41. THE COMPUTER: RUIN OF SCIENCE AND THREAT TO MANKIND (1980/1982)

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PREFATORY ADMONITION

This essay is designed to be read by an intelligent layman: one who is expert neither in computing nor in mathematics but is competent in some other science such as chemistry or one of the biologies.

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PREFATORY ADMONITION

This essay is designed to be read by an intelligent layman: one who is expert neither in computing nor in mathematics but is competent in some other science such as chemistry or one of the biologies.

While mathematicians and numerical analysts will find the explanations in this essay too obvious to mention, experience over many decades has taught me that much of what is second nature to persons with some training in mathematics is utterly unknown and indeed scarcely believable by those whose schooling did not include serious introduction to the mathematics of infinite processes.

> Victrix causa deis placuit, sed victa Catoni.
>
> LUCAN

> Unangenehme Seher werden meistens als Narren abgeschrieben.
>
> CHARGAFF

1. SPATIAL FLIGHT WOULD HAVE BEEN IMPOSSIBLE WITHOUT COMPUTERS

We have seen men shot into parts of space where they became weightless; directed from the ground of this earth, they have themselves moved like planets, have then been ejected from their own newly acquired orbits and given moonweight instead of their former earthweight; after falling upon the moon they have risen from it, reversed their earlier voyage, turned earthward, and finally dropped back upon the old ground of human life and death, the old sea of once boundless wealth and now boundless trouble. Long before the voyage, each step of it was not only imagined but planned in minute detail. Each change of motion was cannily contrived, each span of coasting craftily released and craftily commuted, each error human or mechanical nicely corrected, and thereupon a new course and program calculated and effected. Asking ourselves what has made possible this astonishing effort and astonishing achievement, what resources could be drawn upon that no previous culture had and that even so little as twenty years earlier ours lacked, we easily recognize many. Some of these are political, some social, some financial, some industrial, some technical. All were needed to provide the one most obviously essential tool. That was numerical calculation: swift, copious, directed, accurate. Without great computing machines the entire program of interplanetary flight as well as many activities less flamboyant but equally peculiar to the turn human effort and organization now take had failed, had never even begun.

2. SPATIAL FLIGHT WOULD HAVE BEEN IMPOSSIBLE WITHOUT THE CLASSIC EQUATIONS OF MOTION

Calculation must not be taken for mathematics. Calculation is a thoughtless routine, like tightening two counter-rotating nuts on an assembly line. Just as a human being had to design both the belt that presents the two nuts and the product that requires them, a human being had to tell the computer, or properly, the computer's team of owners and bosses and hands, which equations to solve. Without those equations, it would have been impossible to conceive what "coefficients" should be determined by programs of experiment, what initial conditions should be ascertained by measurement or assigned by man's will. Without those equations, how could any computer—a brute which can only take common numbers in the order it is told to follow, then add them, then retain or discard the result or enter it upon a selected blank—how could any pile of integrated circuit chips flash out orders continuously directing and adjusting man's voyage to the moon? How could a million digits be put to any use whatever, had the use not commanded the accumulation of those digits in the first place and so provided the key to interpreting them?

I speak of transplanetation not from any love or hate of it but because it is familiar to everyone and easy to dissect in principle. Many factors are indispensable to it, some of them numerical; one is inherently beyond numerics; the mechanics of the motion of the capsule, for without that all the military, political, social, economic, geological, medicinal, chemical, biological, astrophysical (and perhaps astrological) aspects would have failed to exist for want of an object to which to attach themselves. The mechanics of the motion provided the conceptual bones of the undertaking and the central equations which the computers were ordered to solve again and again, thousands or perhaps even millions of times as different initial conditions and different empirical parameters were called for. This is the aspect the mass media never mention. The intellectual proletariat—the masses who believe as divine revelation what "doctors say" and "scientists say" in today's press and forget what those modern priests and astrologers said yesterday—the intellectual proletariat that happily sees billions of dollars it itself paid in taxes spent to stage the greatest television show of all time (until the next nuclear bomb is dropped or biological warfare begins), and which lends to the jingoists of science a credulity beyond a mediæval peasant's before his parish priest, has no idea that this aspect exists.

These central equations are more than 200 years old. They were obtained by men, great mathematicians, who pondered the results of astronomical observations and who put their naked, disciplined

minds to the discovery of the simple in the apparent complexity of numbers and numbers upon numbers, numbers seemingly almost casual—ugly numbers.

The differential equations governing the motions of punctual masses and rigid bodies were not enough to determine the conditions of flight through space. Also the physics of gases and heat and radiation, meteorology, the chemistry of fuels, and for manned flight biological and medical experience were needed. It was truly a triumph of science applied. In it was no element of scientific discovery. Without classic science it would have been impossible.

3. CALCULATION WITHOUT CLASSIC STANDARDS IS DANGEROUS. A COMPUTER IS INCAPABLE OF SETTING ITS OWN STANDARDS

In science and engineering today some of NEWTON's and EULER's ideas and discoveries make the very ground we stand upon. Wherever classical physics is applied, when computation goes wrong we can often recognize it; we can say "this outcome is nonsense, because it violates geometry", or "impossible: that contradicts NEWTON's Laws". Frequently in discussing computer codes we hear the statement, "The results do not respect conservation of energy, but that is a computing error, which we can correct by taking a finer mesh if we need greater accuracy." The programmer or his colleague responsible for the physics of the problem has a standard against which he can check, to which he can have recourse in need. This standard is the classics: the conceptual clarity, the logical analysis effected by great men of the past, great thinkers. Today, indeed, there are a few mathematicians—unfortunately very few—who can make sane and sound use of numerical computation an adjunct in the application of mathematics.

In fully modern fields like genetic alteration and the physics of particles with great energies there is no such standard. Research there is based upon semi-empirical guesses and, far more dangerous, uncontrolled numerical calculation. When something goes wrong in the computing, there is no classic foundation to which the student may return. The same mathematical problem usually gets different answers if "solved" on different machines. Hence arises the ugly noun-pair "machine-independence" to denote instances in which disagreement does not follow. Ordinarily only one machine is used, and its spew is accepted forthwith, without giving another machine a chance to fight.

But that is not all. Different codes used to solve the same problem on the same machine often give different answers. If the disagreement is serious, a "benchmark code" can be applied to see which of the combatants comes closer to a true solution known in some simple case because some mathematician has obtained it already without appeal to any machine. It is another instance where the classics are called in to help, but benchmark problems are simple. The fact that a code is accurate for a known and simple instance then breeds confidence, merely emotional, that it will be accurate also for hitherto unsolved problems. The risk of such inference is plain and great. The true solution of the unsolved problem need not be even roughly like the solution of the simple, classical instance. The unsolved problem may well be unsolved just because its solution is in essence different, far more complicated and far more delicate. A field in which such a difference is already familiar—because experiment and human reasoning made it familiar before there were any automatic computers—is fluid mechanics. There the methods used to study flows at low Reynolds number fail altogether for flows at high Reynolds number. Very well. No computer in competent hands will mislead us here. But had the matter first arisen in our day, the day of great computers, all benchmark problems would have referred to flows at low Reynolds number because no true solution was known for any turbulent flow, and no degree of accuracy in application to known solutions would have had any bearing at all on the rightness or wrongness of the code when applied to the far more difficult problems at high Reynolds number. Exploration by computer, no matter how abundant, would have been little likely to discover the fundamental difference. Computers may be used in intelligent application of theories already well understood, but to place confidence in them for exploring unknown domains of science is as dangerous as to suppose that if a small dose of medicine will cure the measles, a large dose of it will cure smallpox.

Then there are the questions of "verification" and "qualification". How can we tell whether the code is really correct for the problem it is set up to solve? Rarely does it so much as touch that problem directly. Instead, the original problem is replaced by a model problem, a problem which can be set and solved in terms of sequences of two marks, say 0 and 1, for the computer can handle nothing else. To see whether the code really can lead to the solution of the model problem—to detect the errors made by the programmer—is something before which the computer stands useless. A human expert on computing, or a team of such experts, is given the task. That is "verification". Next comes "qualification": Does the model problem, the problem cut down to the capacity of the machine, truly represent the problem of natural science it is designed to approximate? A theory is itself a model of nature; the computer is given a model of that model. It is not impossible that the computer can lead us through

these detours and pitfalls to natural science, but how can we know whether it does or does not? The very fact that we have appealed to the computer implies that we are floating with no secure bases in human thought: human science and human mathematics.

Even when the original mathematical question is fully and correctly set forth, calculation can introduce disastrous errors. The computer's code replaces the assigned problem by a finite algebraic system, and calculation through such systems tends to smoothe over occurrences that may be catastrophic in the mathematically correct theory. For example, in a situation in hydrodynamics that leads to a shock wave or turbulent flow a computer may deliver smooth answers. I have heard long, inconclusive arguments among experts as to whether a particular, regular, gradual "solution" by computer represented the facts or was merely a result of "numerical diffusion" and hence worthless. Also errors of the opposite kind have occurred. In a notorious calculation directed by FERMI, PASTA, & ULAM, of which I shall say more in § 8, below, the computer was programmed to solve a problem of a type classical in gas dynamics and long known to lead to a catastrophe after a finite time. The proposers, unaware of that, had fixed and very different expectations. CAPRIZ & ONESTO[1] state that

> ... in the first series of [computer] experiments some sort of explosion was observed but was dismissed as being due to instability numerical rather than real—to phenomena in the numerical model rather than in the physical model.

The later computations by the famous directors failed to lead either to the correct "explosion" or—fortunately!—to the conclusions that they desired to get, which in fact were incorrect.

