

Debunking The Pretty Picture Myth: Teaching Basic Physics Using Color Maps

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ABSTRACT

The color time-domain maps of fields produced by computer graphics packages are visually striking and the danger exists that they are considered just pretty pictures. On the contrary, they represent a powerful technique for exploring fields. We do not, in general, spend enough time on graphing and interpreting graphs in our science courses and our students do not develop the interpretive skills that are so necessary in science today. We describe computer-based exercises that help students develop the skills to read graphs.

1. IT'S NOT JUST A PRETTY FACE

Lately, there have been editorials on the abuses of computer graphics in the professional scientific journals and I have heard many comments of a similar nature made at professional meetings. Some have made points that anyone would do well to heed Miller (1994), Globus (1994), Bailey (1991). The blind application of any technique or methodology without engaging the mind is a fruitless, at best, and often self-deceiving activity. In order to reap the benefits of a given technique one must understand how the technique works and not just pull off the shrink wrap and blindly apply it.

Although the proliferation of simulation and visualization packages for desktop computers has placed sophisticated computational and graphical tools into the hands of people who are not necessarily trained in their use, these techniques are hardly "eyewash". There is a frequently expressed view that graphical representations of a data set are nothing more than pretty pictures and use of these techniques is not "real" science. Whether such views stem from scientific machismo or a tradition of frequency domain techniques, the "pretty picture" view is a misrepresentation of the role of computer graphics in science, and accents that we do not place enough emphasis in science courses on how to make either a good graph, or how to interpret a graph. The appropriate use of computer visualization techniques is an educational issue that we need to address.

On one level there is the perspective of Astrophysicist Larry Smarr (1994) who commented on the application of computer visualization techniques to General Relativity, "The most important thing that this [visualization] is going to lead to is the development of the

intuitive sense of our science. General Relativity has always been a science for mathematicians. Most physics you do with your guts." His comment applies to electromagnetics which for most students is formidable and abstract.

On another level, however, this problem has much more significance. How can software engineers verify the code they have written. I am often reminded of a quote I heard second-hand attributed to Hans Bethe, "The problem with computers is that they always give you an answer". Whether that answer has anything to do with the real world is the crux of the problem. Teaching people to critically evaluate the output of the code they have written is a non-trivial task.

As desktop PC's have increased in power to the point that they are comparable to scientific workstations, and the linear physics problems have become solved, we have seen a great migration to the desktop for computational solutions of the very difficult non-linear problems. These problems are difficult enough that analytic solutions are not possible, and the data sets large enough that poring over reams of numbers is no longer an efficient nor plausible method of attack. As pointed out by Steen (1988) and further explored by Miller et al. (1988), science is a process of recognizing and understanding patterns that exist in nature. Efficient graphical and animation techniques have been developed to explore large data sets and visually enhance our pattern recognition capabilities Tufte (1987), Friedhoff and Benzon (1989), Wolff and Yeager (1994), Cole (1986).

2. THE EFFICACY OF SCIENTIFIC VISUALIZATION

What is it then that graphs tell us? To illustrate, consider the three representations of a problem in Table 1, Equation 1 and Figure 1. By looking at the data in Table 1 what can you see immediately? What strikes you about the data? What are its noteworthy features? Looking at just the numbers, it is hard to tell. It takes a careful analysis of the data to obtain these features. One technique is to fit the data with a polynomial. Equation 1 is a function that fits the data. What does it tell you--significantly more than the data? Not really, it provides the same information as the data but it is organized differently, in a readily accessible form. Another technique would be to plot the data as shown in Figure 1. Looking at the simple graph of

the data can you see any interesting points? Does the graph tell you anything interesting about the data?

TABLE 1

U(r) starting at r = 0.5 in steps of 0.05			
4032.	1269.	437.9	162.5
63.75	25.95	10.73	4.379
1.659	0.4902	0.0000	-0.1894
-0.2458	-0.2454	-0.2227	-0.1934
-0.1642	-0.1379	-0.1152	-0.0960
-0.0801	-0.0669	-0.0561	-0.0471
-0.0397	-0.0336	-0.0285	-0.0243
-0.0208	-0.01786	-0.0154	-0.0133
-0.0115	-0.0100	-0.0087	-0.0076
-0.0067	-0.0059	-0.0052	-0.0046
-0.0041	-0.0036	-0.0032	-0.0029
-0.0026	-0.0023	-0.0021	-0.0019
-0.0017	-0.0015	-0.0014	

