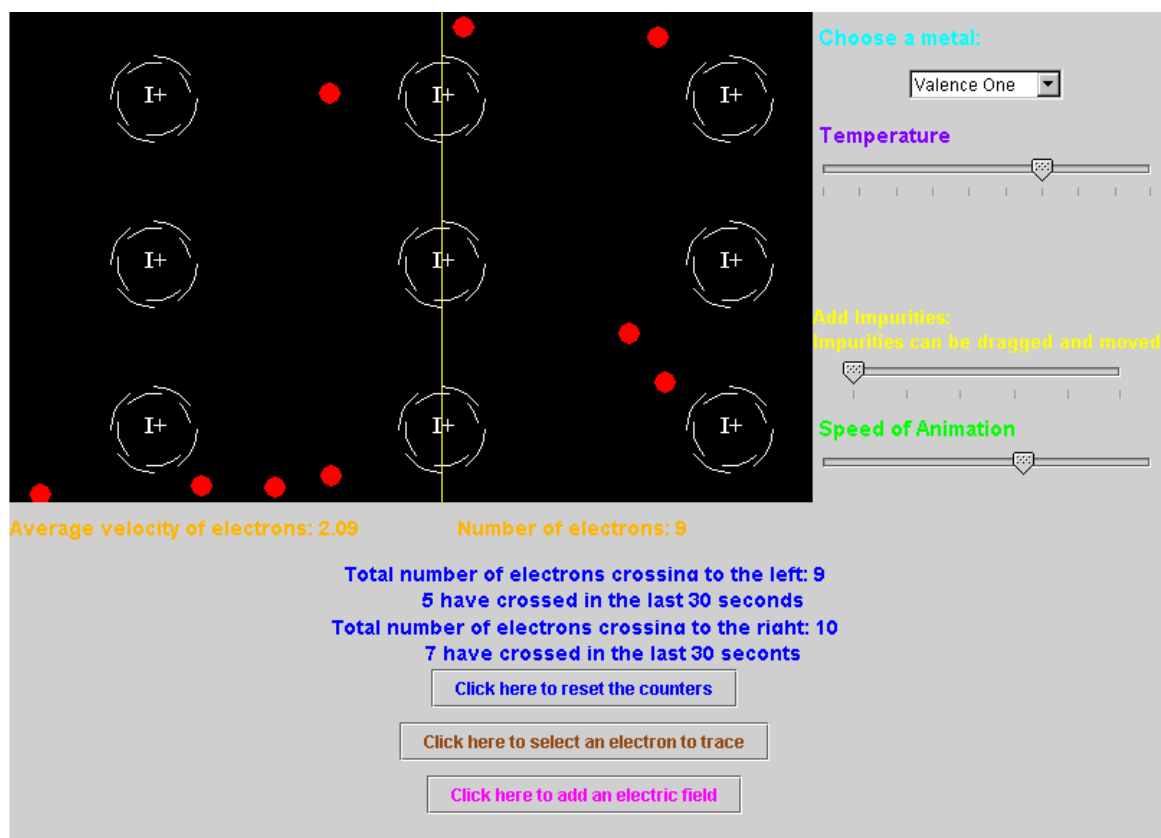


Figure 4.2: Electrons in Metal Simulation: counters enabled

The simulation also displays the current number of electrons and their average velocity. The first feature of the simulation is the counters, which are enabled in Figure 4.2. The counters keep a running tab of the number of electrons that have crossed an arbitrary plane from left to right and from right to left. The counters also keep a rolling count of the number of electrons crossing the plane in the last thirty seconds. The counters should help the students become more familiar with the concept of electron drift and diffusion. Students should notice that with no outside forces, there are an approximately equal number of electrons crossing in each direction. The counters can be reset to zero at any time.

Electrons can be traced to keep track of their path, as shown in Figure 4.3. The

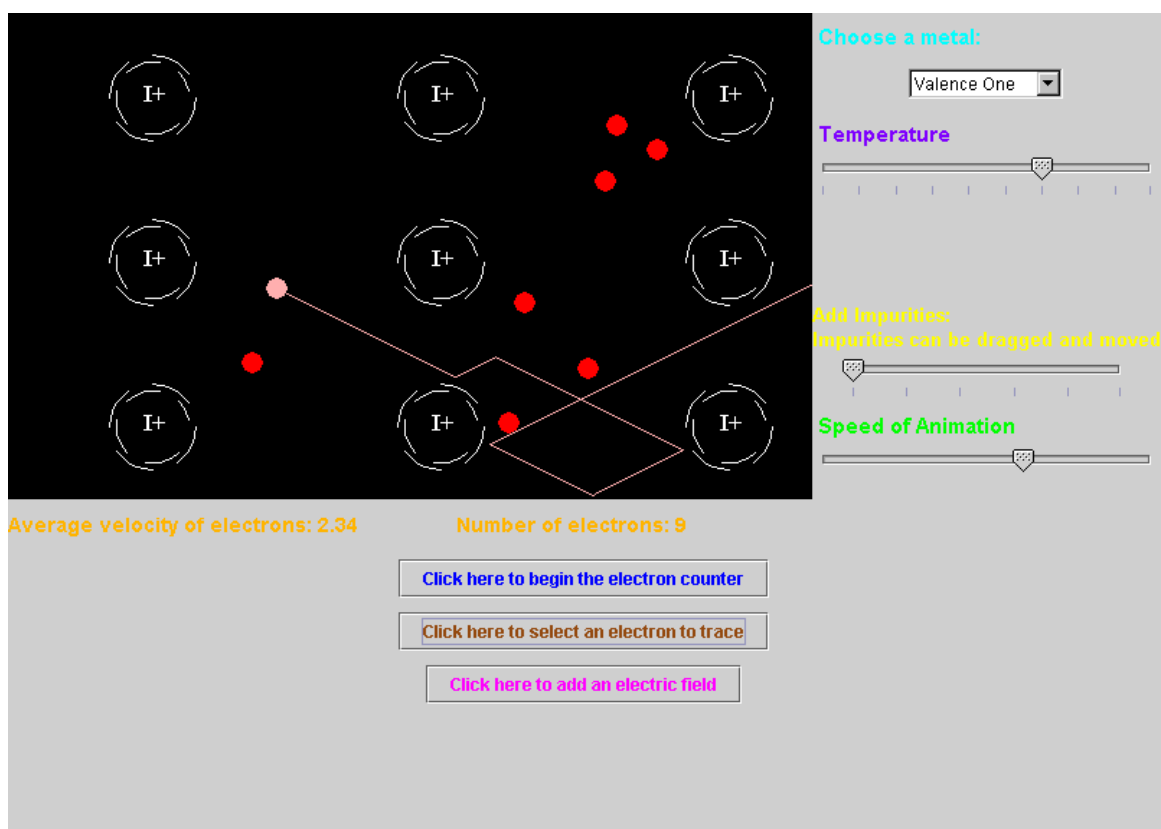


Figure 4.3: Electrons in Metal Simulation: electron trace enabled

simulation is temporarily stopped and students can select which electron to trace. This electron then leaves a pink path. Student should notice the random movement of electrons when there are no outside forces acting on the metal.