To the double and opposite dangers just specified must be added another listed by BOGGS in a recent, sober, and critical survey[2]:

> Many people erroneously believe that, simply because the computer uses fifteen significant digits, their answers will be accurate to fifteen digits. However, the speed with which some computations can be rendered useless by the cumulative effect of small errors is quite amazing. ...

[1] G. CAPRIZ & N. ONESTO, "L'elaborazione elettronica nelle scienze esatte", pages 83–94 of *Atti della LIII Riunione della SIPS*, Pisa, 1975.

[2] P. T. BOGGS, "Mathematical software: How to sell mathematics", pages 221–229 of *Mathematics Tomorrow*, edited by L. A. STEEN, New York *etc.*, Springer-Verlag, 1981. See pages 224–226 and 228.

> [It is a] basic requirement that the computation should continue only as long as meaningful results can be obtained. This implies that estimates must be derived which indicate when the boundaries of the problem domain are exceeded. . . . It is safe to say that, as of today, there are very few problem classes for which such estimates have been derived and implemented in widely available routines. . . .
>
> On the dark side there is the danger, as with all powerful tools, of misuse. Selection of the wrong routine can result in erroneous answers of much poorer performance than necessary. A routine can be applied outside of its range in a way which is impossible to detect. For example, much of classical statistical analysis is based on the assumption of an underlying normal distribution. If this assumption is not warranted, the numbers produced will be meaningless. Unfortunately, there are still those who believe that if numbers are produced by the computer, they must be right.
>
> A critical problem is that managers are sometimes deceived into thinking that with a computer and a good library of programs, they no longer need a mathematician or statistician on their staff. This is a case of over-selling, or failing to provide an honest assessment of the limitations of the product.
>
> With such tools readily available there is a tendency among some to rush to the computer without doing any preliminary analysis or critical thinking about their problem. In some cases, such a practice is institutionalized in the sense that certain computer analyses are required even though the results provide little or no (or even misleading) information. People in this situation often prefer poor codes which always return "answers" to those which warn when problems are present. Of course this is not the fault of mathematical software, but the mere existence of such tools encourages this type of mindless activity.

It is safe to say that for every instance of the sound mathematical guidance that BOGGS recommends in use of computers, in practice there are thousands of the "mindless activity" he deplores.

Failed guesses are usually indistinguishable from faulty numerics. Mountains of digits are become the result of science, not merely its planned and checked application. The answer to failed guesses and failed numerics is more of both. Get a bigger team, spend more money!

The sale of dynamite, cyanide, machine guns, explosive rockets, nerve gas, and thousands of other dangerous things is controlled in an attempt to save mankind from the ubiquitous destruction they might effect if put in the hands of the untrained or unskilled or unscrupulous, not to mention thieves, gangsters, and terrorists. Our lives and fortunes already lie at the mercy of what is promoted as "science" based on calculation by computer. Anybody can buy a computer and use it as he pleases; the merchants of computers urge everyone to do just that. Reactor safety is noisily familiar to everyone. "Computer safety" is a term unheard. Reactors are dangerous in an accident. Computers can be dangerous when they function perfectly.

4. Computers have Harmed Science Already

H. R. POST in a brilliant lecture[2a] listed four ways in which the computer has harmed science:

(1) The computer has probably maintained as problems for computation problems which could have been solved meanwhile by mathematics.

(2) "The Computer is certainly the perfect instrument for inevitable research", that is, research which is certain to deliver *some* "results", right or wrong or meaningless, on any problem proposed.

(3) The computer, writes POST, provides

> another example of the modern mania for means instead of ends. Any amount of traffic, but the place of starting and the place of arrival are equally awful because of the traffic. The longest queue of students I have seen was . . . to register for a computer programming course. I would have been delighted if any of these students had a real problem in the first place that might warrant the use of the computer or anything else. . . . A . . . head of a post-graduate college explained in an interview that he had been looking for a central element unifying the many disciplines represented in his college ranging from Literature to Physics. He had found the Computer to constitute the Central Unifying Element.

(4) Use of the computer, says POST,

> substitutes specific knowledge for understanding. You understand a subject when you have grasped its structure, not when you are merely informed of specific numerical results.

[2a] H. R. POST, *Against Ideologies* (Inaugural lecture), Chelsea College, London, 1974.

POST's third count applies an observation of HEIDEGGER[3]:

> In the sciences the subject is not only set by the method; at the same time it is set into the method and remains subordinate to the method. The raging race that sweeps along the sciences today—they themselves have no idea whereto—comes from the increased drive, ever more surrendered to technique, of the method and its possibilities. In the method lies all the power of knowledge. The subject belongs to the method.

HEIDEGGER goes on to say that the way of thought differs from the way of science, but perhaps he has not learnt much of the ways of great mathematicians. True science seeks methods to solve important problems. Once a method has been invented, we may indeed turn it to new applications. In contrast, the addicts of computation, which is only a method, tout it as a panacea, an imperial pill that will cure all diseases, and so no diagnosis is needed before taking it. Any problem will do. No dosage is mentioned. Evidently the bigger the better. Computing will cure what ails you.

Two of POST's accusations, the first and the fourth, need to be enlarged upon. A layman may well ask, "Why would a mathematician's solution be worth waiting for if a computer can solve the problem faster?" Even persons well educated in literature and arts commonly confuse mathematics and numerical calculation. A dear friend of mine is still sure that when I retire to my desk I sit down with delight to add a huge column of figures; we often read in the press that one computer does the work of a thousand mathematicians. Nothing could be more wrong. My wife long ago persuaded me never to attempt the additions and subtractions of entries in the family's checkbook; the thousands of persons whose services the computer replaces, in fact whose potential ultimate capacity the computer renders negligible, are computresses and abacists, much as a gigantic power scoop replaces thousands of coolies with shovels and buckets. Obviously such work is needed in medical analysis and surgery, financial accounting, traffic control, spying by tax officers, totting up bills in stores tended by clerks who after twelve years of democratic schooling still cannot add and never will learn to, some aspects of engineering design, weather prediction, polling illiterate voters, and thousands of other activities essential to the modern state. Herein lies the computer's value to society. Like many other of today's dangerous gadgets, it does work nobody wishes to do or could do even if he wished to. In accord with PARKINSON's Law, work of this kind grows daily more and more colossal, more tremendous, and more indispensable to society. Thus we need more and more computers just to get through tonight and survive until the morrow.

[3] M. HEIDEGGER, *Unterwegs zur Sprache*, Pfullingen, Neske, 1959. See page 178. The translation loses some of the subtleties of the German language: "... gestellt ... hereingestellt ... untergestellt ...".

As CHARGAFF writes in his essay *Little ado about much*[4],

> It is not hard to talk people into believing they cannot possibly live without something that a few years earlier they had not the slightest idea existed. In fact the West's entire economy rests on this principle.... Some day this diabolical circle must be broken, or mankind will perish.

5. MATHEMATICS IS THE SCIENCE OF INFINITIES. COMPUTATION IS ESSENTIALLY FINITE

Bov! Contrast Wiener

POST's words distinguish a "problem for computation" from a problem "solved ... by mathematics". Consider a very old example: to find a number x such that $x^2 = 2$. This problem was solved long ago to everyone's satisfaction, though not everybody was satisfied by the same solution. For practical purposes you draw a right triangle with short sides of length 1, then take a ruler and measure the length of the long leg. If you prefer arithmetic, just try numbers. You quickly see that $1 < x < 2$. Next, $1.4 < x < 1.5$. You can go on and on systematically. Multiply out $(1.41)^2, (1.42)^2, \dots (1.49)^2$; here the first two multiplications suffice to show that $1.41 < x < 1.42$; for each further decimal place at most nine multiplications are needed, and only rarely that many. Soon the multiplications get too big for you, but a computer will come to your rescue! The process of systematic, exhaustive, and exhausting trial illustrates what POST calls "a problem for computation".

A computer could use the very process I have just described, but its bosses would know much faster methods, methods which have been invented over the centuries by mathematicians. These methods involve rapidly convergent infinite series, infinite products, infinitely continued fractions, *etc.* The computer cannot think. Therefore it could neither invent such methods nor demonstrate that they are valid, but mathematicians have proved by strict logic that they are correct and have provided rigorous estimates of error at each stage. A single arithmetic step calculated by one of these methods can supply many correct decimal places. Here is an example of what mathemati-

[4] E. CHARGAFF, "Wenig Lärm um Viel", *Scheidewege* 8 (1978): 289–309. See § III.

cal thinking can do: It can guide and check numerics in ways no machine could invent. The mathematical work to which I refer was done long before there were any machines. Using these theorems of mathematics, a programmer can enable his machine to calculate the number $\sqrt{2}$ to hundreds of decimal places with great accuracy and speed.

But how many? Any computer can do before it breaks down only a finite number of calculations. Thus no matter how big and dear the computer is, it can calculate the solution of $x^2 = 2$ only so far. The next decimal place will exceed the capacity of the machine. Mathematicians since the beginnings of mathematics have dealt precisely and successfully with infinitely many quantities. When today's largest computer has calculated all the decimals of $\sqrt{2}$ that it can, any good sophomore student of mathematics will be able to tell you what has to be calculated by the next and bigger machine if it is to get further decimals accurately, and any competent mathematician will know how many accurate decimals the next step will deliver. No machine gives information like that. It comes from logical study of infinite sets of numbers.

