Is It Chaos, or Is It Just Noise?

Epidemiologists have traditionally assumed that the seemingly random fluctuations in patterns of epidemics are caused by environmental noise. The possibility that the fluctuations are instead due to deterministic chaos opens a new window to understanding human disease

IN THE YEARS BEFORE MASS MEASLES vaccinations, outbreaks of the disease in New York City followed a curious pattern. As one might expect, the number of infections surged each winter, when children were in school and everyone stayed inside and traded germs. But in the two decades following World War II, something else was going on. Every second winter, the number of measles cases exploded—one winter would have a relatively mild outbreak, and the next would see five to ten times as many cases, sometimes as many as 10,000 a month.

Strangely enough, this biennial cycle did not appear until after 1945. From 1928 to 1944, measles did peak each winter, but there seemed to be no pattern to mild and severe years. A relatively light winter might be followed by two intense ones, or vice versa. Once, after two very mild years, the city had a particularly heavy epidemic where nearly 25,000 cases were reported in 1 month.

A vaccination program begun in the early 1960s put an end to these dramatic yearly fluctuations, but the New York City case remains a textbook example of how outbreaks of disease can vary rather mysteriously over time. Measles and other childhood diseases—poliomyelitis, rubella, and scarlet fever, to name a few—often show patterns that seem to be a mixture of regularity and randomness.

What causes these patterns? Recent research suggests the culprit may be chaos, a strange type of mathematical order that appears to be random but actually follows very precise rules (see box on page 27). Using this insight, several scientists have developed epidemiological models that predict infection patterns strikingly similar to the real thing. One model, for instance, mimics measles infections in New York City from 1928 to 1963. Researchers say the study of chaos and other complicated behavior in patterns of epidemics could have important implications for public health policy, suggesting the best ways of carrying out vaccination programs.

Chaos is a mathematical concept that is somewhat difficult to define precisely, but it is probably best described as "deterministic randomness." A chaotic system is deterministic—it obeys certain equations that can seem quite simple—but behavior of the system is so complicated that it looks random. It is impossible to predict the long-term behavior of a chaotic system because any uncertainty in the initial conditions of the system increases exponentially with time. Chaos is order disguised as disorder, a sheep in wolf's clothing.

This is the first in a series of articles on chaos and its applications in various fields of science. Articles to come will include chaos in ecology, chaos in medicine, and quantum chaos.

This disorderly order (or perhaps it is orderly disorder) has been discovered in many areas of science. Researchers have found or claimed to have found chaos in chemical reactions, the weather, the movement of asteroids, the motion of atoms held in an electromagnetic field, lasers, the electrical activity of the heart and brain, population fluctuations of plants and animals, and even in the stock market. Indeed, chaos has become rather fashionable, especially with the success of James Gleick's book, *Chaos*, which was a surprise best seller.

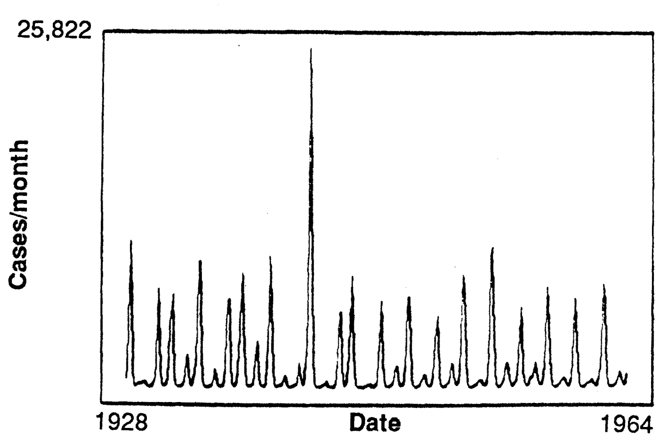
Although researchers have proven chaos exists in many physical systems, its presence in epidemiological systems is still under debate.