$$U(r) = \frac{1}{r^{12}} - \frac{1}{r^6} \quad (1)$$

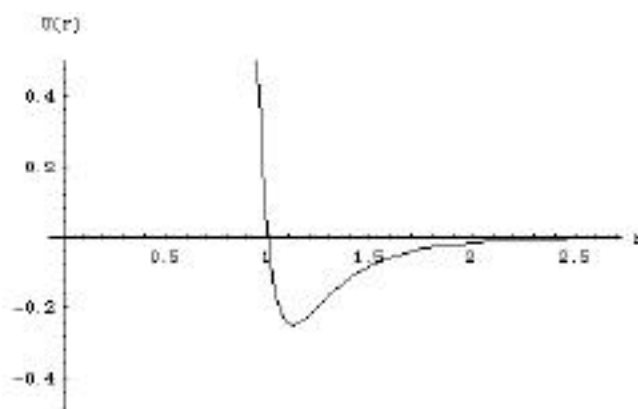


Figure 1—A graph of the Lennard-Jones potential.

By looking at the graph or the equation, one can instantly see that it is a plot of a Lennard-Jones potential which is a semi-empirical potential used to model the interaction between molecules. The hard core, attractive tail and potential minimum are key points hidden in the data set that the graphing has given emphasis. This information is contained in the data, but it is more readily accessible in the graph. From this graph you can easily see where the force on a charged particle placed in this potential is repulsive, where it is attractive and where it goes to zero. Places where the extrema of a data set occur and where the gradients are large provide insight into a data set.

This simple example serves to remind us how powerful and useful graphic techniques can be. Consider the problem of understanding something as complicated as a jet of fluid where turbulence exists at the boundary between the jet and the bulk fluid as shown in Plate-1, Michael Norman NCSA. The visualization of the numerical data produced by the computer can readily be compared to experimental data sets such as shown in Plate-2, Stanford Gas Dynamics Laboratory, which were obtained using lasers to optically enhance the turbulence. In these cases, the problem is considerably more complex and understanding the critical patterns is difficult and would be impossible without the computer visualization techniques. Understanding the patterns hidden in nature is the role of science, and graphs are a time-honored tool for recognizing patterns and studying features of complicated data sets. The task is then two-fold: first to develop exercises that teach students how to interpret complicated graphs and second to develop the ability to relate the graphs to the mathematical model that describes a phenomenon. This second point has been treated previously, Cole et al. (1994a), so we will concentrate on the first.

3. EXERCISES FOR INTERPRETING TWO DIMENSIONAL STATIC FIELD MAPS

We want the students to work with interactive computer tutorials and simulation exercises that help them develop the ability to accurately interpret field maps. This ability to interpret maps is not easy to acquire, but is very powerful and can save one from making mistakes. As an example consider a problem on electrostatics typically assigned in introductory physics texts, Giancoli (1982).

Exercise 2.1 Three charges q of the same sign and magnitude exist at the corners of an equilateral triangle. Make a map of the electric potential. Find the places where the electric field will be zero. Hint: there is more than one place.

The point at the center is easily identifiable as having zero field, but there are also places on the midpoint of each side of the triangle where the field is also zero. The mathematical solution is non-trivial and algebraically messy (a good task for a Mathematica exercise). One can use superposition to find the potential, and then find the extrema of this potential. On the other hand, a field map of the potential easily shows that there is minimum or slight "well" in the potential at the center and also there are saddle points at the mid-point of each side as shown in Plate 3(a). In this example the program "SilverHammer" available from the Center for Computer Applications in Electromagnetic Education (CAEME) has been described elsewhere Cole et al. (1994b). Places where the extrema occur are sometimes subtle, and it requires skill to readily locate them on the map. On the other hand, it is very easy to locate places where the gradient is zero on the false height map shown in Plate 3(b).

The second group of exercises use a program called "Electric Field Hockey" by Ruth Chabry (1993) and is described in Sherwood and Andersen (1993). In these

exercises the student is to dynamically explore the inverse square nature of the electric field. The word dynamics is important because the lessons learned by using a dynamic, interactive program are much more convincing than the static lessons in a textbook. In "Electric Field Hockey" the "puck" is electrically charged and you can place other fixed charges at strategically located places to deflect its trajectory such that the puck circumvents various barriers and lands in the goal. We previously described, Cole et. al. (1994c), an exercise in which students graph the electric potential due to the deflecting charges and plot the trajectory of the puck through the potential map. In practice, the exercise was too difficult for students and did not work well without considerable modification. We first have them work with individual charges and then they progress to the effect that a saddle point or well will have on a charged particle. They thus gain an understanding of how a charged particle will react to a given potential.

Exercise 2.2 Use a charge with the same sign as the puck to shoot the puck toward a charge of the opposite sign of the puck such that the puck passes near the charge, but does not hit it. What are the characteristics of the trajectory? Make a map of the electric potential. How do the features of the electric potential cause the particle to follow this path?