Will the computers, bigger and bigger as they spawn themselves, ever get so far that every succeeding decimal they find in their attempt to calculate $\sqrt{2}$ will be 0? That is, will the expression of $\sqrt{2}$ as a decimal fraction ever terminate? No computer can answer this question, blind and brainless brute that it is, for even if it produced a string of 1,000,000 zeros before it stopped, we could still ask it what the next decimal would be, and it would have to remain silent. But Greek mathematicians found the final answer to this question more than 2000 years before the invention of the most primitive digital machine. The answer is no. The solution x of $x^2 = 2$ cannot equal the ratio of any two integers p and q. The equation $p^2 = 2q^2$ has no solution for integers p and q. A statement of this kind cannot be approached by any computer. It is a mathematical statement not amenable to numerics. No matter how many integers a computer could try out, there would always remain bigger ones, millions and billions and trillions of times as large as the computer's maximum entry. In fact nobody needs to know more than a few figures of the approximate value of $\sqrt{2}$; to calculate more, by any means, would be useless; but by every person inclined toward mathematics the fact that $\sqrt{2}$ is an irrational number is cherished as the first step toward comprehending the structure of the set of all real numbers. Computers cannot touch that structure; they cannot handle any irrational number; but the minds of ancient Greek mathematicians succeeded in constructing all of them. You can read about it in EUCLID's *Elements*, Book V.

The mass media have told us that a computer recently solved a famous problem attempted by mathematicians in vain for more than 100 years: To color a map properly (under strict mathematical definitions of "color", "map", and "properly"), do we ever need more than four colors? This problem as it stands involves infinitely many maps, and a computer cannot handle infinitely many anythings. Thus the claim is false. In fact a chain of fine mathematicians stretching over a century, included among them being APPEL & HAKEN, the men who directed the final work by the computer, had by use of regular, traditional, mental mathematics reduced the problem to investigation of *a finite number of instances*. Only this reduction made it possible even to consider appeal to a computer. The finite number was too large for unaided human efforts, so recourse was properly had to a computer to try the cases, one by one. Nonetheless, the algorism for doing so had to be conceived by mathematicians; to this end, theorems demonstrated by a constellation of great men from the past 250 years were called upon.

The press did not mention these heroes of former days and made little of the essential mathematics contributed by APPEL & HAKEN. With fraudulence by omission, doubtless encouraged by the addicts and the merchants of computers, it told the public that the computer solved a problem which had beaten all mathematicians past and present.

No such impression could be gained from anything stated by APPEL & HAKEN. Let them speak for themselves[5]:

> The fundamental reason that the unavoidable set argument worked whereas other approaches to the Four-Color Conjecture did not is that all other approaches need somewhat stronger theoretical tools to make their methods apply. While these might be possible to create, there is no guarantee that they are actually possible; and if they are, there is no obvious way to go about finding them.
>
> On the other hand, many mathematicians have believed that an unavoidable set of reducible configurations might exist, but that a smallest such set was beyond the bounds of reasonable computation. This attitude appears justified when the problem is considered with respect to the tools available prior to 1960. After 1960, with the advent of faster computers, there were still strong reasons to believe that the computations would be infeasibly large,

[5] Pages 178–179 of KENNETH APPEL & WOLFGANG HAKEN, "The Four-color problem", in *Mathematics Today*, edited by L. A. STEEN, New York, Vintage Books, 1980, reprinted with their consent.

> but there were certainly no theoretical difficulties to overcome other than the choice of a method for obtaining an unavoidable set. Thus by 1970 it became a problem of discovering whether efficient use of known techniques and technical (as opposed to theoretical) improvements would enable one to find an unavoidable set of reducible configurations.
>
> Most mathematicians who were educated prior to the development of fast computers tend not to think of the computer as a routine tool to be used in conjunction with other older and more theoretical tools in advancing mathematical knowledge. Thus they intuitively feel that if an argument contains parts that are not verifiable by hand calculations it is on rather insecure ground. There is a tendency to feel that verification of computer results by independent computer programs is not as certain to be correct as independent hand checking of the proof of theorems proved in the standard way.
>
> This point of view is reasonable for those theorems whose proofs are of moderate length and highly theoretical. When proofs are long and highly computational, it may be argued that even when hand checking is possible, the probability of human error is considerably higher than that of machine error; moreover, if the computations are sufficiently routine, the validity of programs themselves is easier to verify than the correctness of hand computations.
>
> In any event, even if the Four-Color Theorem turns out to have a simpler proof, mathematicians might be well advised to consider more carefully other problems that might have solutions of this new type, requiring computation or analysis of a type not possible for humans alone. There is every reason to believe that there are a large number of such problems. After all, the argument that almost all known proofs are reasonably short can be answered by the argument that if one only employs tools which will yield short proofs that is all one is likely to get.
>
> . . . The example of the Four-Color Theorem may help to clarify the possibilities and the limitations of the methods of pure mathematics and those of computation. It may be that a problem cannot be solved by either of these alone but can be solved by a combination of the two methods.

No-one who reads this balanced estimate will fail to see that the computer here was servant to mathematics and to mathematicians. Let us hope it was a good one. A nasty doubt remains. Did it make just one little mistake? We shall never be sure of that until some mathematician answers the question, which is purely logical, by purely

logical means, without intervention of any black boxes. Even so, the computer might have been lucky. It might have made two mistakes which cancelled each other, as mathematicians themselves sometimes inadvertently do. Such mistakes of mathematicians are found by their own checking or by others'. Work of this kind by a computer cannot be checked logically, for appeal to the computer in the first place reflected surrender of logic in favor of routine, routine which was so long that no human being could follow it out even once. The referees of APPEL & HAKEN's paper resorted to an independent computer program to check the correctness of the reducibility calculations, giving some assurance for all parties, but that assurance is only psychological. The doubts mathematicians feel—not only those educated before there were fast computers but many young ones, too—rest on more than an intuitive feeling. That some problems "cannot be solved" by one method or another, is scarcely a valid basis for any conclusion. Our time (not to mention machines' time) being finite, as long as there are mathematicians or computing machines there will be more problems left unsolved than solved by either. We can no more complain because that is so than because we shall not live to see our great grandchildren's grandchildren. As for "a problem that cannot be solved" by traditional mathematics, who can say? Is not the skeleton of the history of mathematics a list of problems that for long could not be solved and then were solved? Much as I respect every statement in the passage quoted from APPEL & HAKEN's paper, I do not think their arguments justify their conclusion. Mathematicians in their search for proof use and always have used many heuristic methods which do not themselves provide a tight proof but may aid in finding one. Among these, computation on fast machines deserves wider use *in mathematicians' hands* than it presently has, but to regard its products even then as being more than guesses toward what can be proved would be foolhardy. Moreover, in the history of mathematics some problems that at first and long afterward seemed to require numerical work have later been solved by other mathematical processes, making no use of numerics. A famous example in this century is provided by the evaluation of "Koebe's constant". It would be wrong to exclude the possibility that one day the Four-Color Theorem may be seen in a new light that delivers a proof making no appeal to the arithmetic of bookkeepers.

Even problems that concern only the integers 1, 2, 3, . . . are often beyond the powers of the greatest machine. Take, for example, another old and celebrated problem, to prove what is deceptively called "Fermat's Last Theorem": There are no integers x, y, z such that $x^p+y^p=z^p$ if p is an odd prime number. Many of the great mathematicians for the last 300 years have struggled in vain to prove this simple statement. To this day, they have failed, but their attempts have produced so many wonderful discoveries in number theory that HAROLD M. EDWARDS has been able to write a beautiful textbook in which he develops the subject genetically by telling the story of this one problem. In that book, called *Fermat's Last Theorem*, New York, Springer-Verlag, 1977, on page vi EDWARDS writes "... one is in the position of being able to prove Fermat's Last Theorem for virtually any prime within computational range, but one cannot rule out the possibility that the Theorem is *false* for *all* primes beyond some large bound." I know no clearer example of the difference between computing and mathematics. I should add here that computation on great machines has provided valuable information on this problem already and may provide more in the future. For example, it might disprove FERMAT's statement by finding one or more primes for which his equation does have a solution. But computation could never settle the question as EDWARDS has put it. On the contrary, that question may well be solved some day by a mathematician—perhaps, as often in the past, by a young beginner who is just teaching himself mathematics—the lonely realm of thought whence FERMAT and his successors, working with paper, pen, and brain, just a little human brain in a fragile box of bone, have drawn great clarity and beauty for thousands of years.

The layman may not care a whit about all this. He knows that the makers of geographical maps use more than four colors, whether or not they have to; he does not know what a prime number is; he knows that for most practical purposes the inequality $1<\sqrt{2}<2$ tells him all he needs to know about $\sqrt{2}$, that the carpenter never needs anything better than $\sqrt{2}=1.4$, that the machinist rarely goes beyond 1.414 if that far. All that is true. There is no need for the layman to bother with mathematics; arithmetic is more than enough for him, and a cheap little gadget relieves him from even trying to recall what he learned in the subject he hated most in school. Arithmetic will do also for most of the practical engineers and for many kinds of scientists. Wherever there is routine arithmetic to be done, the computer can do it.

It is the scientist concerned with domains which presently make essential use of mathematics or are likely to do so in future who must know better. He must master the tools he is using; otherwise he may hurt himself. This is POST's fourth point: "You understand a subject when you have grasped its structure, not when you are merely informed of specific numerical results." Structure means precise, clear concepts linked by logical inferences. In the United States the justices appointed to the Supreme Court by F. D. ROOSEVELT and their innumerable imitators appointed by later Commanders-in-Chief of various political hues have shown us how a person who knows nothing

about a language in its history or the men who spoke it may take old writ and distort it into meanings undreamt of by those who wrote it but politically rewarding for present ends. The latest act for Freedom of Something or Other surely empowers me to imitate those Great Men and go on to abuse classic literature as I please, for my ends. Thus I may wrest to my favor a famous statement by DANTE[6], making use of my freedom to delete two commas and to use one word in a modern sense, unknown in DANTE's day: ... Don't do theory unless you think you have understood it.