Students should use the average velocity, number of electrons, electron trace, and electron counters to monitor changes in electron motion. When various parameters are adjusted, such as temperature or an electric field, students should observe how these changes affect the average electron speed, the number of electrons crossing an arbitrary plane, a random electron's path, and the total number of electrons. The effect will be different depending on whether the student is viewing the Electrons in Metal Simulation, the Electrons in Intrin-

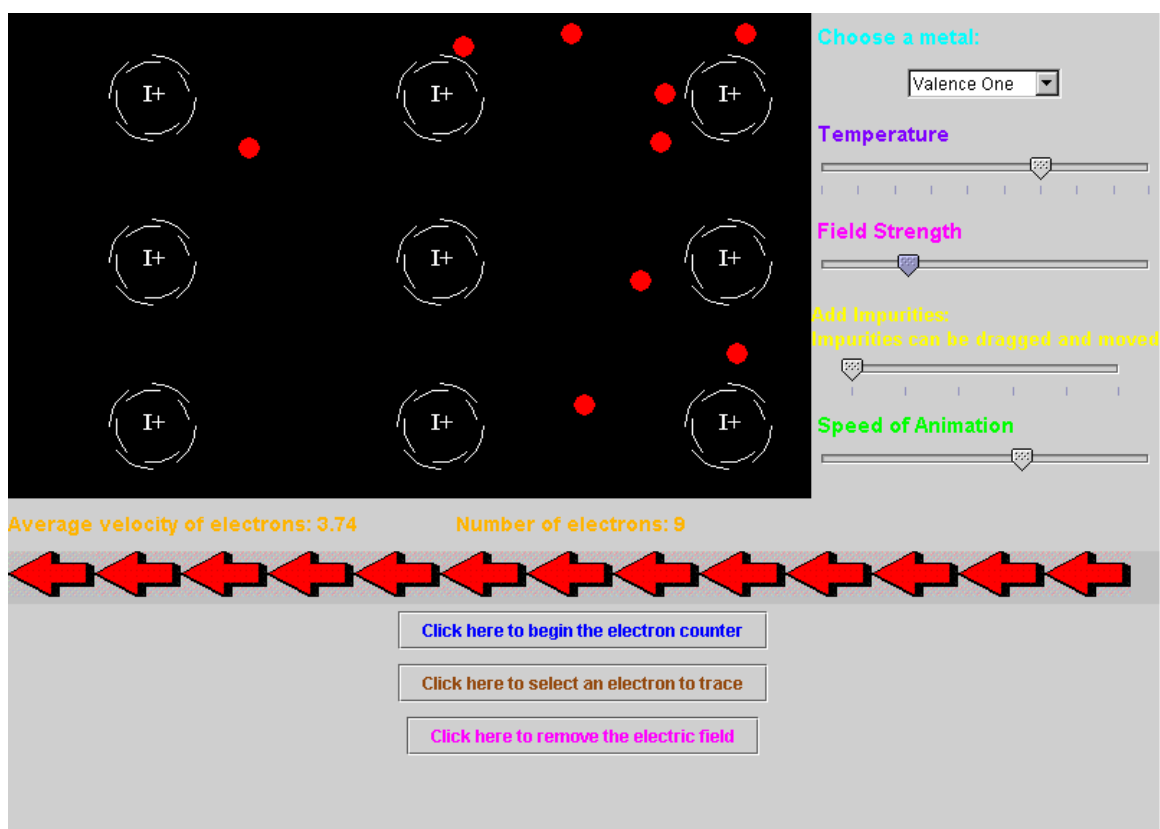


Figure 4.4: Electrons in Metal Simulation: electric field enabled

sic Semiconductor Simulation, or the Electrons in Extrinsic Semiconductor Simulation. The velocity, trace, and electron counters are the “benchmarks” on which students can gage the effects of the parameter changes.

The next feature of the simulation is the ability to add an electric field (Figure 4.4). When students add a field, electrons are drawn opposite the direction of the field, which is indicated by the red arrows. When there is an electric field added, students should notice electrons seem “pulled” in the direction of the field. They should also notice that the counters now reflect more electrons crossing toward the field than in the opposite direction. Finally, the students should note that electrons traced now have a curvature to their motion caused by the