The path is shown in Figure 2 and the map of the potential in Plate-4. From simple exercises such as this, students learn how an electric potential affects the motion of charge. For introductory students, the electric potential is an abstract concept that is difficult to understand. The next step is to make the exercises considerably more difficult by

Level 0
(ball moveable)

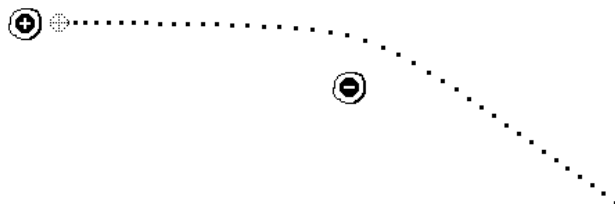


Figure 2 - Trajectory of a particle through a potential well when the energy of the particle is larger than well.

leading students to understand how bound systems work.

Exercise 2.3 Place a charge of the same sign as the puck on each corner of a square. Describe the region where the puck can be placed such that it is trapped within the square in a stable orbit. Make a map of the electric potential for the four charges. What characteristics of the map help you determine the region that traps the puck?

In this exercise students can try to shoot the puck into the well and find that it does not work. Because of the

conservative nature of the field, the particle will always have enough energy to escape the well. To be trapped inside the well, it must start inside the well. Also, they learn it is quite easy to give the puck enough energy to escape the well if it starts close to one of the other charges.

Exercise 2.4 Find the minimum number of charges of opposite charge that will trap a puck in a stable orbit. Make a map of the electric potential for this arrangement of charge and draw the orbit on the map. How is this case different than the last case using only similarly signed charges?

The answer to this last exercise is just one because the opposite signed charge will attract the puck and trap it in its potential well. The similarities between the cases is what is of interest. In both cases we are trying to create a potential well. Students learn it is easy to create a well with charges of the opposite sign, but much harder using particles of the same sign.

These exercises build upon the lessons learned previously and teach the students the importance of minimums and maximums in the electric potential. There are a wealth of things that one can do with this type of exploration, such as, having students try to balance charges at saddle points so they gain an understanding of the stability of a potential. One of the biggest attributes of this learning is that the students learn the concepts. They quickly develop an intuitive sense for electrostatics. Once they develop the ability to read a map, we move into dynamics by considering magnetic fields.

4. DYNAMICS AND MOVING CHARGE

When charge moves it produces a magnetic field as well as an electric field. Because the charge is moving, the fields must be evaluated at the retarded time. Laws such as the Biot-Savart law work for wires which produce static fields, but cannot be used for more than obtaining a qualitative behavior of the magnetic field for moving point particles. Because of the difficulty in computing retarded times, students are not usually given practice with magnetic fields from point particles. However, using computers we can easily plot the fields even from point particles.

$$d\mathbf{B} = \frac{\mu_0 I}{4\pi} \frac{d\mathbf{l} \times \mathbf{r}}{r^3} \quad \text{Biot-Savart Law}$$

Exercise 3.1 Use "SilverHammer" to make a contour plot the magnetic field for a point particle moving with a constant velocity. Use the Biot-Savart law to find the direction of the magnetic field and then sketch the magnetic field lines. Where is the magnetic field strongest? Where is it zero?

The first exercise is just a simple mapping exercise for a magnetic field from a single point charge, Plate 5. It draws upon the student's previous experience in using maps. This exercise is also the student's first encounter with a field that is zero along a particular axis which is a configuration that is important for understanding dipole radiation in

which the radiated field is zero along the axis of the dipole. Note that this exercise also asks the student to interpret various attributes of the map and links them to the traditional mathematical statement of the Biot-Savart law. This is a key point. The students must learn how to couple their map reading skills with the traditional mathematics. I have found that this improves the mathematical skills of the students because they gain additional insight into the mathematics when they have to connect it to a map.

Exercise 3.2 Compare the superposition effects of the magnetic fields from multiple charged particles. Place two like charged particles side by side. Describe the fields when the particles are moving along parallel paths. Describe the fields when the particles are moving along perpendicular paths, and finally, describe the magnetic field when the particles move along anti-parallel paths (parallel but in the opposite direction). Where do the fields add constructively. Where do the fields add destructively.

We treated simple superposition effects with potentials and now the superposition of the fields is considerably more complex as shown in Plate 6 (a) - (c). The magnetic field lines form circles about the particles. The regions where the fields constructively interfere are determined using a right hand rule. This set of exercises gives they students practice with the right hand rule, superposition, and map reading.

Exercise 3.3 Place 5 identical particles in a line. Give each the same velocity directed along the line. Make a contour map of the magnetic field. Discuss the superposition of the magnetic fields. Where is the magnetic field strong, where is it weak? Are the directions of the field the same on both sides of the line?