It is not "pure" mathematics alone that the essential finiteness of computation puts beyond the reach of machines. The differential equations that govern the motion of a real or artificial satellite refer to limits, which involve infinitely many numbers. The computer, no matter how much the taxpayer pays for it, cannot calculate any limit. In the sense of the simple calculus every student of engineering is taught in his freshman year—the calculus in terms of which the differential equations governing the motion of a satellite are expressed—the computer can never give us more than discrete approximations. These may be, and often are, good enough, but only a person who understands the structure of the exact problem can decide when an approximation is accurate. "Approximation" makes no sense except in terms of a prior concept of exactness. The test of accuracy lies not in the number of digits a thousand human computresses or the largest acreage of electronic monsters can emit, but in the mind of a man who understands the mathematical problem which the computer is programmed to solve. Here recent developments in mathematics go beyond the capacities of any computer, present or future. In what is called "qualitative analysis" the mathematician demonstrates precise bounds for the effects of variation of the data that must be supplied from experiment or be prescribed by him who controls and directs the process being analysed. Qualitative analysis can prove that the outcome is largely insensitive to change of some parameters, and so those need not be determined or assigned with great accuracy; that small changes of other parameters may give rise to violent alteration of the results, and so these parameters must be measured or assigned precisely. Here the computer is almost helpless. At best it can provide the effects of some particular choices of parameters. It cannot tell us whether those choices are typical; its results are at best points on a graph, not limits within which that graph must lie. For computer graphics to be used safely, the curve sought must

[6] *Paradiso* V, 41–42: "... non fa scïenza, sanza lo ritenere, avere inteso". SINGLETON's translation, following old commentators: "... to have heard without retaining makes not knowledge".

have been first proved mathematically to be smooth; if ordered to determine and graph a function that is not smooth, a computer may draw for it a graph of meretricious smoothness.

I regret I cannot make this distinction clear to the total layman; an example reveals it at once to anyone who understands a bit about trigonometric functions. Namely, every beginner is taught how to analyse precisely the behavior of $x \sin (1/x)$ near $x = 0$. Suppose we should ask a computer to solve a problem whose solution—a solution of course unknown to us, because if we knew it we should not ask the computer to get it for us—just happened to involve a function like $x \sin (1/x)$. Such a function has infinitely many maxima and minima in an arbitrarily small neighborhood of $x = 0$. The computer would provide at best a meaningless scatter of points, as dense as its mesh would allow. In fairness to the machine we must say that it would itself announce or otherwise manifest its failure. Failure it would be nevertheless, blank failure in facing a problem of a kind that every beginner learns how to analyse and understand. Data can be and often are far from sufficient to promote understanding; they can even hinder it.

Failure of this kind is not limited to "pure" mathematics. In attempting to estimate the trend to equilibrium according to the kinetic theory of gases three authors[7] in an extensive computation, financed by the taxpayer through three of the biggest Federal foundations and by private industry as well, attempted to verify a conjecture making the entropy a completely monotone function of time. For "a wide range" of times they found that the first thirty derivatives of the entropy had the right sign "with double precision, significant to 33 figures". Thereupon Professor ELLIOTT LIEB[8] by a few lines of elegant, rigorous analysis resting upon a mathematical theorem half a century old proved the conjecture false. He writes that "this case exemplifies the need for great care in using computers to study delicate mathematical properties. . . ." Indeed, it exemplifies how misleading computer calculations may be! LIEB reports also that Dr. K. OLAUSSEN, using asymptotic analysis, has estimated that for a computer to reach the correct conclusion it would need to calculate 102 derivatives. In a private communication Professor LIEB has remarked, "Although computers can sometimes give useful hints about properties of solutions to analytic problems, it should be understood (and often is not) that the more delicate is the property under

[7] R. M. ZIFF, S. D. MERAJVER, & G. STELL, "Approach to equilibrium of a Boltzmann-Equation solution", *Physical Review Letters* 47 (1981): 1493–1496.

[8] E. H. LIEB, "Comment upon 'Approach to equilibrium of a Boltzmann-Equation solution'", *Physical Review Letters* 48 (1982): 1057.

investigation, the more computer time is needed. In particular, infinitely subtle properties (e.g. the analyticity or complete monotonicity of a function) require infinitely much computer time to verify directly."

If guided by competent mathematicians, computation can offer modest help to mathematical research. It can provide numerical examples which render abstract statements explicit; it can disprove false guesses; it can accumulate material which may suggest conjectures which later somebody may prove true or false. It can do a fine job of plotting graphs, which are easier to assess than are tables of numbers, and can make mathematical statements visual. Beautiful results of a computation of this kind, directed by mathematicians and designed by them to illustrate their completion of the theory of a long-known but perplexing aspect of the convergence of trigonometric series, may be seen in a recent paper by E. & R. E. HEWITT[9].

A computer can even be programmed to deliver exact solutions to problems which can be solved by a finite number of routine substitutions of solutions of problems already solved by mathematicians. For example, it can be taught to replace x^2 by $2x$ or $x^3/3$, leaving x a symbol. It can be made to replace the symbol $\sin x$ by the symbol $\cos x$ without calculating the value of the sine or cosine of x for any particular number x. Thus the parts of literal algebra and calculus that can be reduced to *finite arithmetic routines* can be handled by computers and often should be.

The mathematics of computation is interesting in itself and can be developed abstractly. Computers, like other gadgets, occasion demand for new mathematics; some has been provided already by mathematicians, and more remains to be created.

But how much of the activity surrounding computers is directed by competent mathematicians?

6. Computers Bring Power and the Abuses of Power. Advocates of Computing Seek to Destroy Mathematics

Calculation on huge machines is democratic and costs dearly. The small army garrisoned around a big computer is composed of specialists and experts, dear fellows, indoctrinated in computer-worship. Like those engineers and physicists who use computers by habit, most of them never so much as consider the possibility that a problem of theirs might have a mathematical solution.

[9] E. HEWITT & R. E. HEWITT, "The Gibbs-Wilbraham phenomenon: An episode in Fourier-analysis", *Archive for History of Exact Sciences* 21 (1979): 129–160.

Well and good, the innocent may say. To each his own. It is not so easy. For every mathematician who relies on his mind alone, there are now thousands of navvies on computer gangs. In the United States today there are more than 500,000 programmers and systems analysts; these form the officer corps of the computer army; their number grows swiftly. The American Mathematical Society has about 17,000 members; the number of these whose main activity is research is hard to determine, but I guess that it would not reach 500. In our social democracy, numbers bring power. Not only a population but also wealth pushes computers; computers are incessantly promoted by advertising; mountains of money are gained by those who design, manufacture, and sell computers. Wealth, too, brings power. In any society, power creates abuse. Nobody who knows the computer folk will expect to find them ready for peaceful co-existence with the tiny realm of intellectual mathematics—the only source whence informed criticism of computer-worship may spring. Not only can the computer addict, benumbed as he is to mathematical ends, perceive only means of reaching them; not only does he depreciate and deprecate every means other than computing; but most of all he condemns mathematical research that is not numerical. The tyranny of computers now threatens to destroy mathematics even as an activity in universities.

Do you think I exaggerate? Rather than adduce instances I quote in its entirety a manifesto by JAMES C. FRAUENTHAL as issue editor of *SIAM News* for April, 1980, under the title *Change in applied mathematics is revolutionary*[10]:

[10] Reprinted with permission of *SIAM News* and of JAMES C. FRAUENTHAL.

Many other writers have published similar statements, usually less violent. In *Mathematics Tomorrow*, edited by L. A. STEEN, New York *etc.*, Springer-Verlag, 1981, PAUL HALMOS in an article on his favorite subject, "Applied mathematics is bad mathematics", writes

> I should guess that in the foreseeable future (as in the present) discrete mathematics will be an increasingly useful tool in the attempt to understand the world, and that analysis will therefore play a proportionally smaller role. That is not to say that analysis in general and partial differential equations in particular have had their day and are declining in power; but, I am guessing, not only combinatorics but also relatively sophisticated number theory and geometry will displace some fraction of the many pages that analysis has been occupying in all books on applied mathematics.

ANTHONY RALSTON in his article "The decline of calculus—the rise of discrete mathematics", pages 213–220 of the same volume, quotes WALLACE GIVENS as follows:

> There is a simple and basic fact about a computer which will, in the decades and centuries to come, affect not so much what is known in mathematics as what is thought important in it. This is its finiteness.

Shortly after the turn of the century, Niels Bohr and Albert Einstein presented theoretical results which revolutionized physics. This is not news; a quick look through the catalog of my university convinced me that not one of the fifty-five members of the Department of Physics lists classical mechanics as an area of interest. I doubt if a single Ph.D. will be awarded in 1980 by a physics department for the solution of a problem in Newtonian mechanics. Of course Bohr and Einstein and their friends did not instantly solve all the old problems; instead, they created a new set. What happened to all of the old problems which did not simply disappear? They moved into other disciplines called by names like applied mechanics and mechanical engineering.

And what happened to the people who were professors of physics at the turn of the century? What they had been trained to do was out of fashion. Some, no doubt, retrained themselves by learning about quantum mechanics and relativity. Most, I suspect, stayed right where they were and continued to do more or less what they had always done. From an evolutionary point of view, the classicists became extinct in physics departments in a single academic generation (the time from Ph.D. to retirement).

While some of us in a country of medium size and barely two centuries old may hesitate to endorse a declaration of what will happen to the world in "centuries to come", with the sober and factual parts of these statements it would be hard to find reason to disagree.