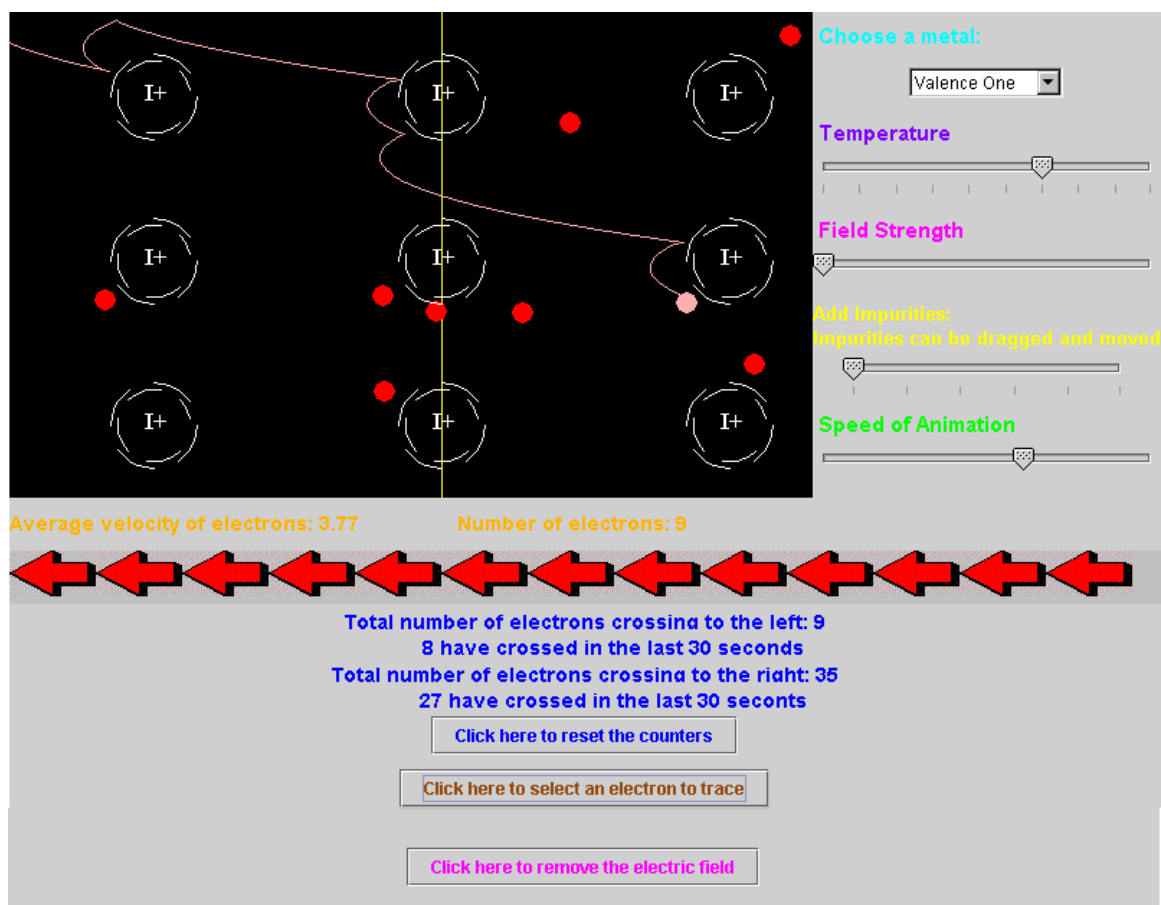


Figure 4.5: Electrons in Metal Simulation: electric field, electron trace, and counters enabled

electric field, as seen in Figure 4.5.

The temperature of the metal can be changed in the simulation. With increases in temperature, the vibration of atoms increases. This is represented by the circle around the atoms getting larger at high temperatures, and smaller at low temperatures (Figure 4.6, Figure 4.7). Although the atoms do not actually change size, they take up more room with their vibration. Students should notice the change in the area encompassed by the atoms. Also, students should notice that fewer electrons can cross the arbitrary plane. This illustrates the concept of resistivity.

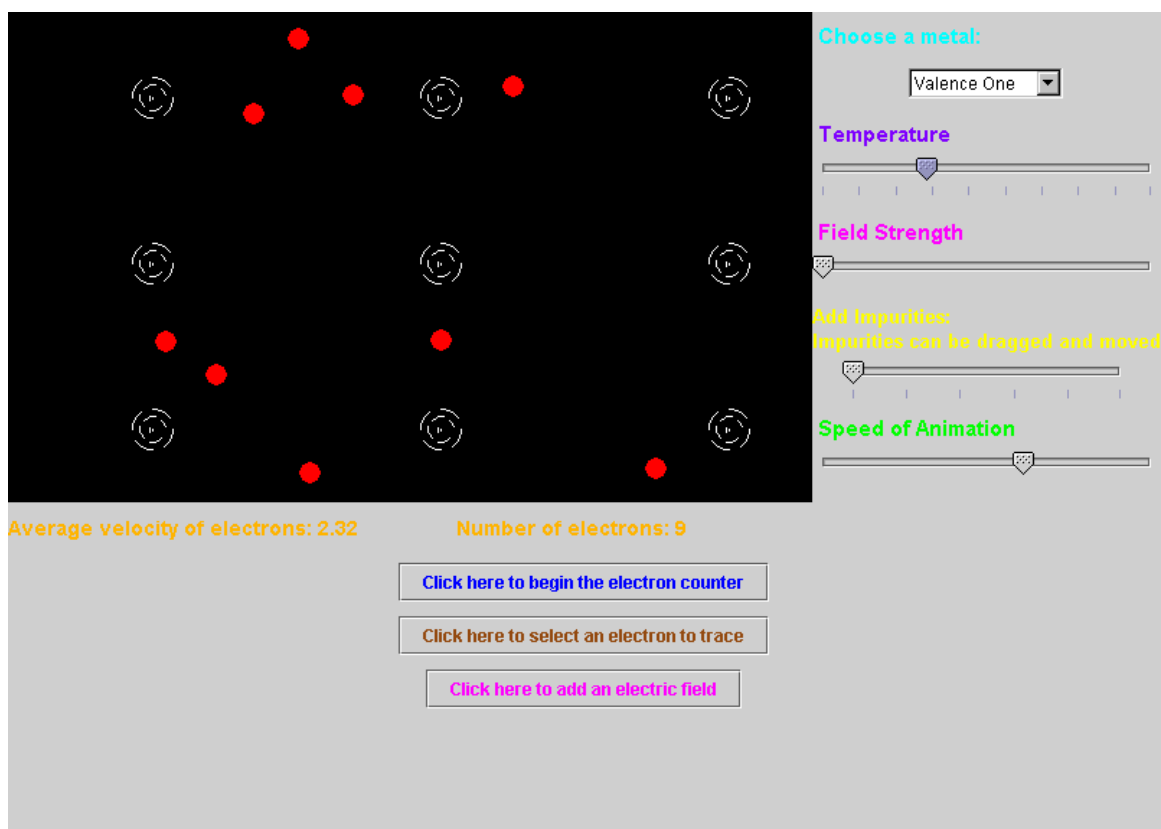


Figure 4.6: Electrons in Metal Simulation: low temperature

Interstitial impurities can be added to the metal. These are not dopant atoms like those in an extrinsic semiconductor, but foreign objects or defects in the metal, as shown in Figure 4.8. These impurities are not affected by changes in the electric field or temperature. Students can drag the impurities around the metal to see how the placement of the impurities changes the electron motion.

