Understanding Real Experiments in Electricity by Computer Based Simulation of Electrical Forces between Charged Particles

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Abstract. *Modern technology enables several approaches to learning of natural sciences. Real experiments can be nicely supplemented with virtual experiments. In this investigation we have coupled real and virtual experiment of a light conductive ball jumping between two electrodes of high DC voltage. Virtual experiment is performed with a program JaCob that is utilizing particle-particle simulation to model interaction of charged particles in space and time. Strength of the applied method is portability enabled by the Java coding, high solution speed enabling »real time« observation of electrical phenomena, direct simulation of forces between charges instead of calculation of (abstract) electric fields and a special scripting language for fast and simplified creation of new experiments.*

Keywords. Virtual experiments, electricity, physics, particle simulation, electrical ping pong.

1. Introduction

With the advent of technology new approaches to teaching natural sciences have appeared. They are particularly related to possibilities offered by modern computers with increasing sizes of displays and resolution and of course day-to-day increasing computing power [1]. Especially young people are more easily becoming interested in learning technical sciences if the learning process includes the use of modern technology. Those teaching natural/technical sciences should be particularly aware of the strengths of modern approaches and should continually develop new methods to engage students in the learning process.

In this paper we discuss the teaching of electrical phenomena through a combination of demonstrations of virtual and real experiments. In our opinion there is no adequate replacement to real experiments. They should remain the strongest teaching/demonstration tool as no simulation can mimic a real experiment in full detail. Every simulation is to a certain extent only a simplified model of the real experiment. Moreover, students should learn that – especially in the learning of physical sciences – we are in fact applying mathematical models to real life phenomena in order to better understand and control them and to profit by using these principles to develop new devices. To achieve this goal all methods that facilitate the teaching process are justifiable.

Virtual experiments are based on computer simulations that have already found widespread (worldwide) use as a supplementary material in the teaching process. The major advantage of computer simulations is an excellent visualization effect that is of special interest in the description of electrical phenomena since the effects of electrical forces are described through action of abstract fields that are hard to imagine.

Various kinds of computer simulations can be used. Most frequently these simulations are based on numerical solving of differential equations. The equations describing basic physical laws can be solved in a certain discretized domain, as for instance solving discretized Maxwell equations for analysing electrical phenomena. Several programs are available for such purpose (EMAS; FEMLAB; MAXWELL). Some offer even student versions of the program free of charge. Advantages of this approach are several possible visualizations of (abstract) electric and magnetic fields and potentials, two-dimensional contours, vector plots, color graphs, 3D color graphs, etc. The disadvantage of this approach is a rather time consuming procedure for calculation, especially when dynamic phenomena are observed. In such cases the simulations can be performed in advance and the solutions merged into a movie type demonstration. With the advancement of this type of programs, a hands-on approach is possible and even recommended, however, students of electrical engineering at our institution get fully acquainted with a discretized form of Maxwell equations in the third year of study. As a consequence, it seems more appropriate to use such programs in the first year only for demonstration purposes and eventually for freely chosen student seminars. In this article, we will demonstrate a program for the construction of virtual experiments in electricity that is based on solving fundamental equations describing forces between charged particles/elements. As such, the program is suitable for use even for novice students, since it is based on fundamental law for electric and magnetic forces between the charged particles (Lorentz force). In electrostatics only a Coulomb force is considered that describes attractive and repelling force between charges. By obeying a superposition principle it is possible to calculate forces between large numbers of charges in "real" time. This means that for a reasonable number of charges the calculation can be performed in a short time allowing visualizing the movements of charges in response to electrical forces on a computer screen.

2. Real experiment

Electrical ping-pong is chosen as a demonstration experiment for two reasons. Firstly, it is an experiment that is sufficiently dynamic to stir the interest of the students and secondly, it is probably one of the most popular experiments in physics performed around the world [3]. The concept of an experiment is shown in figure 1. A small conductive ball is