In the same article RALSTON himself on pages 214–215 takes a position somewhat like FRAUENTHAL's but not so immoderate:

> ...sharp changes should be viewed with great skepticism and should be undertaken only for the most compelling reasons.
>
> Still, I suggest the need for such a revolution [in the teaching of mathematics]. Its cause? The invention and development over the past three decades of the digital computer, perhaps the most important development in science and technology since the invention of the printing press. In any case, it is a development which will not only have profound effects on human life and the social fabric, but which will also—and this is the point here—have a most important influence on the problems on which scientists work and, in particular, on the mathematics they use. (Which is not to say, I emphasize here, that calculus and classical analysis will not continue to enjoy much success; it is only to say that their position of dominance in mathematics and its applications is about to be challenged.)
>
> ...[T]o a considerable degree, the wellsprings of mathematics have always been in the applications of mathematics. Today it is computers generally and computer scientists in particular which generate the need for applications of mathematics in greater volume—and at a much more rapid rate of increase—than does any other area of science or technology. Since the mathematical problems generated by computers and by computer scientists overwhelmingly require discrete rather than continuous mathematical tools, it is hardly surprising that research in discrete mathematics is rapidly increasing.

Although this all seems simple and obvious to us in retrospect, I would guess that the future looked very uncertain in 1920.

As in physics, so in mathematics

What does the revolution in physics have to do with us? Very simply, I believe that we are presently experiencing in mathematics a change which is as dramatic and irreversible as the one which took place in physics earlier this century. The genesis of this change happened some years ago and the effects seem more apparent to me each day. The motivating force: the invention of the computer. The effect: a one time, inevitable change in the field of mathematics. We who consider ourselves to be applied mathematicians must not be so smug as to think that we are either immune to the change, or its only logical beneficiaries.

As I see it, within another academic generation, the mainstream of mathematics will not be analysis, number theory and topology, but rather numerical analysis, operations research and statistics. Already the areas of mathematics which are computation oriented are the most successful in drawing students at all levels and, more important, in drawing funds from university administrators for new faculty members. I am not suggesting that the pure areas of mathematics, or for that matter the classical topics in applied mathematics such as transform methods, partial differential equations and approximation theory, will disappear. Instead, like Newtonian mechanics, they may move permanently from center stage in mathematics departments.

An alternate scenario

There is of course an alternate scenario, though it is no more pleasant for those who enjoy the status quo. Mathematicians can resist the incursion of the computer into their field. They can argue that it is not mathematics to solve a problem using numerical techniques. In fact, at many universities this argument or its equivalent appears to have been made. The result is inevitably that a new department with a name like computer science or mathematical science is created in response to student demand. Then slowly, the mathematics faculty end up doing little more than teaching calculus. The irony is that, as with physics departments where modern physicists teach classical mechanics, computer-oriented mathematicians could offer a more relevant introduction to calculus than many classically trained mathematicians.

Whether it is the name that changes or the focus of the members of the faculty is really irrelevant. What does matter is that by the year 2025 (in my opinion), the vast majority of the mathematicians on university campuses will be either using computers in their work, or studying the fundamental problems which must be solved to advance computer algorithms. In only a few places will there remain centers for research in pure mathematics as we know it today.

This *Bekanntmachung* proclaims the new *tausendjähriges Reich* of science. Not only do computers bring the revolution, displacing 3,000 years of feudal-absolutist-capitalist slavery to naked thought; beyond the computer there is nothing. Computers provide "a one time, inevitable change, ... dramatic and irreversible", the *final solution* of the mathematician question! I confess I cannot see why calculus will be worth anyone's while to learn after the Cultural Revolution shall have reduced all science, discretized, to currying computers; calculus is a theory of limits, and the concept of limit, since it is inherently beyond numerics, must be superseded; but the future serfs who, permanently off "center stage", will "end up doing little more than teaching calculus", will be grateful that the *Sturmtruppen* of the master race, goose-stepping behind the university *Gauleiter*s, permit them to live out their useless days in some silly asylum for private enterprise in the realm of thought. Certainly mathematics done by human minds—before the "one time, inevitable" revolution the modifier "done by human minds" would have been redundant—will find few defenders in an age when everything is decided by some kind of opinion poll, staged and manipulated by mass media.

7. Computing Promotes Factual Fraud. It has Harmed Experimental and Applied Science in the Past and is Continuing to do so. By its Emphasis on Application of the Already Known, it can Delay Basic Discovery and thus Reduce the Field of Application in the Future.

Most citizens will feel no regret if creative mathematics disappears. They always hated what little mathematics they met in school. Of the few who liked mathematics, many have no idea that it is possible to discover anything new in it. But mathematics is not the only science that computer addiction can kill. Since computing is advertised by its addicts, by the press, and by the computer merchants as being the oracle of science and society, computer codes are sold or given away gratis to all comers. They can be and have been applied blindly, in disregard of the warnings to users which often are attached to each copy. Fraudulent exploiters can and do promise their clients to solve for a fee any problem posed. He who resorts to a whore may with some confidence expect personal service in fair return for the price or prices he pays; the client of a computer faker is most likely a charlatan himself, who uses his purchase as a tool to help him deceive the public. Fraud is fraud; it can be practised anywhere in any activity; but while a charlatan in medicine is apt to be exposed in time by his victims or their surviving relatives, who can unfrock a computer charlatan?

Many experimental arrangements today feed their data directly into a computer for digesting. Nobody could reverse the process, even if he could disentangle the horrid mess of numbers. The data cannot be recovered; only its interpretation emerges. Scandals in business show us how easy it is for skilled hands to make computers lie. In science now it is even easier to fudge the data as well. If the aim is an explosion of journalism or a Nobel prize, the temptation is great. There are no auditors who must certify the books. The computer not only discourages the attempt to understand before applying, it smoothes the way for factual fraud.

Even in instances when the data can be recovered, computers can and do give contrary interpretations of them. Recently the public, which had been forced to pay billions in taxes for exploring the face of Mars, was shown two conflicting sets of pictures, extracted by "computer-enhanced imaging" from the same dearly bought data by different groups of computer experts. One group found only the grey fog which is the astronomers' usual reward. The other claimed to penetrate the clouds and to discover beneath them a huge face in a desert pocked by pyramids. The work of the second group is either a hoax or not a hoax. If not a hoax, it shows that computer interpretation of data cannot be trusted. If a hoax, it shows that computer experts cannot be trusted. Well and good, the face of Mars, be it but dust or be it a gallery of masterpieces of modern art, is little likely to hurt or help us. The reflections of this affair upon the processing of data by computers are grave. The computer is programmed to remove the "noise" that blurs the image, but criteria to determine what is noise and what is the faint trace of a record of some object must be prescribed for the programmer or by him. The danger to a populace which has confided its welfare to "science" ruled by computers and computer experts is equal, whichever way lie the truth about the diorama of Mars. Just think what mad warriors could do—perhaps now regularly do do—by "computer-enhanced imaging" of spy photographs of the weapons of potential enemies!

Factual fraud in science has reached the public press. In an article called "Fudging data for fun and profit" which appeared in *Time*, December 7, 1981, FREDERICK GOLDEN writes "Findings that were touted only last summer as a fundamental breakthrough in the understanding of carcinogenesis have been branded fraudulent." As

he reminds us, "cheating . . . is common to many professions these days . . . ." The earliest meaning of "charlatan" is "a mountebank who sells wonderful drugs"; charlatanism has been the inseparable companion of medicine ever since there have been medicine men (now called "physicians"), and it is no wonder that molecular biology and biochemistry, which are so close to medicine as to be able to gouge into the billions milked annually from the taxpayer by the government and the further billions given by the timorous rich to support the gang warfare euphemistically called "research" in the world of healing, should have learnt what profits mafia science can yield. GOLDEN mentions the frauds discovered at Cornell, Yale, Massachusetts General Hospital, Boston University, the University of California—the tip of the iceberg. It is time for similar scandals in high-energy physics and observational astronomy and every other part of science where there are costly experiment and costly computing which must lead to frequent "breakthroughs" if their funding is to continue. Nothing is more easily forgotten than the "breakthrough" three years ago, for all old accounts have been quitted by the auditors.

Figure 30. Big science as summarized by SIDNEY HARRIS, 1981, reproduced with his permission.

Experiment, yes experiment, is the touchstone of science! GOLDEN observes that "So much is being done in every field that unless an experiment is really important, years may pass before anyone tries to repeat it. Especially at a time when new ideas are at a premium, there is not much profit in doing over someone else's work. Furthermore, repetition is sometimes all but impossible...." Indeed. Experiment and advertising are scarcely distinguishable in today's science.

The mania for bigness rules. GOLDEN writes,

> Senior scientists are often so busy scrambling for funds to keep their labs running that they rarely have time to look so closely at what their young whizzes are doing as they would like. What was once a sportsman-like rivalry between researchers has become cutthroat competition. By publishing a paper first, even if some of the data are not quite accurate, a young scientist may beat out a rival for any number of prizes: a tenured post or promotion, a big grant from the Government, an offer from industry... and ultimately perhaps the trip to Stockholm.

The foregoing quotations do not mention use of computers. That is so because it is nowadays taken for granted that big science is totally computerized. Computer fraud being the easiest of all kinds of fraud today, anyone who chooses to falsify problems and data will as a matter of course call to his aid the total obfuscation that computed statistics and computed analysis of data can easily be programmed to provide. Indeed, it is unlikely that recent and future frauds have been and will be discovered except through somebody's peaching. In matters such as biological warfare and genetic alteration it could be too late: when it came time to peach, everyone who might be able to do so might be already reduced to functionlessness in mind or body if not actually dead.