This exercise has the students approximate the magnetic field from a wire segment by using a collection of point particles. The student must again use superposition and the Biot-Savart law to interpret the map. The fields are shown in Plate 7.

The purpose of these exercises is to improve students' map reading skills and their understanding of the basic principles of electromagnetics. This process culminates with understanding the fundamentals of electromagnetic radiation. The radiation process is complex enough that it requires sufficient map reading skills, Cole (1994a). The fields from an impulsively excited point particle are shown in Plate 8. As in the previous examples, the students should understand where the field is zero and where it is strong. Furthermore, the student should be able to use the fundamental principles, Ampere's law and Faraday's law, to show why the fields are strong perpendicular to the axis of acceleration and why the fields are zero along this axis.

5. CONCLUSION

The previous work has been done with two-dimensional maps; however, many data sets must be

analyzed in three-dimensions. Particularly exercise 3.1 would benefit greatly with the ability to visualize the fields in three dimensions. Whenever the fields are given by right-hand rules, a three dimensional visualization technique is required. One promising type of volume rendering has been developed by Johnson et al. (1994) in which a smoke rendering technique is used to visualize the structure of molecules and solids. Layers are rendered with different colors and each layer has a transparent nature that allows one to effectively see into an object, Plate 9. The density of the smoke can be changed so that the structure of object is thus visible and is in contrast to a "slicing" technique employed in Plate 2(b) and used in the NCSA program "Dicer" which is available from Spyglass. We hope to apply the technique to electricity and magnetism. Volume rendering is computationally intense and is not practical in the classroom at present. However, we are optimistic that the progress in processing power will soon make such visualizations possible. As with any technique, one cannot just show these new 3-D visualizations and expect students to understand them. Just as we gave done with the 2-D maps, we must work with students so that they understand how to use them and how to interpret them.

There is always a danger, when introducing new techniques, to assume that everyone else can see the same things that you do. However, map reading is an acquired skill that takes practice. Although maps are not a cure-all for electricity and magnetism, they are an efficient mechanism for understanding field interactions. They are more than just pretty pictures. When carefully applied, they can produce a deeper intuitive understanding of a field.

REFERENCES

Bailey, D., (1991) "Twelve Ways to Fool the Masses When Giving Performance Results on Parallel Computers," *Supercomputer Benchm.* pp. 54-55 (1991).

Center for Computer Applications in Electromagnetic Education, Department of Electrical Engineering, University of Utah, Salt Lake City, UT 84112 (801-581-6944)

Chabay, R.,(1993) "Electric Field Hockey, *Physics Academic Software*.

Cole, R. W.; (1994a), "Simulation and Visualization: Improving Our Understanding of Dipole Radiation," Proceedings: *Antennas and Propagation Society International Symposium*, IEEE, Vol. 1, pp. 87-93.

Cole, R. W.; Banks, D.; Brune, C.; Tooker, S.; (1994b), "Modeling Radiated Fields From Moving Charge Distributions," Vol. 2, *CAEME Software*, to be published.

Cole, R. W.; Banks, D.; Tooker, S.; (1994c), "Improving Interpretive Skills With Visualization and Simulation Exercises in Electromagnetic Radiation," Proceedings: *International Conference on Simulation in Engineering Education*, Vol. 26, pp. 199-202.

Cole, R. W.; Brune, C., (1992), "Visualization, Simulation, and Computing: New Tools for Learning, New Paradigm for Teaching," *Computer Applications in Engineering Education*, Vol. 1(1), pp. 65-72.

Cole, R. W., (1986), "Graphics as a Learning Aid," *Avionics*, December, pp. 26-30.

Friedhoff, R. M., and Benzon, W., (1989), "The Second Computer Revolution: Visualization," N.Y., Harry N. Abrams, Inc.

Globus, A., (1994), "13 Ways to Say Nothing With Scientific Visualization," to be published, *Computational Science & Engineering*.

Johnson, S., Potter, W., Malkin, K., (1994) "Visualizing the Quantum World: Volume Rendering Applied to Quantum Mechanics," Proceedings: *International Conference on Simulation in Engineering Education*, Vol. 25, pp. 199-202.

Miller, E. K., (1994) "PC's For AP And Other EM Reflections," *Antennas and Propagation Magazine*, Vol. 36, pp. 81-82, June.

Miller, E. K., Merrill, R. D., Cole, R. W., (1988) "Computer Movies for Education," *IEEE Transactions On Education*, Vol. 31, May, pp. 58-68.

Physics Academic Software, North Carolina State University, P.O. Box 8202, Raleigh, NC 27690-0739 (1 - 800-955-TASL)

Sherwood, B. A., (1993), "Visualizing Electric and Magnetic Fields," *American Association of Physics Teachers*, Summer Meeting August 1993, *Announcements*, Vol. 23, No. 2, p.65.