One of the strongest advocates of chaos in this debate is William Schaffer of the University of Arizona. In 1985, Schaffer and Mark Kot, then also at Arizona, claimed evidence for chaotic fluctuations in measles epidemics in New York City and Baltimore. Since then, Schaffer and Kot, now at the University of Tennessee, along with Lars Olsen of Odense University in Denmark and Greg Truty at Arizona, have analyzed outbreaks of measles, mumps, and rubella in Milwaukee, Detroit, St. Louis, Copenhagen, and Aberdeen, Scotland. Their work shows that simple epidemiological models exhibiting chaotic behavior can reproduce the historical patterns to a surprising degree.

"We can get equations to mimic the data with astonishing regularity," Schaffer says. This success leads Schaffer to claim that chaos plays an important role in shaping patterns of infection.

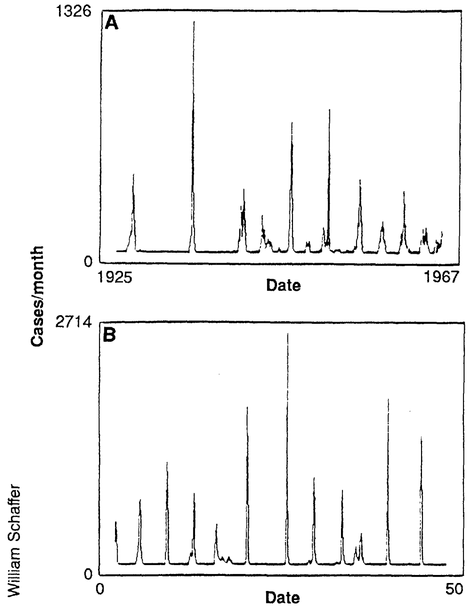
Other epidemiologists view this work with interest, but some suggest Schaffer and colleagues may be trying to explain too much with chaos. "I think they're taking the model too literally," says Joan Aron at the Johns Hopkins University School of Hygiene and Public Health. "The claim that we have found chaos in epidemics is too strong."

The debate has its roots in the nature of the epidemiological data. These data usually show very obvious regularities, such as winter peaks or the 2-year low/high cycle in New York City, but they often have irregular fluctuations as well, such as the way the magnitude of the peaks changes year to year in the New York City data. The traditional



William Schaffer

A mix of order and disorder: *Measles in New York City, 1928 to 1964.*



A computer simulation *of measles in Bornholm, Denmark (B), is qualitatively very similar to the historical data (A).*

assumption has been that the irregularities are the result of "noise"—random, unpredictable events such as population movements or variations in the weather—and that in an ideal world without all this noise, the patterns of infection would be quite regular.

Although the debate about the role of chaos in epidemics may seem rather technical, it has profound implications for how much can be understood and predicted about the outbreaks of infectious diseases. If the fluctuations in epidemics are due to chaos, they have more structure than previously believed. Understanding this extra structure will help predict such things as the effects of a vaccination program.

If the fluctuations really are nothing more than noise—nothing more than the result of random fluctuations in the host population—then predicting the course of these infections will be much harder. Forecasting would ultimately depend on understanding the source of the noise and learning to predict it.

Most epidemiologists, whether or not they believe in chaos, work with the same epidemiological models. The basic model for infectious childhood diseases, the so-called SEIR model, splits a population into four categories—susceptibles (S), exposed (E), infected (I), and immune, or recovered (R). The simple differential equations of the model relate how the numbers of people in each of these groups change with time, taking into account such things as birth and death rates, the average latency period of the infection, and the average time a person is infectious.

One important parameter in the model is the contact rate, or the average number of susceptibles that will catch the disease from each infected person. In many models, this parameter fluctuates over the course of the year, reflecting the fact that people are more likely to pass a disease on at some times of the year (winter) than at others.