For factual fraud there are old precedents. Even in less democratic ages science based upon heaps of data and numerical work has been perilous. PTOLEMY, the Alexandrian astronomer of the second century, made tables of the planetary system which throughout more than 1000 years following were to provide an unshakable bastion for scientific faith and against new doctrines. His work long served as the classic example for comparison of abundant measured data with theory. In the last decade the Royal Astronomical Society has published articles by ROBERT R. NEWTON[11] which show to the satisfaction

[11] R. R. NEWTON's work is available also in his book, *The Crime of Claudius Ptolemy*, Baltimore, Johns Hopkins University Press, 1977. NEWTON's arguments are denounced for bias and inconsequence by N. M. SWERDLOW. "Ptolemy on trial", *American Scientist* 48 (1979): 523–553.

of many historians of astronomy that all the observations PTOLEMY claimed to have made himself he in fact fudged to fit his theory. Even the way he went about his fudging has been reconstructed. The late WILLY HARTNER, a profoundly respected and indeed revered historian, claimed to have found similar fudging in the data added by Arab astronomers who later upheld PTOLEMY's system at all costs. Of course, anybody can cheat, at any time and about anything. PTOLEMY's system made factual fraud easy because in its practice it was a numerical scheme. Science is different. As POINCARÉ said, science is not a collection of facts, any more than a heap of stones is a house. Science organizes facts by reason in such a way as to correlate what seems disjoint and to foreshadow facts not yet observed. NEWTON's laws and EINSTEIN's theory of gravitation are not reducible to tables of numbers. No amount of factual fraud could have preserved the NEWTONian planetary system and stopped EINSTEIN's, for they are not numerical. They are mathematical ideas, simple ideas which can be understood structurally first and then applied to instances. The slight correction of planetary orbits that EINSTEIN's theory provides is a minor instance of its value. A small alteration in the NEWTONian scheme could have fitted it to the orbit of Mercury without altering the orbits it delivers for the other planets. That would have been adjusting theory to fit data. Such alteration was proposed and was rejected as being unedifying. EINSTEIN's theory did nothing of that sort. It arose because the NEWTONian view of space-time had proven conceptually inadequate in itself as well as incoherent with electromagnetism. As DIRAC explains[12],

> What makes the theory of relativity so acceptable to physicists... is its great *mathematical beauty*.

Its formulæ for motions of gravitating bodies emerged as one product of its general revision of basic ideas; the emendment of Mercury's orbit provided not motivation for the change but a test of it. Other relativistic theories of gravitation, for example G. D. BIRKHOFF's, imply the same results as EINSTEIN's in regard to presently possible tests by experiment. NEWTON's theory of the heavens remains today, even in much of cosmology, the basis of our ordinary thought regarding them. The gush of journalism about the advance of the perihelion of Mercury—a tiny and eccentric detail—is no more than an example of the accepted social doctrine that "revolution" is a good thing for everybody. Nobody who does not understand the mathematical theory

[12] P. A. M. DIRAC, "The relation between mathematics and physics", *Proceedings of the Royal Society of Edinburgh* 59 (1938/9): 122–129 (1939).

of the electromagnetic field should let the word "relativity" cross his lips except in a question[13].

Against the Scylla of factual fraud stands the Charybdis of the Ptolemaic system itself. If we regard it in its kinetic essence, not in just the particular numerical state PTOLEMY himself decided upon, we find that it contains potentially as many adjustable entries as we like. Inherently the array of deferents, epicycles, and epicycles upon epicycles is a method of interpolation with as many adjustable parameters as the adjuster may wish. In principle it could fit all known planetary observations and be refitted each time a new observation was made[14]. Only the practical limits of numerical calculation in PTOLEMY's day made fudging necessary to get agreement. Only the limits of numerical calculation in KEPLER's day made it impractical to add further epicycles which could have adjusted PTOLEMY's system to agree perfectly with observation for another 1000 years. Had modern machines been available then, KEPLER himself might have formulated his laws nevertheless, but astronomers would not have accepted them. "The old way is more accurate," they would have said: "anyway, our machines are already programmed for it, and we cannot afford the money and delay needed to try a new theory that is, after all, just a theory. Besides, think how many senior epicyclists would be put out of

[13] I mean nothing advanced or difficult for any mathematically literate person. In an elegant, limpid textbook for mathematically qualified senior undergraduates, starting from first principles C.-C. WANG presents in less than 200 pages the classical and relativistic theories of electromagnetism and gravitation. I refer to his *Mathematical Principles of Mechanics and Electromagnetism*, Part B, New York and London, Plenum, 1979. Pages 311–314 present and compare the classical and relativistic determinations of orbits for pairs of gravitating bodies and derive in a few simple lines the relativistic advance of 43″ per century in the perihelion of Mercury. Only the two-body problem is considered. In comparison with astronomical observations the effect of NEWTONian perturbations by other planets must also be taken into account. K. P. WILLIAMS in *The Transits of Mercury*, Indiana University Publications Science Series No. 9, 1939, by painstaking reduction and estimate of errors in the data concluded that the non-NEWTONian advance was 42″.93.

To the mathematically illiterate (I use the term not as an insult but as a factual qualification) it is harder to explain relativity than it is to teach the musically illiterate the difference between one canon and another. In music, sound helps; in relativity, sound seems to hinder.

[14] Nothing I state above regarding the Ptolemaic system should suggest that "piling up sufficiently many epicycles" could represent "any conceivable phenomena". I refer only to the phenomena associated with the motions of the centers of the seven great and near heavenly bodies, and I suggest that the approach basic to the Ptolemaic system would not suffice to describe the motions of artificial satellites. I may be wrong in either or both of these opinions. Many common, loose statements about Ptolemaic astronomy are shown to be false in a splendid paper by the late R. C. RIDDELL, "Parameter disposition in pre-Newtonian planetary theories", *Archive for History of Exact Sciences* **23** (1980): 87–177.

their jobs!" Had machines been available in NEWTON's day, I doubt he would have used them, but I doubt also he would have been impelled to devote years of intense study to the mathematics of the planetary system, and had he done so, I doubt his theory would have been accepted. Had machines been available to the creators of mechanics, I doubt we should have the law of universal gravitation today. To predict the planetary motions, with their obvious near regularities, methods of numerical interpolation can do very well. To get a body out of one orbit and into another is a problem of a different kind entirely. There it is the irregularities that predominate. I doubt that computers of celestial orbits, no matter how large their capacity, could have by any method of mere interpolation, mere fitting of epicycles to data, determined conditions for interplanetary travel. Computers make transplanetation possible today; had they been available 200 years ago, the basis for transplanetation today would never have been discovered.

Computers promote applications of known science; by inhibiting creation of new science, they limit the field of future application. You cannot apply a scientific theory if you do not yet have it.

Here we may return for a moment to FRAUENTHAL's simile of the computer revolution in mathematics to the revolution in physics effected by BOHR and EINSTEIN. To do their work, both BOHR and EINSTEIN used the kind of tools NEWTON had used long before them: their own minds, applied to what physics they knew and aided by what mathematics they knew. I have not perused their writings; in looking over the pages I do not see a single instance where a great computing machine could have helped them. In contrast with the drudges of their day, who sought to determine one more decimal place by measurement or arithmetic, they were content with simple calculations. It is their successors who have made monstrous and inevitable numerics an essential part of physics. Have these successors effected any revolutions? Possibly so, but I must leave it to others to judge whether those revolutions have brought us, in addition to terrifying power to destroy human life and works, any clearer understanding of the nature of matter. There is another difference. The revolutions of BOHR and EINSTEIN were not developed for military aims, promoted by governments, financed by speculative capital, promulged in directives by administrators of industry and bureaucracy, or diffused by floods of popular advertising and armies of salesmen.

The physicists themselves, their intellects already wan and flagging from the ravages of malignant computeritis, may be committing seppuku by computer. Lest you think I exaggerate, I quote the final sentences of the inaugural lecture of the physicist STEPHEN HAWKING as Lucasian Professor of Mathematics in the University of Cambridge, 29 August 1980:

> At present computers are a useful aid in research but they have to be directed by human minds. However, if one extrapolates their recent rapid rate of development, it would seem quite possible that they will take over altogether in theoretical physics. So maybe the end is in sight for theoretical physicists if not for theoretical physics.

These words, which in print read like a breathless pronouncement, Professor HAWKING regards as striking "a slightly alarmist note". Perhaps they were spoken in the witty irony for which the British are famous, but many a computer addict preaches the same message in deadly earnest with "theoretical physicists" replaced by "mathematicians".

8. CLASSIC THEORIES USED INDUCTIVE AND DEDUCTIVE MODELS. COMPUTING ENCOURAGES FLOATING MODELS

The old theories, the classic theories of science, provided models of limited aspects of nature. The example set by the rational mechanics of EULER and LAGRANGE, based in part upon the discoveries of HUYGENS, NEWTON, and the BERNOULLIS, illustrates the status of a "Law" of physics: a clear, precise concept of ideal behavior, embracing an enormous variety of precisely specifiable cases. The "Law" when applied to a case restricts but generally does not determine the outcome. Any discrepancy between data of experiment and such an outcome of theory we attribute first and usually finally to our own failure to apply the "Law" well, not to the "Law" itself. Only if an instance can be found for which any direct, not merely *ad hoc* application of the "Law" leads to results contrary to fact, will the "Law" be questioned. The "Laws" of mechanics have been sharpened and broadened but never repealed. Some "Laws" in other domains have indeed been abandoned, but they are few. Lurid journalism of science gloats over crises and "revolutions", distorts them, expands them, just as the common press collects floods, earthquakes, volcanic eruptions, murders, and riots to satisfy the people's thirst for blood. The predominant character of science is not its crises but its stability. Of the national systems of government that were in existence when the laws of rational mechanics were discovered, those laws have outlasted all but one, one which is meanwhile become so altered as to be the same in name only.