Sherwood, B. A., Andersen, D. M., (1993), "cT Creates Prize-Winning Portable Physics Programs," *Computers In Physics*, Vol. 7, pp. 136-143.

Smarr, L., (1994), "Larry Smarr," in the "Talking Heads" folder on the CD accompanying Wolf and Yeager (1994), N.Y., Springer-Verlag.

Steen, L. A., (1988), "The Science of Patterns," *Science*, Vol. 240, p. 611.

Tufte, E. R., (1983) *The Visual Display of Quantitative Information*, "Cheshire, CT: Graphics Press.

Wolff, R. S. and Yeager, L., (1994), "Visualization of Natural Phenomena," N.Y., Springer-Verlag.

Biographical Sketch

Rodney W. Cole is a Lecturer for the Physics Department at the University of California, Davis since 1979, a Senior Learning Skills Counselor for the Learning Skills Center since 1983, and currently serves on the editorial board of "Computer Applications in Engineering Education", a Wiley-Interscience publication. He is co-director for the Minority Undergraduate Research Participation in the Physical and Mathematical Sciences project. He received his Ph.D. from the University of Wyoming in 1978 and his BS from the University of Illinois in 1973. He has been working since 1983 on increasing the persistence and matriculation of at-risk students in the physical sciences and engineering. He has written two books to prepare students for physics. One is a calculus based text and the other is an algebra-trigonometry based text. His research is in physics instructional methodology and computer simulations of time-domain phenomena in electromagnetism. He is a founding faculty member of the NSF/IEEE Center for Computer Applications in Electromagnetic Education (CAEME), a recipient of the UC Davis Academic Federation Excellence in Teaching Award, UC Davis Instructional Technology Award 1989, the 1988 IEEE Best Paper Award (Transactions On Education), and the President's Award for Computer Graphics in Engineering (Orange County Engineering Council).

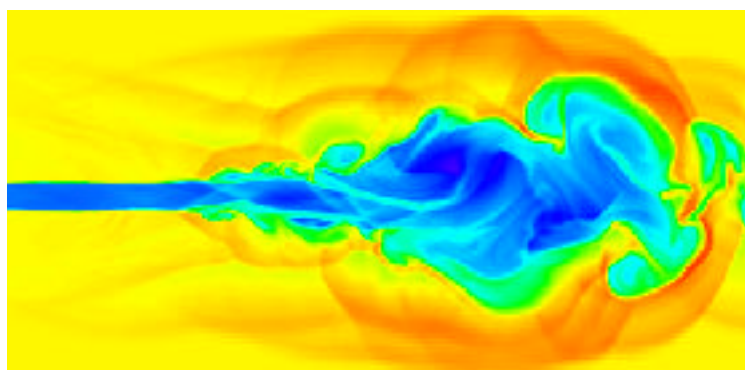
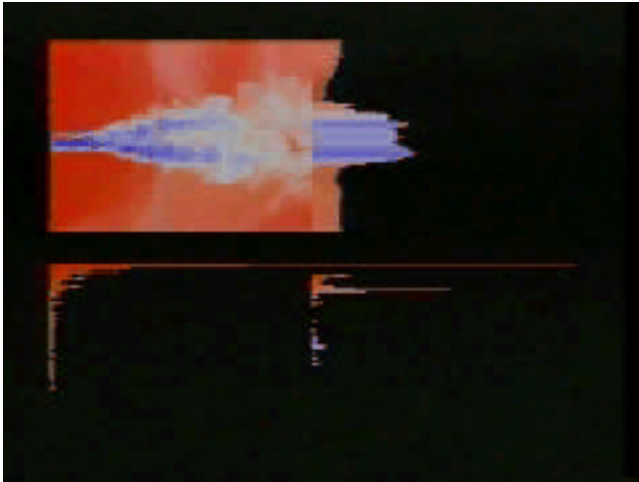
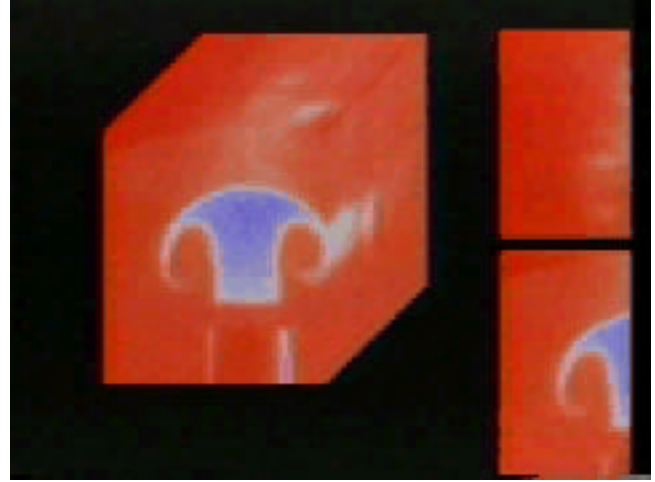