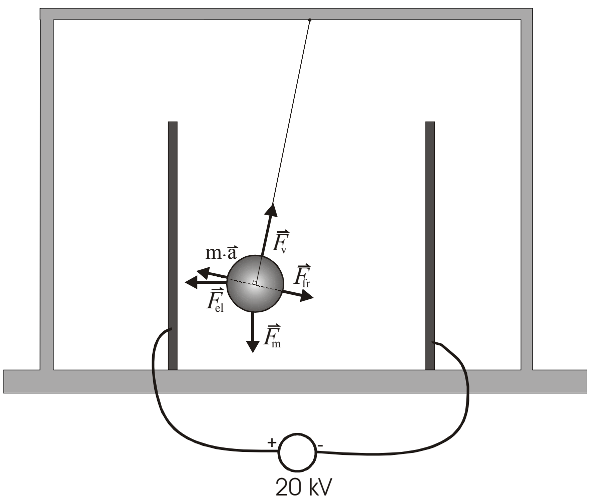

Figure 1: Schematic representation of electrical ping-pong experiment with forces acting on a charged ball.

hanging on an insulating string that is attached to a casing or to a separate stand. The ball is usually a ping- pong ball covered with a thin conductive foil, a ping-pong ball painted with a conductive paint or galvanized (nickeled). The ball is placed between two parallel conductive plates that are connected to a generator of high voltage. Most frequently we use a DC voltage source of aprox. 20 kV, however, an electrostatic generator such as Whimshurst or Van de Graaf can be used for this purpose as well. When a generator is started and the ball is forced to come into contact with one of the charged plates, it starts to bounce between the two plates. The frequency of bouncing can be increased by reducing the distance between the plates or reduced by increasing the distance.

The reason for bouncing is of course due to the action of electrostatic forces: the ball charges to the same charge as the contacted plate. As such the force on these charges is directed toward the opposite plate. This force plus the force from a non-elastic bounce from the plate and the force due to the gravity are sufficient to bring the charged ball to touch the opposite plate where the process is inverted. The ball first discharges and then charges with the charge from that plate. The process repeats itself until the plates are connected to the high voltage source. As a matter of fact, even if the source is disconnected, the voltage between the plates is slowly decreasing due to a discharging process.

From examining the experiments an observer can make some fundamental conclusions: a) since it is obvious that a swinging ball stops after some time, the reason for continued movement of the ball must come from contacting the plates to the electric supply; b) a very high voltage source is required (we are more used to a range of voltages from a few volts to a few tens of volts) to move a small, light, charged ball -> electrostatic forces are week forces; c) the force on a ball is increasing with reduced distance between the plates that electric. With some additional experiments with the same equipment one can see that the charged ball is either attracted to or repelled from the charged plates. From this one can assume that equal charges attract and opposite charges repel. Furthermore, by replacing the conductive ball with a non-conductive (isolative), the experiments show no bounding effect. Non-conductive objects can not be charged as conductive objects and as a consequence there are no electric forces on such balls. There is an interesting exception worth noting, namely, if a non-conductive ball is placed near the conducive bouncing ball, a small movement, mostly rotation, of a non-conductive ball can be observed. This interesting phenomenon can be nicely explained through an electric polarization of a non-conductive ball by the charged plates and an electric force on a dipole.

3. Virtual experiment

Virtual experiment is performed with a program utilizing particle-particle method (PPM). With this method, basic phenomena in electricity can be modeled by calculating the forces between the charged particles and consequently elements in which they reside. The program used has been named JaCoB, which stands for "Java constructive objects" [4, 5]. The program is dynamically solving electric (and magnetic) forces between particles and in each time step moves the particles for a small distance according to the magnitude and direction of a force on each separate particle. The magnitude and direction of force on each charged particle is visualized by arrows as shown in Fig. 2 for a simple simulation of a negatively charged corner and a positively charged cylinder (circle).

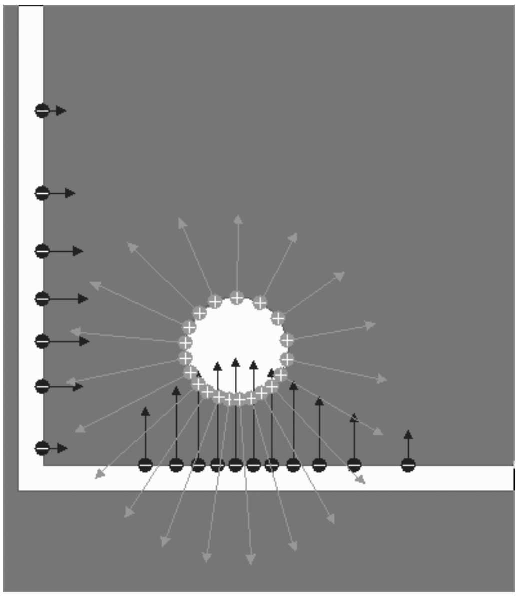

Figure 2: A simple example of two objects with charged particles and electrical forces between them. The particles move until they rest at the position when the force is directed

The particles reside inside primitive objects that can have the form of a circle, ring or an arbitrary polygon. More complex structures can be created by merging the primitive objects.