The models rational mechanics provides are strictly logical; as POST puts it, they are *deductive models*, articulations of a particular theory. Classic science embraces also *inductive models*, summarizing an organized body of experimental data. Models of both these kinds are systematic. They teach us to find structure in experience, not merely to imitate one or another detail.

I have remarked above in Essay 10 that recent research resorts more and more to *floating models*, which treat phenomena severally, with no subsumption under general theory or organized knowledge gained from experiment. The example developed in some detail there is Applied Catastrophe Theory.

Here I mention another, one that originated in computing and is notorious for the renown of the names associated with it. I return to the attempt of FERMI, PASTA, & ULAM[15], mentioned above in § 3, to find a system such as to show "a gradual, continuous flow of energy from the first mode to the higher modes". Starting, as physicists will, with a simple harmonic assembly, which conserves the energy of each mode forever, they introduced hypothetical "non-linear forces acting between the neighboring points...." Thus they arrived at several special members of a class of partial differential equations introduced[16] by EULER (1744, 1766), extended by LAGRANGE (1761, 1781), studied by AIRY (1845), STOKES (1848), EARNSHAW (1861), and many later authors, and familiar to students of mechanics. Apparently knowing nothing of this classical work, FERMI and his collaborators went straight to the biggest computer there then was. It bore the name MANIAC. The results of their long (and no doubt costly) computations, they wrote, showed "features which were, from the beginning, surprising...," and they reported them with words of magic about "limits guaranteed by the ergodic theorem" *etc.*, leaving us to guess which ergodic theorem they had in mind. Some of the classical background of the subject was recognized by ZABUSKY[17], who by resort to the familiar hodograph transformation obtained a linear hyperbolic system which may be solved by the method of RIEMANN (1860), still more classic. ZABUSKY thus rediscovered a famous

[15] E. FERMI, J. PASTA, & S. ULAM, *Studies of non-linear problems*, Document LA-1940, May 1955 = pages 978–988 of Volume 2 of E. FERMI, *Collected Papers*, Chicago & Rome, University of Chicago Press & Accademia Nazionale dei Lincei, 1965.

[16] *Cf.* C. TRUESDELL, §§ 30 and 55 of *The Rational Mechanics of Flexible or Elastic Bodies, 1638–1788*, LEONHARDI EULERI *Opera omnia* (II) 11_2, 1960; page CXXI of "Editor's Introduction", LEONHARDI EULERI *Opera omnia* (II) **12**, 1954; and pages LIX–LX and XCVII–IC of "Editor's Introduction", LEONHARDI EULERI *Opera omnia* (II) **13**, 1956.

[17] N. J. ZABUSKY, "Exact solution for the vibrations of a nonlinear continuous model string", *Journal of Mathematical Physics* **3** (1962): 1028–1039.

observation of STOKES and HUGONIOT: After a finite time, the solution ceases to exist, and the outcome is a shock wave or "catastrophe" (*cf.* Essay 8, above). He concluded that "a continuous nonlinear system described by a partial differential equation of second order cannot describe the vibrations of the equivalent discrete system for 'large' times", and "to account for" the results of FERMI, PASTA, & ULAM he proposed "to include terms ... which involve higher derivatives ...." Thus he seemed to imply that the computer's results must have been right despite the floating origin of the discrete problem FERMI and his collaborators had made it solve. In telling the story KRUSKAL[18] decided that the thing to do was replace the problem of the non-linear string by the result of some mysterious manipulations with FERMI, PASTA, & ULAM's numerical system. He thus arrived at a partial-differential equation involving two derivatives of fourth order, which he magically converted to one with a single third derivative: the Korteweg-de Vries equation, which had arisen half a century earlier on a sound basis in hydrodynamics. Thus, apparently, KRUSKAL kicked aside the problem the computer code was designed to solve but could not; he replaced it by one that the computer perhaps did solve. In this way he and ZABUSKY came upon nonlinear waves which pass through each other with no change of form. Such waves, which were named solitons, were found also among the solutions of other nonlinear equations, and an exuberant literature devoted to them resulted and continues[19]. Opinions differ with respect to how much the original work owed to its authors' ignorance of classical hydrodynamics, in which single solitary waves had long been known and studied. There is room for disagreement also on the value of the hints, right and wrong, that the original exploration by computer provided.

If this story seems confusing, that is because it is:

1. The program given to the computer was incorrect for the analytical problem that was to be solved.
2. The correct solution of the analytical problem predicts a catastrophe. (Let the reader reflect on what might have happened, had the problem been one concerning a real nuclear reactor instead of just some physicists' wild guessing, and had the smooth and safe "solution" given by the computer been applied to the real world.)

[18] M. D. KRUSKAL, "Asymptotology in numerical calculations: progress and plans on the Fermi-Pasta-Ulam problem", pages 43–62 of *Proceedings of the IBM Scientific Computing Symposium on Large-Scale Problems in Physics* (1963), White Plains (N.Y.), IBM Data Processing Division, 1965.

[19] M. D. KRUSKAL, "The Korteweg-de Vries equation and related evolution equations", pages 61–83 of *Lectures in Applied Mathematics*, Volume 15, American Mathematical Society, 1974.

3. While the results of the computation were a disappointment at first, the correct solution of the original problem was a still greater one. The physicists threw away the original problem and sought one to which the computer program might apply.
4. This new problem, like the original problem, had a classic foundation, well enough understood that mathematical analysis, making intelligent and directed use of numerical computation when helpful, could develop it further.

Despite the hectic, unprincipled floundering which the story recounts, at least it has a happy ending: hundreds of mathematical papers on a harmless, beautiful topic in classical hydrodynamics, where computing plays a minor or at least directed role. It illustrates an empirical truth called "the BERS principle": GOD watches over applied mathematicians. Let us hope he continues to do so.

9. COMPUTING PROMOTES LOGICAL FRAUD. COMPUTERS PROGRAMMED TO CONFIRM FALSE THEORY CAN DESTROY MANKIND

The collective's war machine of huge computers, always famished for more and more numerical problems and at the same time always insufficient, always needing reinforcement by more and more bigger armaments, not only encourages floating models subject to no laws, it encourages logical fraud. By logical fraud here I mean mathematics that is not rigorous. The old kind of unrigorous mathematics often praised in circles of application was not so dangerous because the "Laws" stood behind us. A computed result which the "Laws" made suspect would be scrutinized at once. But when there are no "Laws", just floating models, there is nothing to check against! To see this, suppose for a moment that a new floating model be a good one, but as usual (in fact *de rigueur*!) so difficult mathematically that nobody can by mathematics assess the general qualities which applications of that model should have. Problems illustrating it in "important" applications are put straight onto the computer, but necessarily of course in some simplified version—further "approximations" they are called, which involve at bottom nothing but finitely many zeroes and ones. Unrigorous mathematics greases the path for wrong answers to slip out of even right assumptions, for something noxious to man to be by hocuspocus with the lingo of formulæ and a bore of computed digits whitewashed into something apparently useful. Here physics provides the worst of examples. In paraphrase of POST I might say that the classic

ἀεὶ ὁ θεὸς γεομετρίζει,

the god is always doing mathematics, has degenerated in the minds of modern physicists into

God is a bad mathematician.

Unrigorous mathematics, which is failed mathematics, is fraudulent mathematics. Computerized fraudulent mathematics provides abundant food for research which is aimed at confirming what is known already or what ought to be true even if it is not. This kind of research gets commoner and commoner nowadays. Whatever the proclaimed truth be, the computer can be programmed to support it. Science without "Laws" is fine for fields which, unlike physics, have never had "Laws", only dogmas. A dogma does not apply to cases; it can merely be repeated and rephrased and illustrated; the faithful invoke the dogma as a war cry in whatever they do, and their doings have no purpose but to strengthen the dogma. Of course a revolution can replace one dogma by another, perhaps the very opposite. Computerized floating models can always be adjusted so as to conform with a given dogma, no matter what the inputs. It takes no great genius at computing to make the inputs cancel out.

To reveal what computation can do with a floating model, I return to Applied Catastrophe Theory and quote SUSSMAN & ZAHLER[20] in regard to it:

> The interest it has aroused among the public at large is mostly understandable in terms of the fascination which the mystery of mathematics exerts upon the mathematically uneducated. Mathematics, in the perception of many, is like sorcery. The mathematician performs mysterious passes that others cannot understand, and suddenly a prediction, a theory, emerges. Consider, for instance, the description of how Catastrophe Theory works, as provided to its readers by *Newsweek* magazine (Jan. 19, 1976, pp. 54–55):
>
> > To apply catastrophe theory, a mathematician first selects the variables that are relevant to his problem—these might be 'growth' and 'inflation' in a particular economic environment. He then compiles as much statistical and behavioral data as possible and takes stock of the extraneous factors that might influence the economic climate. Finally, using highly complex mathematics and a computer, the mathematician forms a qualitative and quantitative model that, if properly formulated, can make precise forecasts of behavior which Zeeman says are far superior to any that can be achieved with the best statistical techniques known.
>
> The image presented here of the mathematician at work is very much like that of a sorcerer. The statistical data and the computer replace the wand and the flowing robes, but the actual nature of the mathematician's activity is equally mysterious. As in the case of sorcerers who were supposed to have all kinds of powers, yet seldom were able to perform a specific, reproducible feat, the Catastrophist is supposed to be able to make "forecasts" that are "far superior to any that can be achieved with the best statistical techniques available", although not a single example of such a forecast exists.