Plate-1
2-D Map of a Supersonic fluid
jet, Michael Norman, NCSA

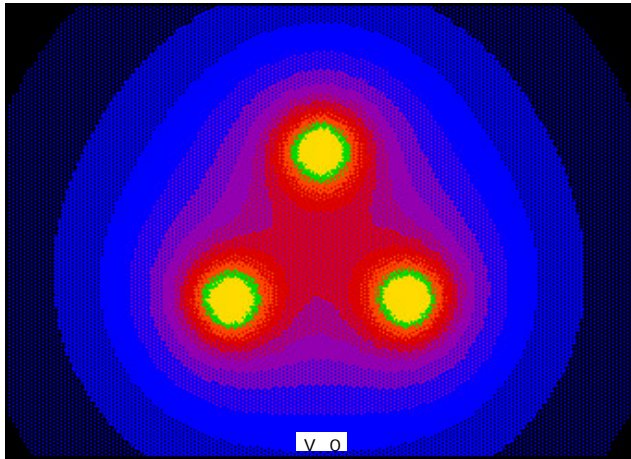


(a)

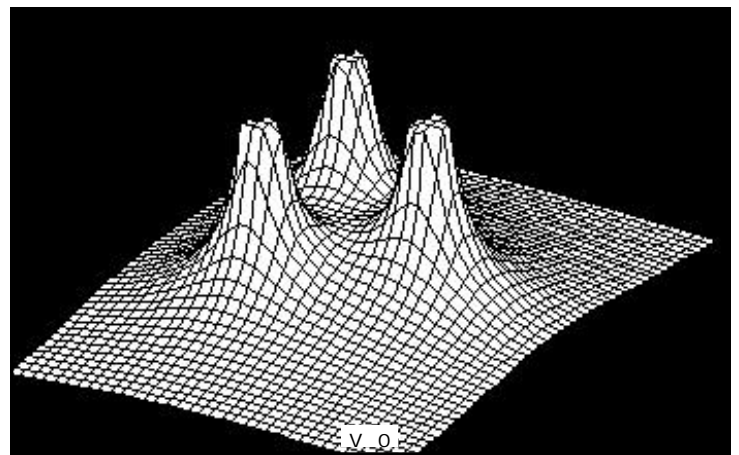


(b)

Plate-2 Experimental data on a gas jet (Stanford)
 (a) 2-D map, (b) Volume display using slices.



(a)



(b)

Plate 3-Electrostatic potential for like charges at the vertices of a triangle.
 (a) Contour map. (b) Pseudo-height map.