Finally, students can change the valence of the metal. By changing the valence, the number of electrons changes. Figure 4.9 and Figure 4.10 illustrate that with different valences, atoms release a different number of free electrons.

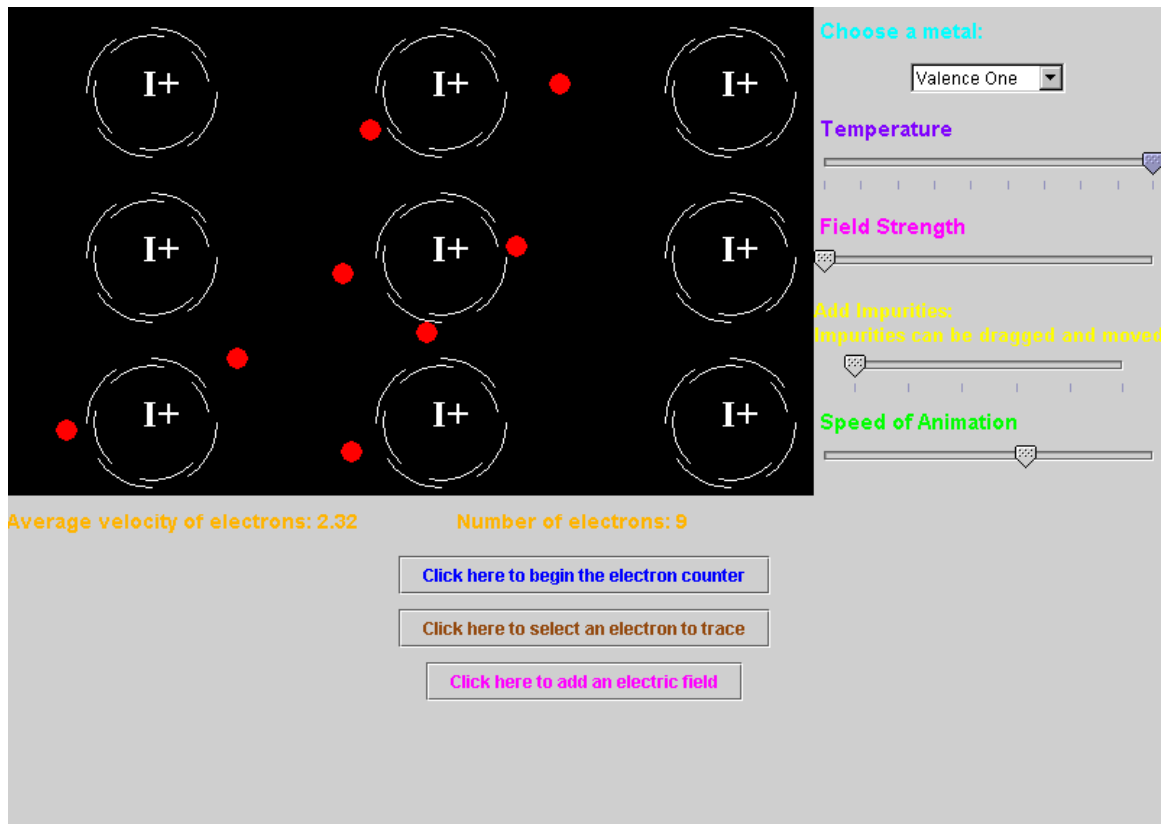


Figure 4.7: Electrons in Metal Simulation: high temperature

4.1.2 Concepts

The Electrons in Metal Simulation is designed to clarify many concepts for students. One such concept is electrical conductivity. By adding an electric field, conductivity or resistivity of a metal is not changed. However, when the temperature is increased, the increased vibration of atoms causes a decrease in the average number of electrons that can pass by any arbitrary plane. Thus there is a decrease in conductivity, or an increase in resistivity. Also, the presence of impurities will decrease the metal's conductivity by obstructing electron motion.

Another concept the simulation is designed to address is that of the mean-free path.