Traditionally, epidemiologists have studied very simple, regular solutions to these models. It is relatively easy, for instance, to choose parameters in a measles model to produce a 2-year low/high cycle that looks something like the New York City history from 1945 to 1963. But since these simple solutions are too regular, epidemiologists have assumed the models needed a little noise to spice things up—changes in birthrate, random movements of infected individuals into or out of the population, or changes in the weather, such as a particularly severe winter that keeps people inside more often than usual.

Schaffer and colleagues have shown that noise is not necessary to produce irregular infection patterns. Working with the SEIR model, they have produced computer simulations of measles epidemics much like those in New York City before the vaccination program (see box). Some of the patterns show an approximate 2-year cycle with the size of the peaks varying from cycle to cycle; others jump around unpredictably, with high and low years interspersed in seemingly random order. The patterns are, to be precise, chaotic.

If the chaotic models are correct, the practical importance is that epidemiologists will not have to fall back on random factors to explain so much of the behavior of epidemics. Noise will always be a fact of life in dealing with epidemiological patterns, but it will not play nearly so large a role. "We are chipping away at the unexplained variance by equating more complex behavior with the deterministic part," as Schaffer puts it.

In their models, Schaffer and co-workers use values for birth and death rates, average latency period, and average infectious period that are estimated directly from historical and medical data. The contact rate, which varies through the year, must be estimated indirectly, however, and it is here that much of the debate arises over the correspondence between the models and the real world.

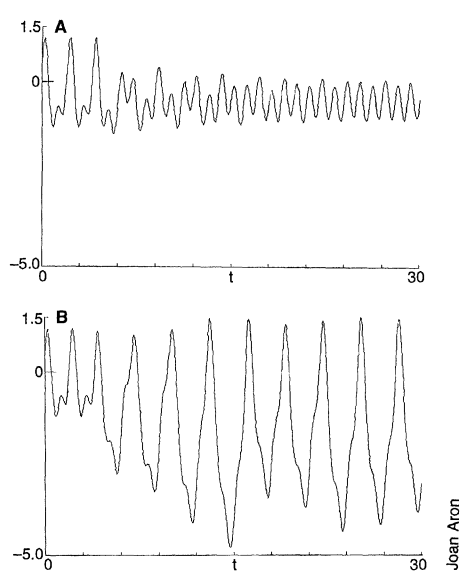
"These models do appear to come up with patterns that look strikingly similar to some of the epidemics they're looking at," Aron admits. "But could other things do that too?" Aron argues that the models are extremely sensitive to certain parameters, such as the contact rate, and if these parameters vary significantly over 30 or 40 years, that could produce the fluctuations.

Schaffer responds that adding such variation to models with chaos removed does not produce patterns like the historical data. "The chaotic hypothesis gives a better explanation," he says.

Ira Schwartz, an applied mathematician at the Naval Research Laboratory, has reservations similar to Aron's. He points out that the available data are very poor because of variations in reporting and other factors. And although he acknowledges that SEIR models can display chaos, he says that because the models make a number of simplifying assumptions—such as positing a constant, uniform population—they are unlikely to parallel the real world quantitatively. "There do exist cases where the qualitative features of the model seem to agree with the data," Schwartz says, but Schaffer is "trying to tie the model in a little too closely with what he sees."

"We know the equations are wrong," Schaffer replies. "All models are idealizations. What we hope is that the sequence of states in these simple models is close enough to what you would see with the real equations that it can be useful."

Eventually, the debate gets rather technical. Schwartz, who emphasizes he is not talking as a spokesman for the Naval Research Lab, argues that the parameters Schaffer uses to model the seasonal change in contact rate are larger than the data indicate. Schaffer responds that the seasonality observed in real measles epidemics is at least high enough so that the system is "almost chaotic," and that this is good enough. "If you take a system that is almost



The effects of a vaccination program *can depend on whether it is done in a mild year (A) or a peak year (B). (The vertical scale is the number of infecteds scaled logarithmically.)*

chaotic and excite it with small perturbations, then its behavior is effectively indistinguishable from true chaos."