[20] H. J. SUSSMAN & R. S. ZAHLER, "Catastrophe theory as applied to the social and biological sciences: a critique", *Synthèse* 13 (1978): 117–216. See page 206.

Their final sentence refers to the status of "the surrealist world of catastrophe theory" in 1978. It prepares us to imagine how computerized research on floating models, particularly in the social sciences, will in the future provide projects ideal for support by the Ministry of Love.

Nothing is easier to apply to human betterment than failed mathematics substantiated by experiments programmed to confirm it. Such mathematics and such computing cannot take men to the moon, but it can destroy all the men on earth.

10. SUMMARY: COMPUTERS ARE HERE TO STAY. THEY ENDANGER THOUGHT, LANGUAGE, SCIENCE, AND THE SURVIVAL OF MAN. LIKE ANY OTHER DANGEROUS TOOL, THEY SHOULD BE PUT UNDER STRICT CONTROLS

A computer, like a knife or a gun or a television network or a nuclear bomb, is an object. An object in itself, even an erupting volcano, is neither good nor bad, but it may be dangerous. Man puts objects to use. Nuclear fission, we know, can produce peaceful power; much of applied engineering today finds the computer indispensable, interplanetary flight being but one of myriad instances of what we can do with the aid of the computer and cannot do without it. I have pointed out what else man can make computers do. As for men, it is not my place to pass judgment on them. Maybe most men are good. Maybe we are entering a new golden age of peace and plenty, in which the lion will lie down with the lamb, the whore with the guileless schoolgirl, the assassin with the prey he has been suborned to shatter.

Maybe man, for the first time in his existence, will turn each of his tools and toys, even the most dangerous, to good uses alone.

Do not misunderstand what I have said. I preach no war on computers. Like Don Quixote's windmills, computers are here to stay, as long as man can afford to make and run them, or until he can replace them by something still more dangerous. I plead only that

(1) As a lead article in *The Wall Street Journal* for 29 September 1980 reminds us, an object code "consists solely of ones and zeroes, the only things even the smartest computer can deal with." The reporter failed to mention that the ones and zeroes are *finite in number.*

(2) Whenever a problem is demonstrably amenable to finite arithmetic, a computer can be used and in most cases should be. Examples: accounting, some aspects of engineering, preliminary exploration of some mathematical problems, *etc.*

(3) Numerics cannot bring understanding of the structure of a mathematical problem unless an informed human being has already conjectured possible structures or inferred them from instances.

(4) Computation is dangerous except in providing details concerning problems whose structure is already understood mathematically.

(5) The importance of numerics to science has been brazenly exaggerated by pressure groups which profit or hope to profit from manufacture, sale, and tending of computers and by addicts who preach computing as the first and last command of Allah.

(6) Preponderance of computation discourages critical analysis, creative thought, and the training of thinkers.

(7) Critical analysis and creative logical thinking are as important today as they were 100 or 2000 years ago—in view of the multitudinous applications of science to the human condition, perhaps even more important.

(8) Mathematics done by human minds should be cherished and fostered.

But it is not only mathematics that the computer vilifies and stifles. It poisons speech. WAN-LEE YIN in a private communication writes:

> Men of all past ages have reserved their better speech for their Gods and for posterity. It was not for the purpose of communicating with their fellow mortals that they invented writing and perfected language. Even in our century, Eliot could write
>
> Since our concern was speech, and speech impelled us
> To purify the dialect of the tribe
> And urge the mind to aftersight and foresight....

I still believe that science ennobles men. But for science to ennoble men, science must speak the language of men and not of the machine. Anyone who has had the misfortune to write his first computer program remembers the humiliation in conversing with a servant or master that insists on a language unworthy of the dullest of intelligences and the lowest of men. For of all human capacities language is traditionally considered the noblest, and hence the impoverishment and adulteration of language is the debasement of the dignity of man. Because freedom consists in an ever-present choice of defying the tyranny of necessity, and because language in its broadest sense as the total medium of expression is the sole means and avenue for that defiance, the abridgement of the structure and form of language by instituting arbitrary yet totally inflexible rules constitutes the most threatening violation of freedom. For what is at stake is not a matter of censoring certain categories of thoughts and ideas; it is rather the suppression of all spontaneous modes of expression and the deprivation of all human elements in speech and gesture for the mere sake of necessity and utility which the machine dictates whenever an individual makes a call and so long as the exchange lasts. The tyranny is total not because the power of the agent is overwhelming, but because the avenue of power is so strictly private and closed to spectators and because the agent himself is so utterly destitute of feeling and understanding (destitute even of sadistic pleasure which, though beastly, is akin to human) that the suffering and debasement of his subject can bear no witness nor meaning—for what is the use of defiance in face of an oppressor who understands not defiance? For such reasons, the tyranny of artificial intelligence represents ontologically a totally wasteful kind of domination in the structure and dynamics of power relations, a kind of domination compared to which even the Hell of Satan or the infamous union of torture chamber and pleasure harem in Marquis de Sade's imagination appears infinitely reasonable and surpassingly humane.

In a communion with machine's intelligence, man's consciousness voluntarily subjects itself to captivity in a barren cell enclosed by stubborn blocks of elementary logic and, like Eliot's spider, suspends its natural operations. It is like the return of the prisoner from the world of ideas to the chains and darkness of the Platonic cave, where he encounters not even the shadows of reality that were granted to him in his earlier captivity, but merely grotesque images, distorted reflections and drawn out echos of his deprived and depraved self. I always hold a low opinion of those obsessed with certain contrived games in which the artistic and communicative elements are totally absent—gadgets like Rubik's cube and video games which are lately in vogue—and I believe any individual so professionally well-disciplined as to entertain a lasting enjoyment in the companionship of machine intelligence has already sucked the Vampire's blood and is condemned to moonlighting as a disciple of the Satan of Bits and Bytes. The future Planet Earth may be ruled by such experts of machine intelligence, but the experts themselves would have to have been so impeccably schooled in the manners and speech of the lowest of slaves as to leave it quite uncertain whether there would be real masters. For once the medium becomes the message, those messages which were previously medium will devour genuine messages until the Vampire's blood runs in the veins of all messages.

In regard to the flamboyant, appalling failures of a computer which, had they not been corrected by human steadiness and human action, would have precipitated a monstrous nuclear war, ART BUCHWALD wrote in the *International Herald-Tribune* for 14/15 June 1980, "... war is too serious a business to be left to computers." The dangers potential in application of such sciences as high-energy physics and genetic alteration make them, also, businesses which if not too serious to be permitted at all are at least too serious to be left to computers. Indeed, I think, to renounce critical and creative use of human language and human reason is the greatest of the many present threats to the survival of mankind. Here the computer for "science" is but one of the Satanic instruments bent on the destruction of mind and man. As Mr. YIN puts it,

> The cult of artificial intelligence and agnostic science is not the source but merely a symptom or a catalyst of that larger process of disintegration and demise in which all living men are actors and spectators.

Acknowledgment

Ever since 1946, when for a time I had to take reluctant command of a battery of computing machines and its officers and crew, I have profited from discussions with friends and others regarding the use and misuse of computation in research on pure science. For their critical reading of parts or all of various draughts of the text and for their helpful suggestions I thank Messrs. CAPRIZ, LIEB, CHI-SING MAN, NUNZIATO, PODIO-GUIDUGLI, VILLAGGIO, and WAN-LEE YIN; of course I do not imply that any of them shares any of the views presented in the foregoing essay beyond those which are quoted from their writings.

Note

The first three sections of this lecture and a few sentences in other sections are taken *verbatim* from my lecture of 10 November 1979 in the Biozentrum at Basel: "The Role of Mathematics in Science as exemplified by the work of the Bernoullis and Euler", published in the *Verhandlungen der Naturforschenden Gesellschaft in Basel* **91** (1981): 5–22. Most of the duplication has been excised in the condensed and revised version of that lecture which is reprinted above as Essay 10 in this volume.

The text printed here is based upon a lecture of the same title read on 7 February 1980 to the international conference "Scientific culture in the contemporary world", organized by *Scientia*, Milano. A version intermediate between that lecture and the final text has been published in translation, "Il calcolatore: rovina della scienza e minaccia per il genere umano", pages 37–65 of *La Nuova Ragione Scienza e Cultura nella Società Contemporanea*, Bologna, Scientia/Il Mulino, 1981.

Note Added in 1986

Whole Earth Review No. 44, December 1984/January 1985, contains three good articles regarding the effects of computers upon human beings and society:

JERRY MANDER, "Six grave doubts about computers"

LANGDON WINNER, "Mythinformation"

LARRY HUNTER, "Public image"

In his book *The Cult of Information. The Folklore of Computers and the True Art of Thinking*, New York, Pantheon Books, 1986, THEODORE ROSZAK provides a detailed, organized survey and analysis of the effects of computers on men's minds and lives. His evidence, abundant and awesome, reports actual occurrences and quotes boasts by promoters and addicts of computers. Three specimens suffice here:

From an authority at Apple Computer: The computer will shift from its role as servant to become a "guide or agent":

> It's going to do more in terms of anticipating what we want and doing it for us, noticing connections and patterns in what we do, asking us if this is some sort of generic thing we'd like to do regularly, so that we're going to have ... the concept of triggers. We're going to be able to ask our computers to monitor things for us, and when certain conditions happen, are triggered, the computers will take certain actions and inform us after the fact.

From a dean of computer science at a university: To become computer-literate

> ... is a chance to spend your life working with devices smarter than you are, and yet have control over them. It's like carrying a six-gun on the old frontier.

From the MIT artificial intelligence agency in 1970: By 1985 computers will be in a position to "decide to keep us as pets".