INTERACTIVE COMPUTATION FOR UNDERGRADUATES

Leo P. Kadanoff

The practice of physics, and indeed of all the sciences, has changed greatly because of the existence and ready availability of computers. Naturally, practice has changed more rapidly than education. Nonetheless, in the last few years the computer revolution has resulted in some revision in the style and content of undergraduate physics instruction.

The tedium of lab data analysis has been mitigated by the use of graphing programs and other similar software for data manipulation and display. (For example the spreadsheet, which is a business oriented display and analysis program, can very easily take a hundred estimates for V and I, convert them into a hundred estimates for R and display the entire result.) A few undergraduate and first-year graduate courses are now aimed at teaching future physicists how medium and large-scale computations are performed.[1]

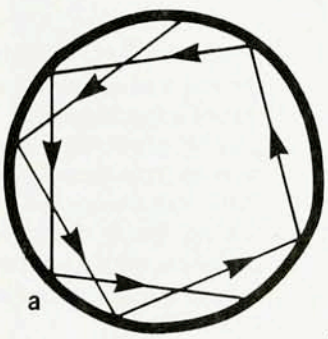
In this column, however, I would like to concentrate upon another style of computation, in which the student or the scientist uses the computer interactively to answer questions. In the best realization of this style, a student works at a graphics terminal or workstation, enters instructions to the computer in a "higher level" language like Basic, Fortran, Pascal, C or APL, and immediately sees the result of these instructions in the form of numbers and pictures. The goal is to answer questions, such as *Given a particle trapped in central force potential that goes like* $1/r^4$*, is a typical orbit closed?* (Almost never) or *What can we say about the frequency-dependence of the response of a forced pendulum?* (It is very complex and most often chaotic).

Questions like these can be asked and answered by the typical undergraduate physicist or engineer who has mastered a year of calculus. In my view, they should be posed to students working in the setting of a computational lab, with perhaps one lab partner. The two would share a workstation or terminal, have available some device to produce hard copy, and would have a lab assistant or professor available to answer or pose questions. This computational lab setup would have a somewhat lower cost than the usual undergraduate experimental lab setup. Some texts related to interactive computer use are available.[2]

Classical mechanics can provide much material for such a course. The US university typically teaches classical mechanics to potential physicists at least thrice: freshman physics (Halliday and Resnick), sophomore–junior mechanics (Marion) and graduate level (Goldstein). (I list common texts in parentheses.) None of these books treats any modern topic in mechanics. Thus there are probably many young physicists who do not know that classical mechanics is a subject of intense research activity.[3]

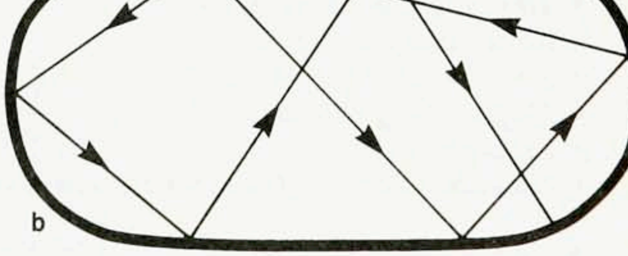
The modern period starts with Poincaré, who was interested in the qualitative properties of motion in classical mechanics and how long it might take for the motion to repeat itself. This question translates in part into whether the motion is orderly or chaotic. On the mathematical side these studies led to the work of A. M. Liapunov, Andrei Kolmogorov, Stephen Smale, Vladmir Arnol'd, Jascha Sinai and others. On the physical side the question was translated into a line of excellent computer experiments conducted, for example, by Enrico Fermi, John Pasta and Stanislaw Ulam, by Norman J. Zabusky and Martin D. Kruskal, and most recently by Gerald Sussman and Jack Wisdom of MIT,[4] who showed that the orbit of Pluto (and hence of the entire solar system) is chaotic. Such questions have consequences for experiment and engineering. One recent example: John Hoffnagle and his collaborators[5] showed that the orbit of two barium atoms caught in an ion trap makes a transition from regular to chaotic behavior as the depth of the well is increased. In this case, the experimental study was backed up by a simulation showing that the presumed transition did indeed occur.