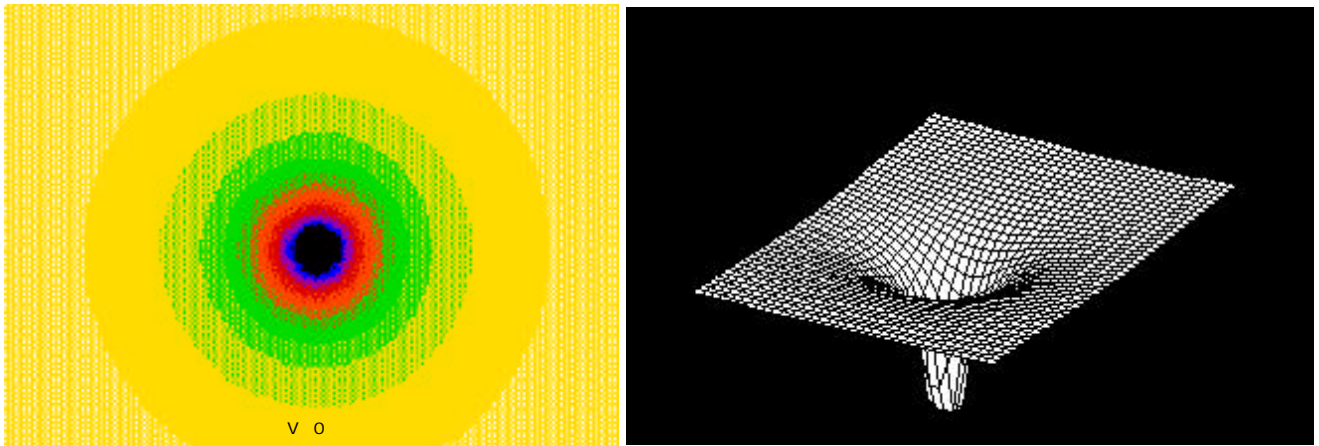
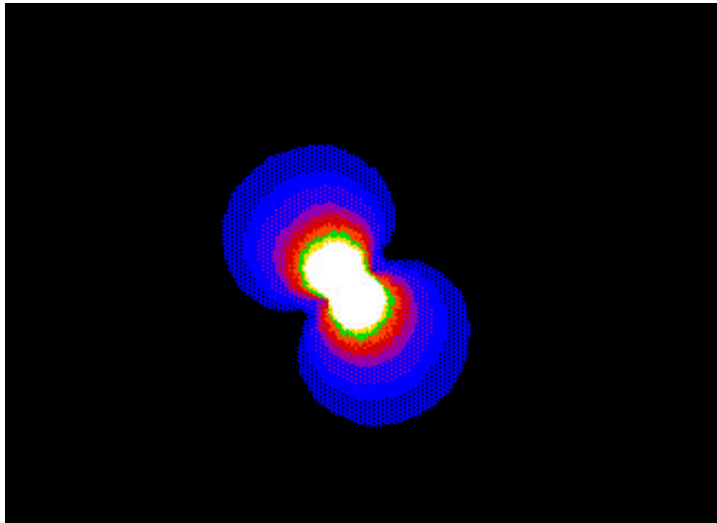
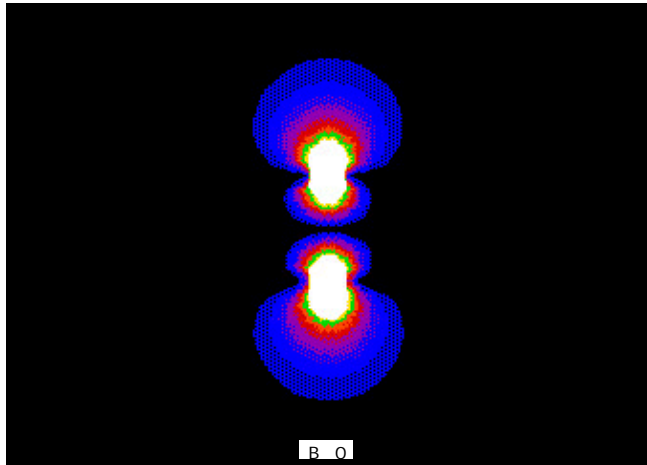
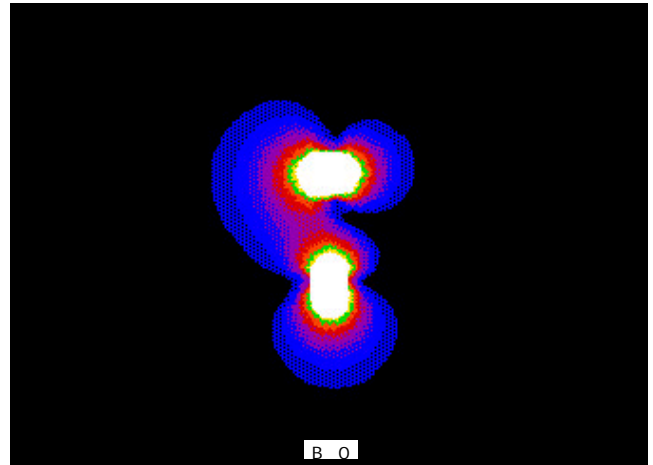


Plate 4-Electrostatic potential for a negatively charged point particle.

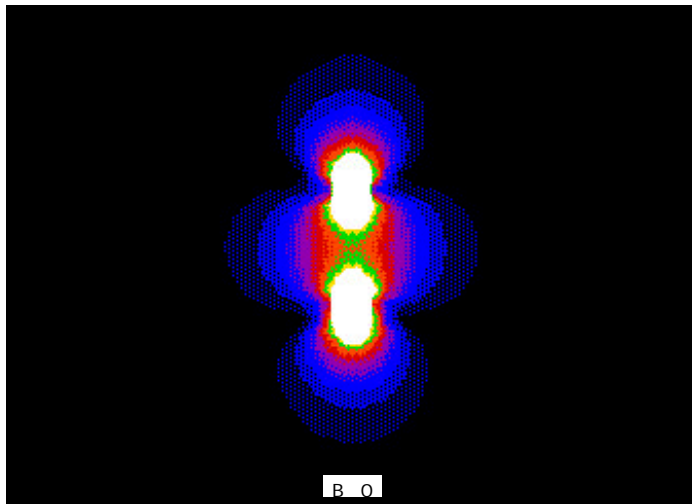




(a)



(b)



(c)

Plate 6- Super position of magnetic fields for two like point charges moving
(a) parallel, (b) perpendicular
(c) anti-parallel.