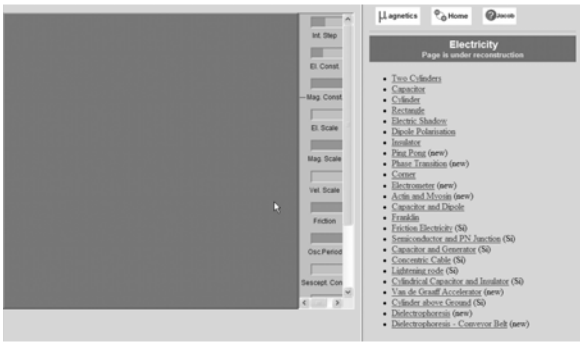

Figure 3: Web page with predetermined virtual experiments and a demonstration table for creation and running of own experiments.

By observing the development of forces between the particles and consequently between the objects containing charged particles, the students can visualize several important concepts of electricity that are otherwise difficult to understand such as electrostatic induction, formation of high electric fields around sharp corners, zero electric field inside conductors (electrostatics), etc.

Fig. 3 shows a Web page of the program with a blank demonstration table for creation and running of the experiments on the left and predefined virtual experiments on the right. These experiments utilize special scripting language similar to JavaScript that enables experienced users of the program rapid development of new virtual experiments.

Virtual electrical ping-pong is created by using two sources, one for positive and one for negative charges. If in contact with other objects, the objects are "open", meaning that the charges are allowed to escape the boundaries of the object. Furthermore, a cylinder (circle in 2D) is created that is allowed to move laterally from the left to the right electrode. At the beginning of the experiment the cylinder needs to be charged or in contact with one of the electrodes. When the program is run, the charges residing in a cylinder discharge when in contact with the electrode of opposite charge and charge to a charge of that electrode. Since equal charges repel, the ball is pushed by electric forces to the other side (electrode) and the process is repeated.

"Real time" observation of particle movements enables clear insight into charging and discharging mechanisms and consequently in the complete operation of a device (experiment).

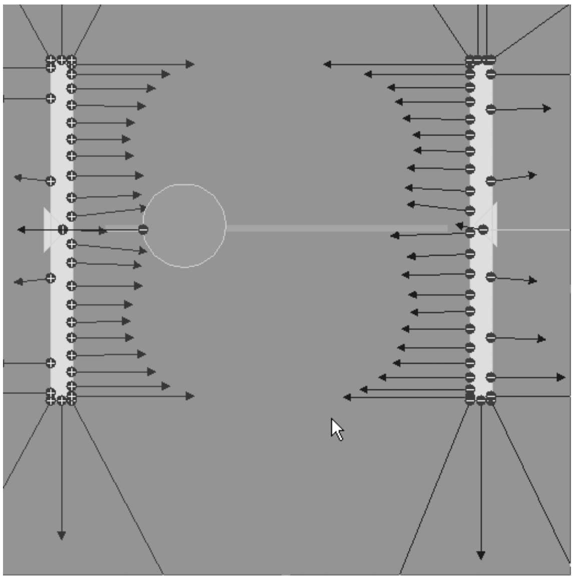

Figure 4: Virtual experiment: electrical pink-ponk.

In the observation of a virtual experiment we can add some tools that give additional visual feedback on certain physical quantities that are otherwise not observable, such as : potential detector, electric energy gauge, capacitance gauge, electric field detector, current gauge, etc. Figure 5 presents two typical gadgets – a voltage gauge and a current gauge. By use of these gadgets we basically created virtual instruments – a voltage and current meter.