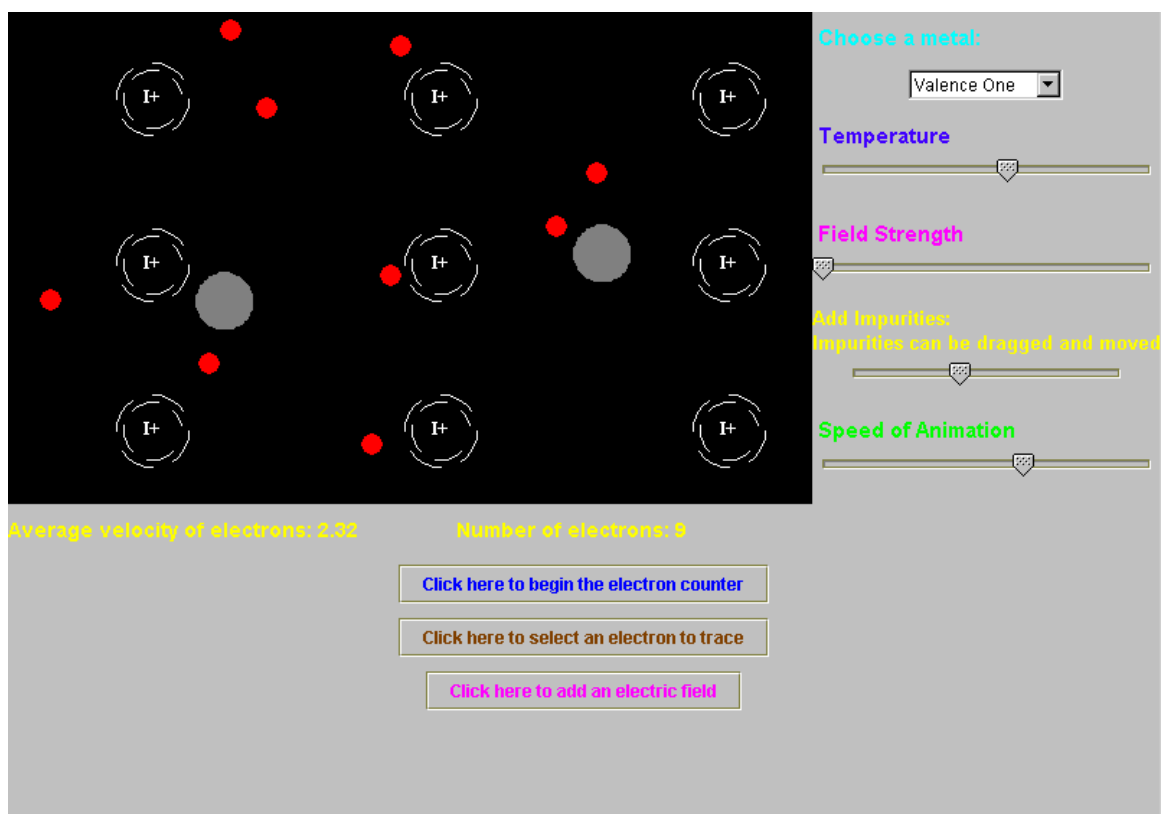


Figure 4.8: Electrons in Metal Simulation: impurities added

The mean-free path is the average distance electrons travel between collisions. Students can visually observe how often an electron collides with another electron or an atom.

Students should understand the effects of adding an outside force, such as an electric field. The average random speed of electrons does not change (this is given by the Fermi velocity of a metal). The electrons are, however, accelerated in the direction of the field.

Finally, students should note that the number of electrons in a metal is not affected by changes in electric field or temperature. The only parameter that affects the number of electrons in a metal is the valence of that metal. This is a property of the material. Depending on the valence, the atoms in the metal will release a different number of free electrons.