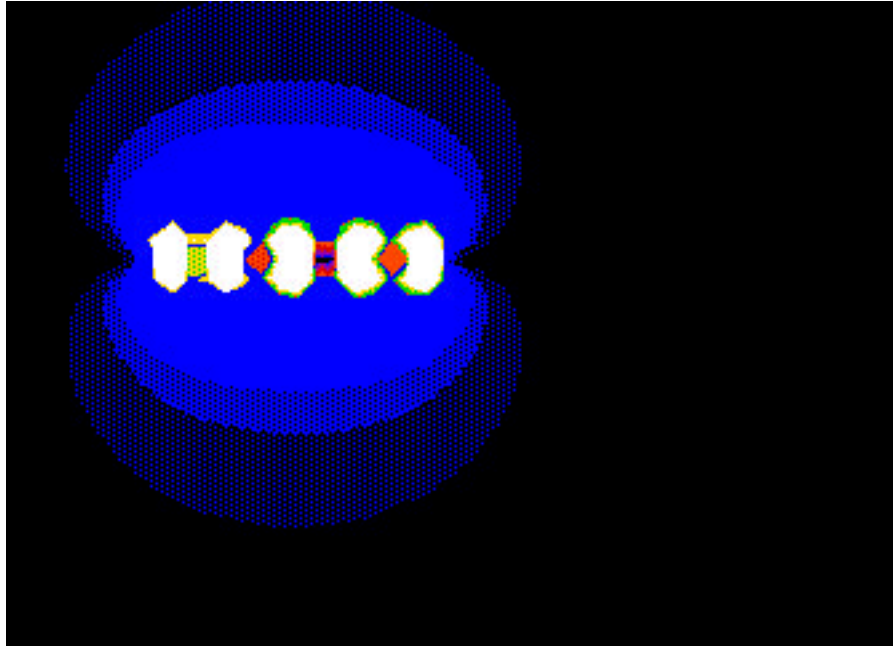


Plate 7- Magnetic field from a line of moving particles.

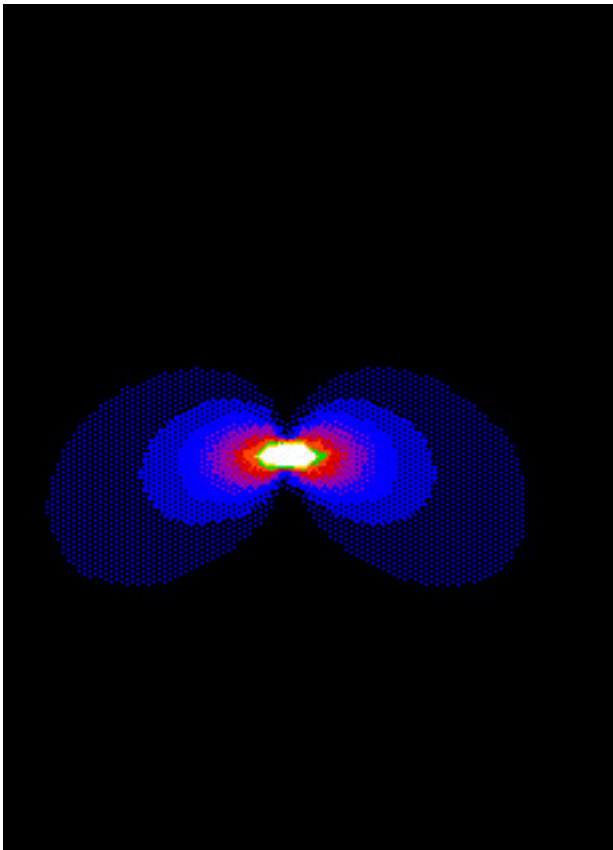
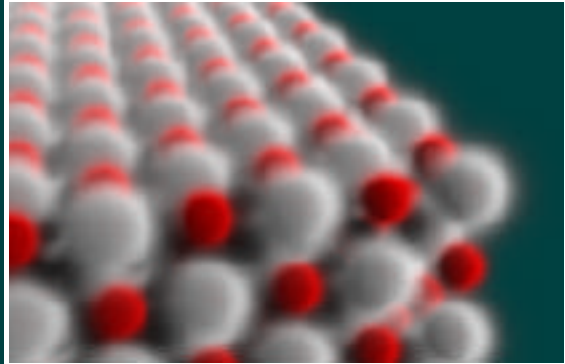


Plate 8-Radiated electric field from an accelerating point particle.



(a)



(b)

Plate 9-Smoke rendering of (a) water molecule, (b) Na-Cl lattice.
Scott Johnson, University of California, Davis.