Concepts of Diffusion Theory and a Graphic Approach to the Description of the Epidemic Flow of Contagious Disease

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ACCURATE FORECASTING OF THE SPATIAL SPREAD of contagious disease remains a central goal of epidemiology. Its utility in determining a strategy for control of disease is evident. To date, advances have been made only in identifying the factors of time and the characteristics of persons that determine contagion. These advances have come from two approaches: (*a*) detailed empirical studies of disease transmission within families and small communities and (*b*) broad mathematical and statistical modeling according to a deterministic or stochastic formulation. The second approach has frequently run into formidable mathematical problems or has yielded models of limited or unknown applicability. It thus seems that, rather than using such formal approaches, an attempt could be made to improve the other, intuitive approach by incorporating into it the conceptual framework of a mathematical model. It was thus decided to use concepts of diffusion theory to improve the intuitive reconstruction of the flow of the variola minor epidemic reported in a series of papers.

Theory of Diffusion

Geographers usually define spatial diffusion as the spread (or dispersion) of a phenomenon within a given area through time. The literature abounds with descriptions of diffusion processes relevant to the locational distribution of innovations, culture traits, and other economic, social, political, or physical items. In all instances, it is expected that the locational or distributional pattern of the phenomenon will change over time.

The current quantitative theory of spatial diffusion had, as its primary architect, Torsten Hägerstrand. This worker (*1*) studied the spread of automobile ownership through southern Sweden and the adoption of agricultural subsidies and of tuberculosis tests for cattle. By plotting these adoptions on maps, he found that the patterns of spread were similar to waves moving out from a source and being distorted by certain barriers to acceptance of the innovation. To attempt to model these patterns, Hägerstrand used a Monte Carlo simulation method, with the probability of receiving information about an innovation and adopting it being directly related to the distatnce from the source of the information. The Monte Carlo method produced patterns similar to the real ones and, although some criticism has been raised (*2*), the basic proposition is correct (that distance from the source is the key factor), and later studies are improvements in the method.

Since Hägerstrand's initial work, numerous geographers, sociologists, economists, and even psychologists (*2–6*) have examined the diffusion of ideas, practices, and people (migration). As a matter of fact, diffusion can be studied at the national or the international level as well as at the regional, city subdivision, or household level. Geographers have examined the epidemic spread

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of cholera, influenza, measles, variola minor, infectious hepatitis, and even fowl pest according to diffusion theory (*7–13*).

Epidemic Data

Field data. An overall description of the epidemic of variola minor (the mild form of smallpox) occurring in 1956, in Bragança Paulista County, State of São Paulo, Brazil, appeared elsewhere (*14*). Identification of cases and the various surveys conducted during the field study of the epidemic have been described. Analytical studies of the epidemic in schools have been published (*15, 16*). It should be emphasized that importation of variola minor into the county and the geographic spread were discrete events (*14*).

Nine medical investigators painstakingly reconstructed the chain of contagion (person-to-person transmission). The dates of onset were carefully investigated for the 498 recorded cases, particularly for the introductory (earliest) case among members of a household or school class. Possible contacts with earlier cases were meticulously sought for the introductory cases and frequently for other cases from the household or school class. This information was checked in the same or other social groups, with emphasis on dates of illness onset and contacts. The dwellings of patients were plotted on maps of the city and rural districts.

Graphic Approach

Specification. Concepts of diffusion-theory models were used to disclose spatial, temporal, and sociological characteristics of the epidemic flow. On the assumption that the sociological attributes of the community influenced the space-time distribution of the epidemic, space and time were schematically represented, as were the modes of diffusion. The modes clearly corresponded to sociological factors and directly disclosed the social group that played a role in the epidemic flow. A diagrammatic stepwise representation was preferred rather than the classic cartographic procedure of spot mapping, because mapping does not directly disclose sociological factors. The procedure is an adaptation and a modification of Semple and Wasilensko's graphic representation (*17*) of modes of diffusion of innovations (commercial products, commercial services, and cultural traits).

Definitions. In the present study, neighborhood diffusion was identified if the source and receptor social units were of the same type (household to household or school class to school class) and both were localized within a single, well-circumscribed area. Hierarchical diffusion was identified if (*a*) transmission of disease occurred between two social units of different type (household to school class or school class to household), even if both social units were in the same geographic area or (*b*) if transmission was examined at the geographic area scale; that is, if spread between two distinct areas was considered. In this instance, the areas might have been of the same or different types (city subdivision to another city subdivision, or city subdivision to a rural district, and so forth.)

Those households where school children introduced variola minor were assumed to have been affected through hierarchical diffusion (school class to household). For reasons discussed subsequently, the households whose introductory cases were in adults or preschool children were assumed to have been affected through neighborhood diffusion, by households from the same area.