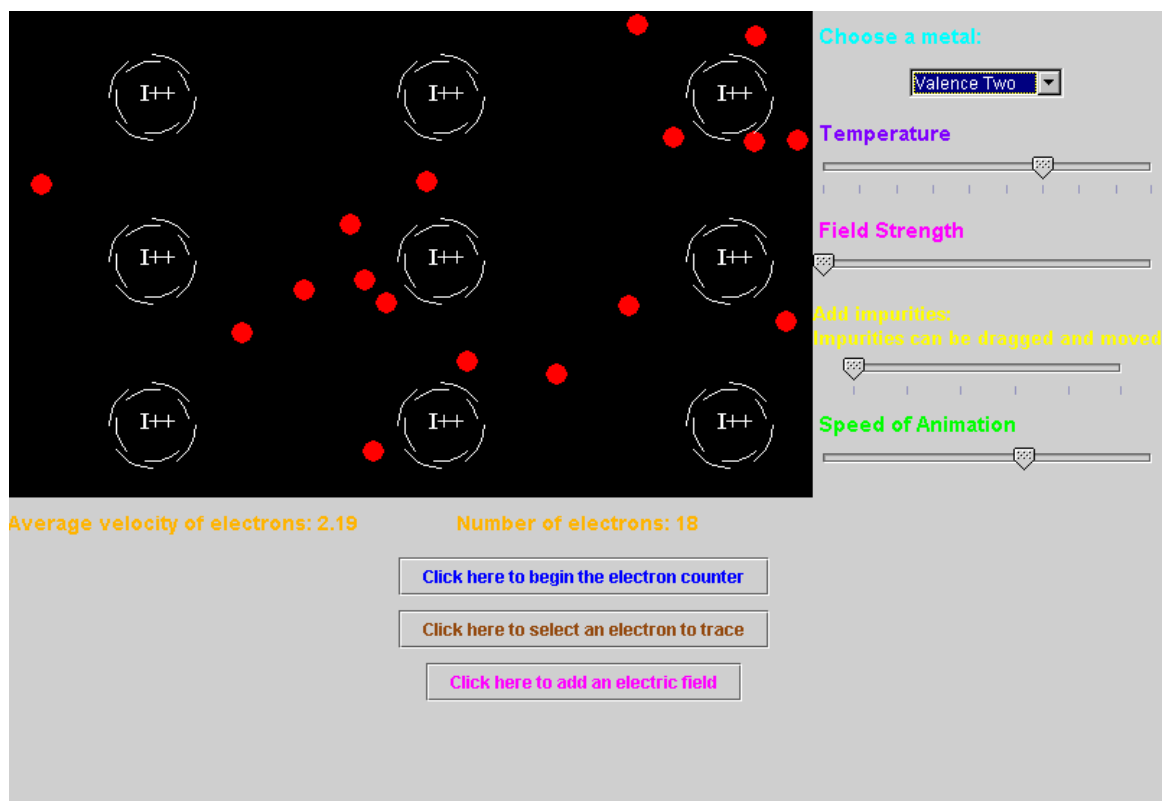


Figure 4.9: Electrons in Metal Simulation: valence two

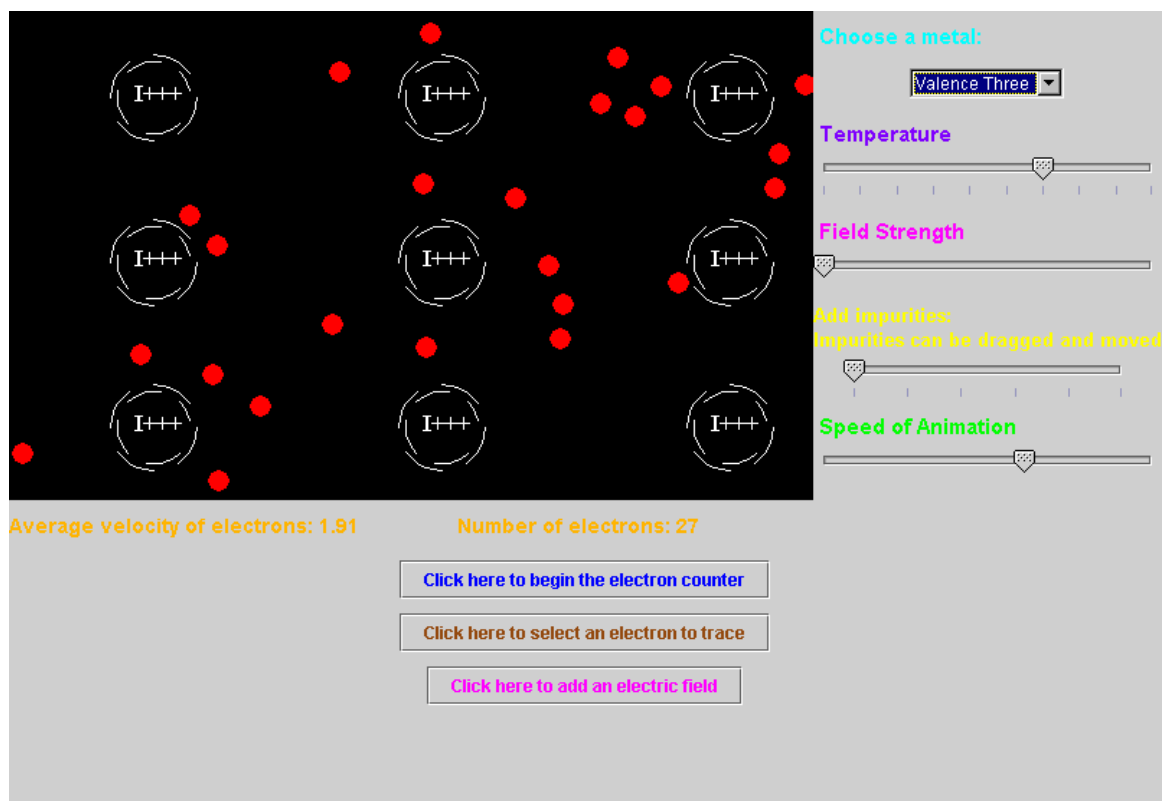


Figure 4.10: Electrons in Metal Simulation: valence three

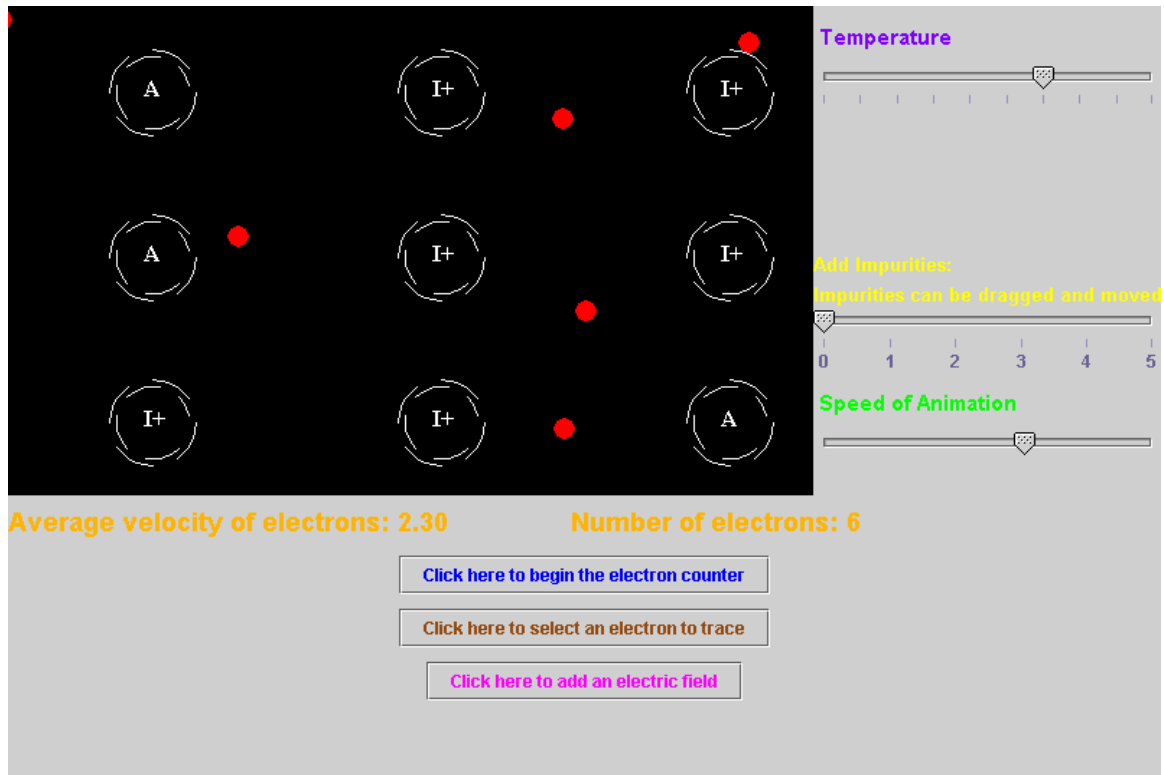


Figure 4.11: Electrons in Intrinsic Semiconductor Simulation: no parameters selected

4.2 Electrons in Intrinsic Semiconductor Simulation

4.2.1 Features

The Electrons in Intrinsic Semiconductor Simulation (Figure 4.11) has many of the same features as the Electrons in Metal Simulation. Students can monitor the number of electrons and their average speed. The students can set the counter to keep track of the number of electrons crossing an arbitrary plane in the semiconductor, as shown in Figure 4.12. Figure 4.13 shows the addition of an electric field. Students can also intensify the field. Students can momentarily stop the simulation to select an electron and trace its path, as shown in Figure 4.14. Figure 4.15 shows added impurities. Students can move these impurities