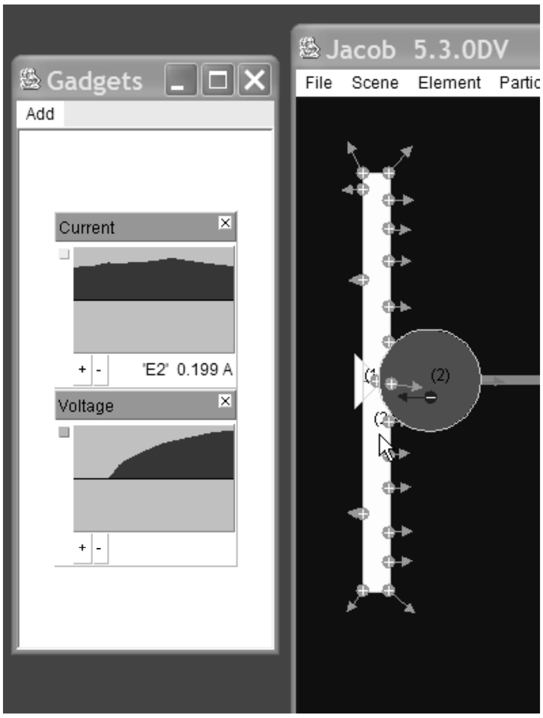

Figure 5: Potential and current gauge acting as virtual voltage and current meters.

4. Discussion

There are many approaches to teaching of natural sciences. In this article we presented one of the possible approaches to utilizing modern technologies in combination with observation of real experiments for learning fundamental electric phenomena. We would like to emphasize the strength and importance of simultaneous use of both approaches – a real and a virtual experiment. In fact, it would be advisable to use several possible approaches offered by modern technology, such as multimedia videos, schematic dynamic models (in Java programming language), simulations on a discretized domain, construction of differential equation(s) describing the fundamental principles of movement of a charged ping-pong ball (that can be solved by such programs as Matematica or Matlab), etc.

We have recognized several important advantages offered by the JaCoB program utilizing particle-particle simulation:

- The program enables "hands-on" approach directly through internet connection (without necessity to load and install the program).
- Fast solution of forces between the particles enables "real-time" observation of fundamental processes (movement of charges).
- Simulation of forces between the charged particles directly and not through the abstract fields gives better insight into interactions between charged objects.
- Additional gadgets (tools) for displaying some additional quantities of interest as for instance potential/field detector, current and voltage meters, etc.
- Special scripting language can be used to facilitate creation of new models and construction of web pages utilizing them.

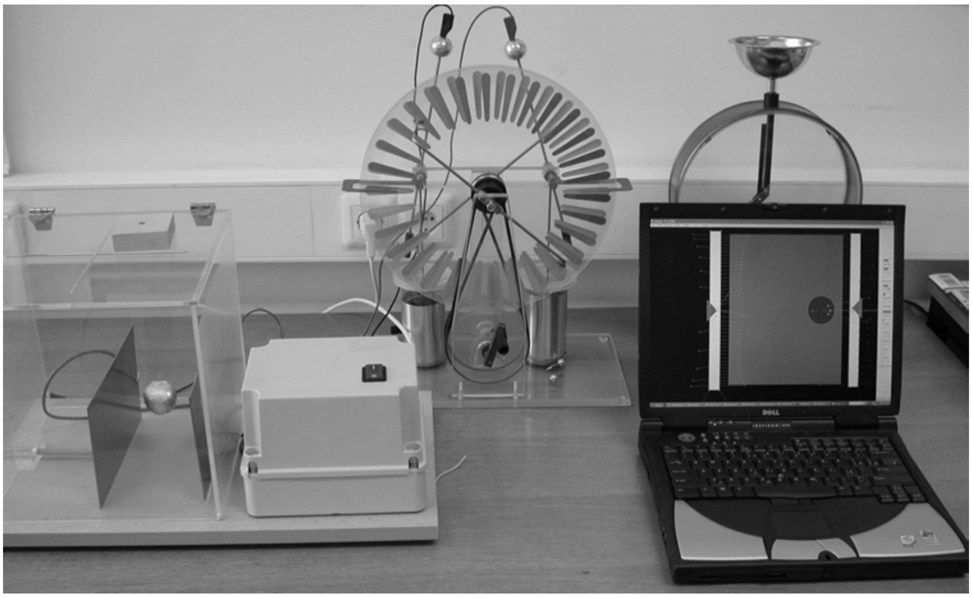

Figure 6: Real and virtual experiment side-by-side. Real experiment can be powered with a 20 kV DC source or with a Wimshurst electrostatic generator.

5. Conclusion

An approach for learning fundamental principles of electricity through a combination of real and virtual experiments has been discussed. A well-known electric ping-pong experiment has been used for this purpose. Virtual experiment was performed with JaCoB program utilizing particle-particle simulation principle. With this method, electric (and magnetic) forces between the charged particles residing in primitive objects is calculated simultaneously and the particles are moved in each time step according to the last calculated force on a particle.

Several advantages of the utilized approach have been identified as well as some shortcomings that will be investigated in the future.

6. References

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