Theoretically, one can distinguish between noise-induced fluctuations and true chaos by calculating certain technical characteristics of the data, such as Lyapunov exponents and fractal dimensions. These numbers will have certain values if chaos is present and others if it is not.

Although the noisiness of the data makes these calculations less than precise, Schaffer and co-workers have run the numbers for several sets of historical data. On this basis they concluded in a recent paper that measles, mumps, and rubella in Copenhagen behaved chaotically, while chicken pox had a simple yearly cycle. The calculations were inconclusive for pertussis and scarlet fever.

Although Schaffer acknowledges that the epidemiological data may not be clean enough to settle the debate entirely, he contends that one can make a strong case for chaos from the combination of chaotic models that mimic real epidemics very closely and data that have the signature of chaos. "I try to be careful and not make claims that won't stand up, but I think the epidemiology work is very solid."

Whether or not true chaos exists in epidemiology, the realization that simple models can produce complex patterns of infection has motivated researchers to take a new look at predicting epidemics. As long as the patterns were believed to be shaped by random factors, there seemed little hope of using this year's data to predict next year's outbreak, but if much of that apparent randomness is deterministic, the behavior may be predictable to a certain extent.

"I think you really can say something about next year's cases," Schaffer says, but only in certain years. In a year with relatively few infections, anything can happen the following year, but in years of medium or high infection, the next year's outbreak can be forecast.

The same models that can predict the course of a natural epidemic can gauge the effects of various vaccination programs. It is here the epidemiological work may prove to be of most practical value.

For instance, congenital rubella syndrome (CRS) causes birth defects in many babies born to mothers who contact rubella while pregnant. To fight CRS, some countries try to inoculate as many children as possible before they enter school in the hopes of immunizing the entire population. Epidemiologists call this the USA strategy. The UK strategy, practiced in many European countries, is to inoculate only girls from the ages of 11 to 14. This allows many children to get rubella and develop natural immunity,

The Onset of Chaos

Chaos often appears in an otherwise well-behaved physical system when it is "pushed"—when a certain parameter of the system is increased so high that irregular motion sets in.

One of the easiest ways to visualize this onset of chaos is to picture a stream of water flowing around a rock. If the water moves slowly, the flow is smooth and its movement is easy to describe mathematically. As the stream starts to flow more swiftly, the water behind the rock develops ripples and eddies. At some point, the water's movement becomes so complicated that it is unpredictable. Chaos has set in.

Chaos can appear in models of epidemiological systems in an analogous way. In this case, the factor being increased is not the speed of the water but the model's seasonality, or change in the contact rate throughout the year, measured by the parameter B_1. If $B_1 = 0$, the contact rate is constant throughout the year. Large values of B_1 imply high contact rates in the winter and low ones in the summer.

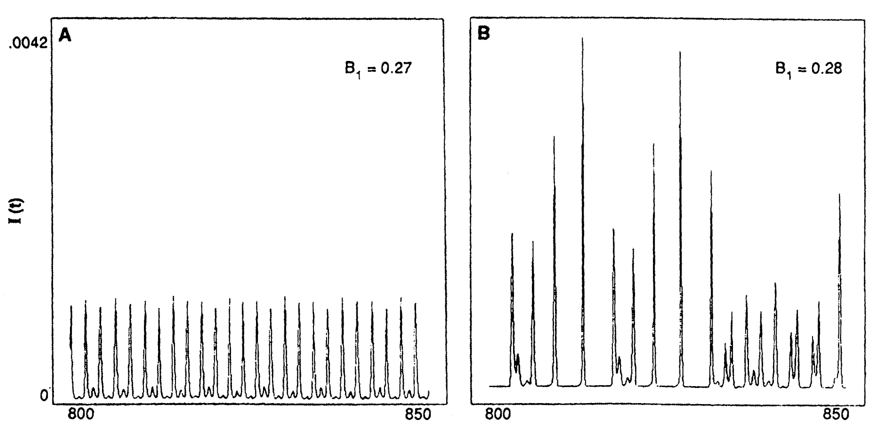
William Schaffer and colleagues at the University of Arizona have shown that increasing the seasonality brings about chaos in computer simulations of measles epidemics, as shown in the two graphs below. The two graphs plot the number of infected persons, $I(t)$, in a model population over the course of 50 years. The only difference between the two simulations is the value of B_1.