The recent progress in dissipative systems[6] has in a remarkable degree combined experimental, theoretical and computational components. On the computational side, most of the



a

Motion inside a circle.

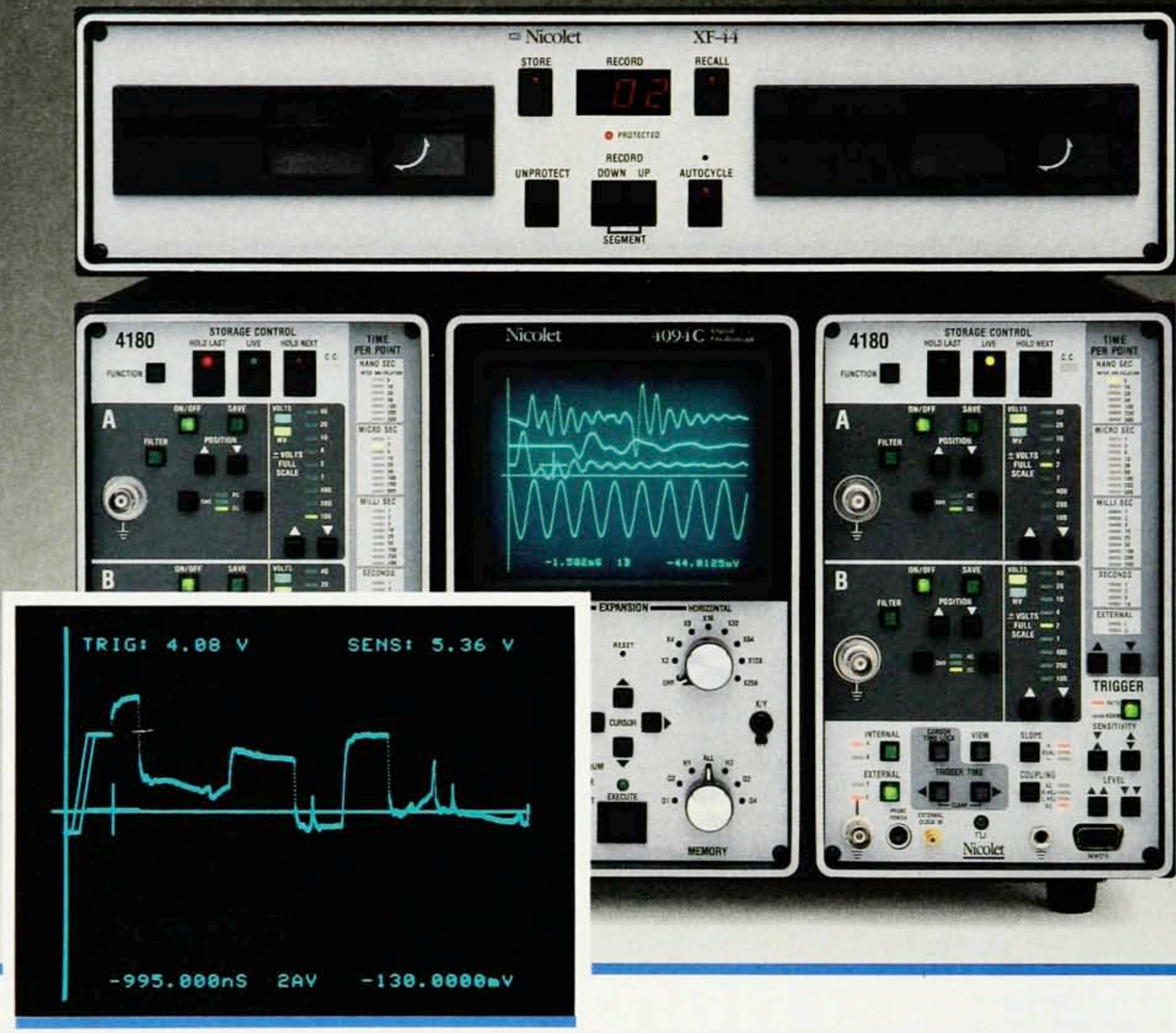


b

Motion inside a stadium.