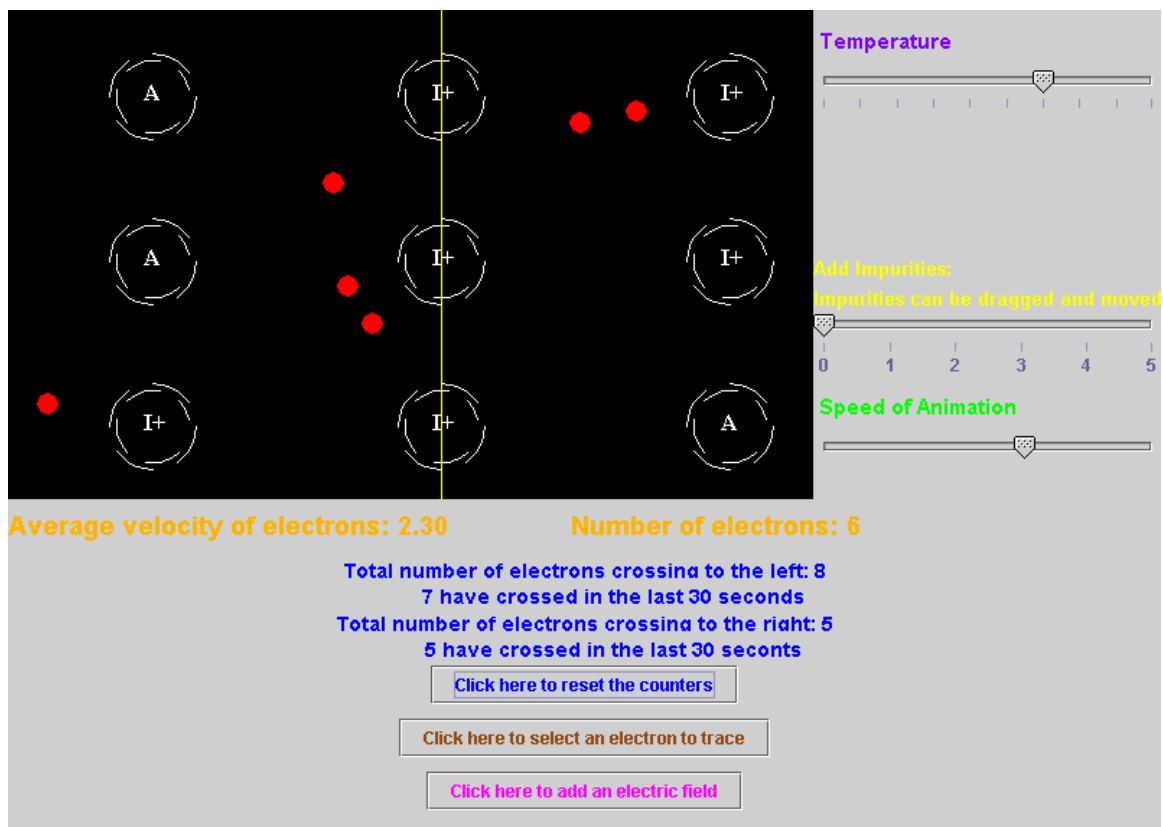


Figure 4.12: Electrons in Intrinsic Semiconductor Simulation: counters enabled

around the semiconductor.

The main difference between metals and intrinsic semiconductors is in the effects of temperature. At low temperatures, there are fewer ionized atoms and fewer free electrons, as shown in Figure 4.16. As temperature increases, more atoms become ionized, thus freeing electrons. The number of free electrons increases with temperature. As in a metal, the vibration of the atoms also increases, as can be seen in Figure 4.17. A student can note the difference between an atom and an ionized atom by the letter inside: “A” or “I+,” which represents atoms that have been ionized, and thus released a free electron. Therefore, the number of atoms labeled “I+” should match the number of free electrons at any time.

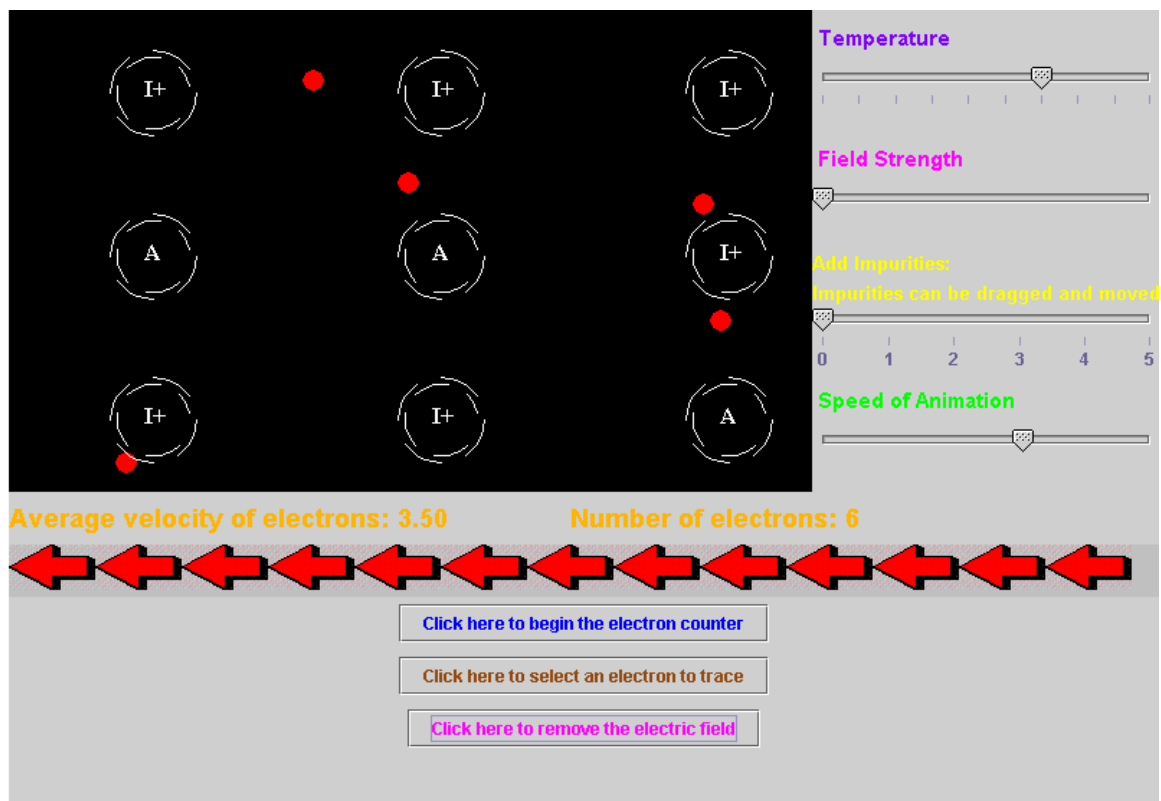


Figure 4.13: Electrons in Intrinsic Semiconductor Simulation: field enabled

4.2.2 Concepts

The most important concept for students to learn from the Electrons in Intrinsic Semiconductor Simulation is that as temperature increases, the number of free electrons increases, as does their average random speed. This is the significant difference between metals and semiconductors. This is due to the quantum-mechanical effect represented by the Fermi-Dirac distribution function for metals. In the case of intrinsic semiconductors, the average random velocity of electrons similar to the thermal velocity in classical gases and it scales with the square root of the temperature.