When $B_1 = 0.27$, the model shows an approximate 2-year cyclic pattern, similar to the records of measles in New York City from 1945 to 1963. The highest number of infections—the peaks on the graph—occur in the winter each year, and winters with relatively few infections alternate with winters that have many.

When B_1 is increased to 0.28, suddenly the computer simulation loses its regularity and large fluctuations set in. Several years may pass with essentially no cases, and then a sharp peak of cases hits; or two winters in a row may have a medium number of cases. This is chaos. And although there are differences, the pattern shares many features with the record of measles infections in New York City from 1928 to 1944.

The chaotic pattern is not completely random. After a big peak, for instance, the next few years have almost no infections because almost everyone who can be infected has been, and it takes a while for the number of susceptibles to build back up.

But even with this short-term order, the long-term pattern of a chaotic epidemic is essentially unpredictable. This is caused by a so-called "sensitivity to initial conditions." Suppose the simulation in graph B began with 10,000 infected persons. If that number were to differ by as little as 1%—if the number of infecteds were 10,100 instead of 10,000—then the pattern of infection would look very different. The two patterns would appear similar the first few years, but they would diverge completely within 10 or 15 years. (In contrast, changing the number of infecteds in graph A would not change the pattern much—the simulation would still show the same 2-year high/low cycle.) Since one can never measure the initial conditions in an epidemiological system exactly, predicting the long-term behavior of a chaotic system is impossible. ■ R.P.



William Schaffer

The pattern of infection *changes dramatically as* B_1 *increases from 0.27 to 0.28.*

and then adds to that natural immunity by vaccinating girls as they approach child-bearing age. Long-range computer simulations find the UK strategy is more effective if less than 80% of the target group is vaccinated, while the USA strategy is superior if the inoculation rate is higher.

Although it is relatively simple to predict the long-term effects of a vaccination program, short-term effects can depend sensitively on how the program is carried out. For instance, several years after the United States began its rubella vaccination program there was actually a sharp jump in birth defects due to CRS.

Schwartz and Aron have shown the timing of a vaccination program can be crucial in determining its results. One of the most striking results comes from Aron, who investigated the effects of vaccinating against a disease with a 2-year high/low pattern of epidemics. She found the timing of a program inoculating one-third of all newborns dramatically affects the resulting pattern of infection. If the vaccinations are given as a mild winter approaches, the epidemics gradually settle down to a 1-year cycle with relatively mild winter peaks. If, however, the vaccinations are performed before a severe winter, the result is a 3-year cycle with very severe epidemics every third winter and mild outbreaks the other two.

Although Aron's work avoids chaotic solutions, it is indicative of chaos's influence on epidemiology. Until recently, researchers restricted themselves to simple solutions of their models, assuming the complicated ones both were too difficult to deal with and had no application to the real world. The work on chaos has lifted a psychological barrier, showing that even the complicated behavior of epidemiological patterns may yield to analysis by uncomplicated mathematical models. ■ ROBERT POOL

ADDITIONAL READING

J. L. Aron, "Simple versus complex epidemiological models," to appear in *Applied Mathematical Ecology* (Springer-Verlag, New York, in press).

J. L. Aron and I. B. Schwartz, "Seasonality and period-doubling bifurcations in an epidemic model," *J. Theor. Biol.* **110**, 665 (1984).

L. F. Olsen, "Poliomyelitis epidemics in Denmark over the period 1928–1958 were chaotic," *Math. Comput. Model.* **10**, 155 (1988).