The city of Bragança Paulista was a polygon, mapped according to geographic and administrative criteria years before the epidemic under study. It could clearly be divided into subdivisions differing from each other geographically and in socioeconomic characteristics. The core (see diagram) was the oldest subdivision from which the periphery grew. The periphery was limited by the administrative boundary of the city. This area was divided into the northern periphery and southern periphery by a street running from east to west and intersecting the core at approximately the middle of the longest axis of the city. The rural districts were seven administrative areas corresponding to spaces demarcated by the highway network and by the villages, ridges, valleys, and other geographic features.

Space and time units. Spatial units and temporal stages were selected and modes of diffusion were disclosed through inspection of spot maps, lists of dates of the introduction of variola minor into households and school classes, and the chain of person-to-person transmission of the disease. A rather large scale of diffusion was chosen for the graphic representation because of the exploratory character of the procedure and to avoid a confusing diagram showing interactions among 212 affected households and 49 affected school classes. Thus, geographic areas (city core, city peripheries, rural districts, and schools) were the spatial-sociological units for disclosing the epidemic flow from one unit to another and within each unit. These areas included agglomerations of households or school classes and were schematically represented in relation to the mode of diffusion prevailing at consecutive time periods. Since partitioning of the time axis by the serial interval or by the incubation period of variola minor seemed to be unrealistic, the month, a period commonly used in epidemiology, was selected. Because the earliest months of the epidemic included very few cases, the first 3 month were pooled (see diagram pp. 482–483).

Graphing procedure. To differentiate when geographic areas of the same type were affected, the symbols for rural districts were numbered, and initials were added to the school symbol. The two peripheral regions of the city were represented by triangles pointing north or south. A square represented the city's core since no portion of it was differentiated on the basis of epidemiologic, geographic, or social criteria.

Introduction of variola minor into an area or spread within this area was represented by concentric rings or layers around the symbol, with each layer representing a month. The outer ring was blank when the disease was introduced or when it was diffusing within the area in the given month. If neither introduction nor within-area spread occurred in the subsequent month, no further concentric ring or layer was added and the outer space was dotted to indicate that saturation of an area had been achieved. Saturation, indeed, did not imply that all households or school classes of the area had suffered attacks, but rather that the epidemic diffusion had ended in that area before the particular month.

Interruption of the spread at various times and its reassumption might easily be disclosed by comparison with previous graphs. In effect, if the given symbol shows the outermost layer or ring dotted in one or more previous graphs, the appearance, in this symbol, of a further blank layer or ring would indicate the reassumption of disease occurrence in the corresponding area and time period.

As mentioned previously, spread between geographically distinct areas implied hierarchical diffusion, whether these areas were or were not of the same type. Hierarchical diffusion was indicated by arrows pointing in the direction of the flow, thus evidencing the source and receptor areas (see diagram). Repeated diffusion in the same month was not indicated, for the sake of clarity.

The stepwise character of the procedure may appear as the consecutive representation of each month's diffusion or as cumulative diagrams of more informative values.

Description of the epidemic flow. The epidemic originated through hierarchical diffusion from a county in a neighboring State. The only person with an imported case of variola minor lived in the city core where his case had onset in November 1955. In that month, and in December 1955 and January 1956, a few households also in the core were affected through neighborhood diffusion (see diagram). In February, there was hierarchical diffusion since a household from the northern periphery was affected through contacts with a household from the core. The receptor household transmitted the disease back into the core.

In March, there was neighborhood diffusion in the city core but not in the northern periphery which had been affected in the previous month. On the other hand, there was hierarchical diffusion from core households to the São Luiz (SL) School and the Jorge Tibiriçá (JT) School with further spread (neighborhood diffusion) in the latter but not in the former school. Subsequently, the JT School transmitted the disease back to the core and to the southern periphery (hierarchical diffusion).

In April, there was neighborhood diffusion in the core and to a lesser extent in the southern periphery. On the other hand, the chain of contagion showed intense hierarchical diffusion from the Jorge Tibiriçá (JT), José Guilherme (JG), and Sagrado Coração de Jesús (SCJ) Schools to households in the core and northern and southern peripheries as well as reverse spread. This happened because in April and subsequent months, many pupils attended classes while ill. Hierarchical diffusion also operated in one instance of spread from the core to the northern periphery, as well as in another instance of transmission from the city core to rural district 3.

The epidemic peak occured in June, and there was introduction into the city of the disease which was affecting the rural districts. In rural districts 2, 3, and 4 there was within-district (neighborhood) diffusion, while hierarchical diffusion operated in the introduction or reintroduction of the disease into rural districts 2, 4, 5, 6, and 7. These introductions originated from the city, mostly from the core.

In July, schools were closed because of the regular winter (Southern Hemisphere) vacation. There was only between-households spread (neighborhood diffusion) in the northern and southern peripheries of the city. In rural districts, 3, 4, and 7 there also was household-to-household diffusion. Besides, there were three reintroductions from the city into rural district 4 and one further reintroduction into district 7 (hierarchical diffusion).