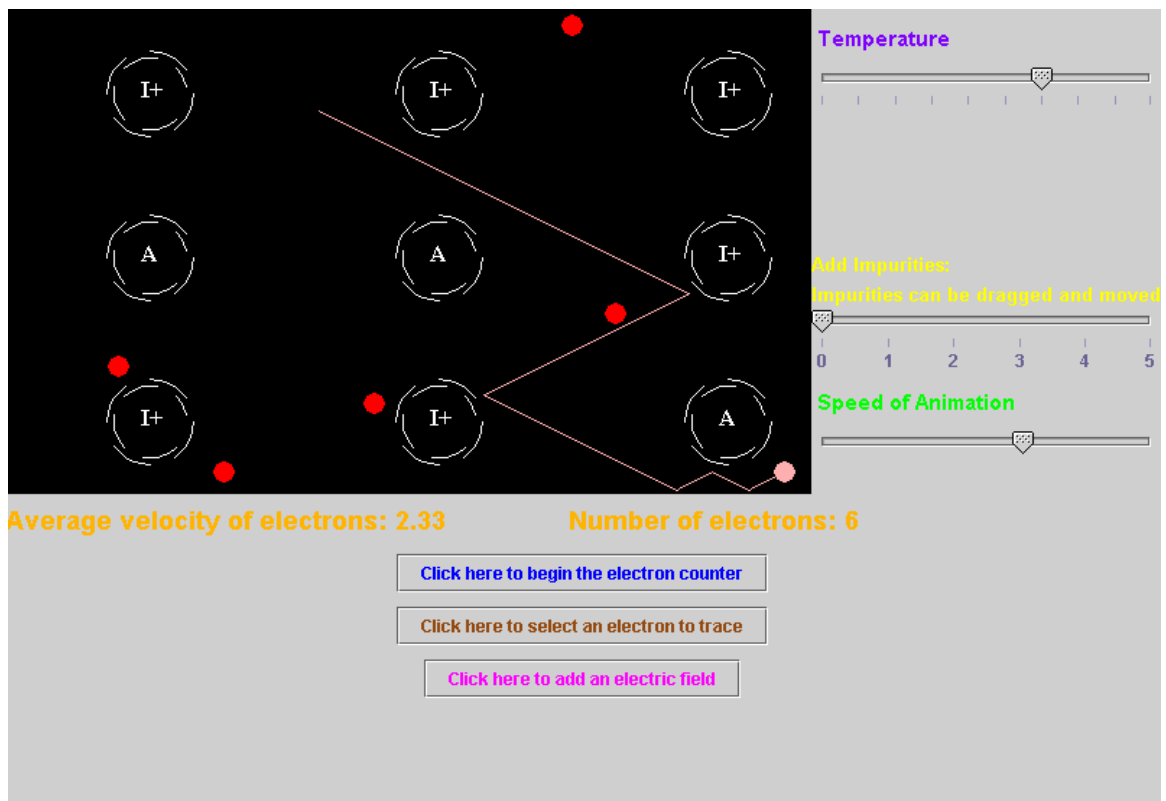


Figure 4.14: Electrons in Intrinsic Semiconductor Simulation: electron trace enabled

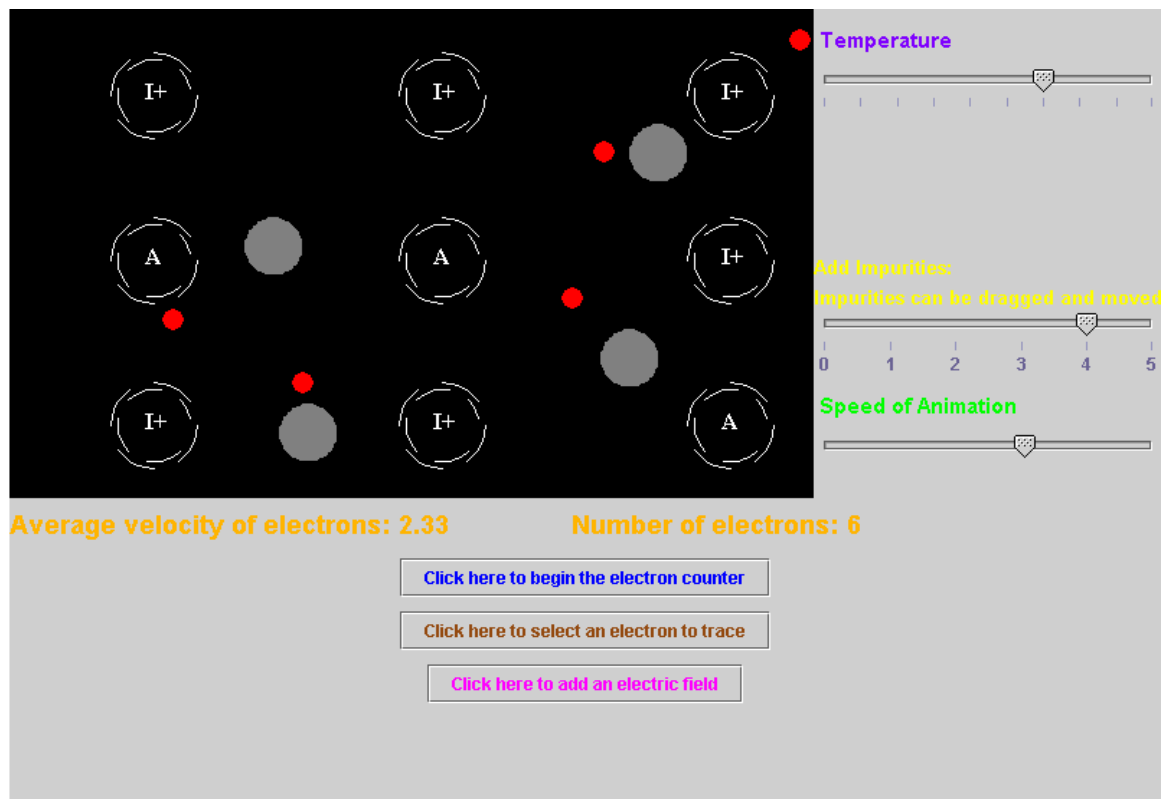


Figure 4.15: Electrons in Intrinsic Semiconductor Simulation: impurities added