L. F. Olsen, G. L. Truty, W. M. Schaffer, "Oscillations and chaos in epidemics: A nonlinear dynamic study of six childhood diseases in Copenhagen, Denmark," *Theor. Pop. Biol.* **33**, 344 (1988).

W. M. Schaffer and M. Kot, "Nearly one dimensional dynamics in an epidemic," *J. Theor. Biol.* **112**, 403 (1985).

W. M. Schaffer, S. Ellner, M. Kot, "Effects of noise on some dynamical models in ecology," *J. Math. Biol.* **24**, 479 (1986).

I. B. Schwartz, "Multiple stable recurrent outbreaks and predictability in seasonally forced nonlinear epidemic models," *ibid.* **21**, 347 (1985).

How to Fix the Clouds in Greenhouse Models

Climate models are moving toward the realistic simulation of clouds needed to calculate the size of the greenhouse warming

CLIMATE RESEARCHERS are convinced that increasing amounts of carbon dioxide and other greenhouse gases will eventually warm Earth noticeably, but they are equally certain that their current computer models cannot be trusted to predict the precise magnitude of that warming. The models are still too unrealistic.

In this issue of *Science* (p. 57), V. Ramanathan of the University of Chicago and his colleagues report a first step toward fixing the weakest part of current models, their clouds. These researchers report that observations by two satellites in the Earth Radiation Budget Experiment (ERBE) show for the first time that the clouds of today's climate cool Earth below the temperature it would be without any clouds. The next step will be the improvement of the models so that their clouds behave the way these and other new observations show clouds do under the present climate. Only then might modelers have some confidence in predictions of cloud behavior and thus climate behavior under the coming greenhouse.

Until ERBE, not enough observations had been taken around the globe for researchers to even be sure whether today's clouds cooled or heated Earth. Clouds cover about half of Earth, doubling the proportion of sunlight reflected back into space to 30%. This reflection by clouds surely tends to cool Earth. But clouds not only can block incoming, shortwave radiation but also the longwave, infrared radiation emitted by the warmed air and surface beneath them. Thus, by trapping longwave radiation, clouds can have a greenhouse effect that tends to counteract the effect of their reflectivity.

The initial ERBE results, including final ones for 1 month and preliminary ones for three other months, show that reflection by clouds wins out by a modest margin. Clouds around the globe in April 1985 reduced absorption of incoming solar radiation (340 watts per square meter) by 44.5 watts per square meter while reducing infrared losses to space by 31.3 watts per square meter. That produces a net reduction in radiative heating of Earth of 13.2 watts per square meter. This gives clouds a major role in the present climate. By contrast, current climate models predict that a doubling of carbon dioxide will warm Earth 2.8° to 5.2°C through an increase in net radiative heating of only 4 watts per square meter.

Working with such small changes to the climate system's energy input is a problem, but a bigger challenge for modelers is that as greenhouse gases change the climate, the clouds will presumably change, in turn altering the climate. Cloud areas, altitudes, proportions by type, and water contents could all change, in the process altering the radiative fluxes in and out of the climate system. Clouds that change with changing climate, thus creating feedbacks affecting climate, have begun to be included in models only in the past few years.

"You have every right to be very, very skeptical of the results" of today's models. "But this is the best that we're doing."

A recent study points up how far the models have to go before they get a handle on these cloud feedbacks. An unprecedented intercomparison of 11 greenhouse models, which was conducted by the models' creators and is headed by Robert Cess of the State University of New York at Stony Brook, shows that although the sensitivity of current models to climate forcing such as greenhouse gases varies by a factor of 3, the same models without clouds are in excellent agreement. "The models aren't bad except for the clouds," says Cess.

When judged by the ERBE data from the present climate, five models taken for illustrative purposes have varying success in reproducing the observed net cloud cooling. They all have a cloud cooling rather than a warming, but the model that comes closest to the observed cooling does so by having its clouds reflect too much solar radiation and trap too much longwave radiation. That does not encourage confidence in the mod-