Leo P. Kadanoff, a condensed matter theorist, is John D. MacArthur Professor of Physics at the University of Chicago.

Flexible Triggering An Issue?



Get the Ultimate in Flexibility and Speed!

- *Preview Of Trigger Settings*
- *Operate With Independent Trigger and Timebase Settings for Each Plug-in.*
- *200 MegaSamples per second*
- *Real Time Functions*
- *Zoom to x256*
- *Floppy Disk Storage*
- *PC Software*
- *Downloadable Software Programs*

Flexibility — With Nicolet's 4180 plug-in and 4094C Digital Storage Oscilloscope, you can take the guesswork out of triggering. The Trigger View feature gives you a graphic representation of trigger slope, level and sensitivity superimposed on the actual trigger input signal. What this means for you is easy and accurate trigger setting. Using the 4094C with two 4180's allows four input channels with each two-channel plug-in having its own independent time base and trigger settings. That's flexibility!

Speed — Wideband input amplifiers allow you to capture signals up to a 100MHz bandwidth at digitizing speeds up to 200 MegaSamples per second.

Support — All this with unequalled factory support. As a user, your questions are answered quickly without the need for customer account numbers or other qualification.

Write or give us a call!

Nicolet

INSTRUMENTS OF DISCOVERY

Nicolet Test Instruments Division

5225-2 Verona Road, Madison, WI 53711 608/273-5008 or 800/356-3090

Circle number 10 on Reader Service Card

progress has been achieved via interactive methods. Students can themselves follow the actual path taken by this kind of research, and thus see for themselves how the period-doubling route to chaos was discovered, or how people first understood the nonlinear interactions of solitons.[7] These hands-on studies are well-suited to help students develop their own physical intuitions.

There are certainly many different ways of designing such a course. In our University of Chicago course,[2] Michael Vinson and I include treatment of phase-plane portraits, the Lorenz equations, closure of orbits, order and chaos in dissipative maps, stability analysis, Liapunov indices, period doubling, fractals, random walks and solitons. These topics are quite elegant and have mathematical depth. In addition, they are closely related to some of the most fundamental questions of present-day physics.

To see the flavor I want, consider the following "trivial" question: Start with the circular and "stadium" shapes shown respectively in parts a and b of the figure on page 9 and imagine that each container includes a particle that bounces elastically off its walls. Given typical values of starting position and direction of the particle, what is the long-run probability distribution for finding the particle at point r in the container? Of course the student will need a few hints. But any well-trained physicist can see at once that one of these problems has a trivial answer. . . . But which one?

References

1. S. E. Koonin, *Computational Physics*, Benjamin/Cummins (1986).
2. D. A. Niguidula, A. van Dam, *Pascal on the Macintosh*, Addison-Wesley (1988) (for first-year computer majors); H. Gould, J. Tobochnik, *An Introduction to Computer Simulation Methods*, Addison-Wesley (1988); L. Kadanoff, M. Vinson preprint (1988) (for junior and senior physics majors).
3. There are a few texts that do take a more modern point of view. See for example I. Percival, D. Richards, *Introduction to Dynamics*, Cambridge U. P. (1986), for a modern but not-too-mathematical treatment at the senior/first-year graduate level.
4. G. Sussman, J. Wisdom, Science **241**, 433 (1988).
5. J. Hoffnagle, R. G. DeVoe, L. Reyna, R. G. Brewer, Phys. Rev. Lett. **61**, 255 (1988). See also the report by R. Pool in Science **241**, 787 (1988).
6. See the text by P. Berge, Y. Pomeau, C. Vidal: *Order within Chaos*, Wiley, New York (1986).
7. N. J. Zabusky, M. D. Kruskal, Phys. Rev. Lett. **15**, 240 (1965). ■