In August, schools were reopened, but there was no case among pupils in either this or subsequent months. Neighborhood diffusion occurred in the northern and southern peripheries but not in the core (see diagram). In rural district 4, there was a reintroduction from the city's northern periphery (hierarchical diffusion), and neighborhood diffusion occurred in district 5. A noteworthy finding is the only example of between-rural-districts spread (hierarchical diffusion) although 43 rural households had been affected in 6 districts. That happened because a peasant boy worked and lived in district 7; when he developed variola minor there, he traveled to his parents' home in nearby district 5, where cases appeared subsequently.

In September and October, there were no cases in the city or the rural districts except for district 5 where neighborhood diffusion occurred (see diagram). The epidemic which had started in the city core in November 1955 ended in the rather distant rural district 5 in early October 1956, as shown by an exhaustive case-finding survey conducted in the whole county.

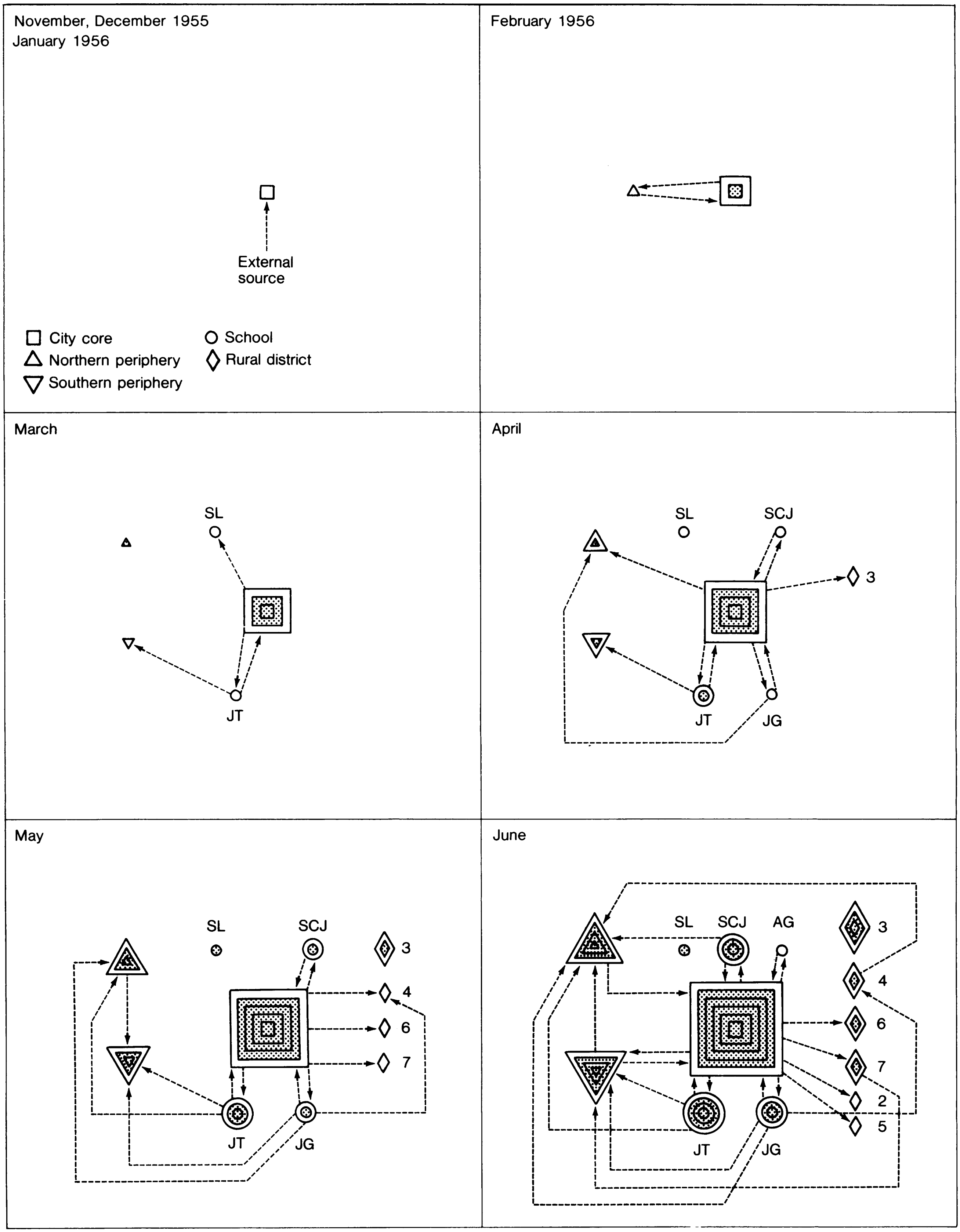
Discussion

The graphing procedure which we propose clearly showed that the epidemic flow temporally and spatially proceeded by stages even though all three city subdivisions, six of the seven rural districts, and five of six schools were affected by the epidemic. This pattern contrasts with the absence of spread in surrounding counties (*14*). However, on a smaller scale (household dwellings and classrooms), there was frequent sparing of small social groups. Neighborhood and hierarchical diffusion clearly occurred isolatedly or simultaneously, depending on the area or time period. Neither the random nor the uniform mode of diffusion was evident; that is, diffusion clearly followed either the hierarchical or the neighborhood mode.

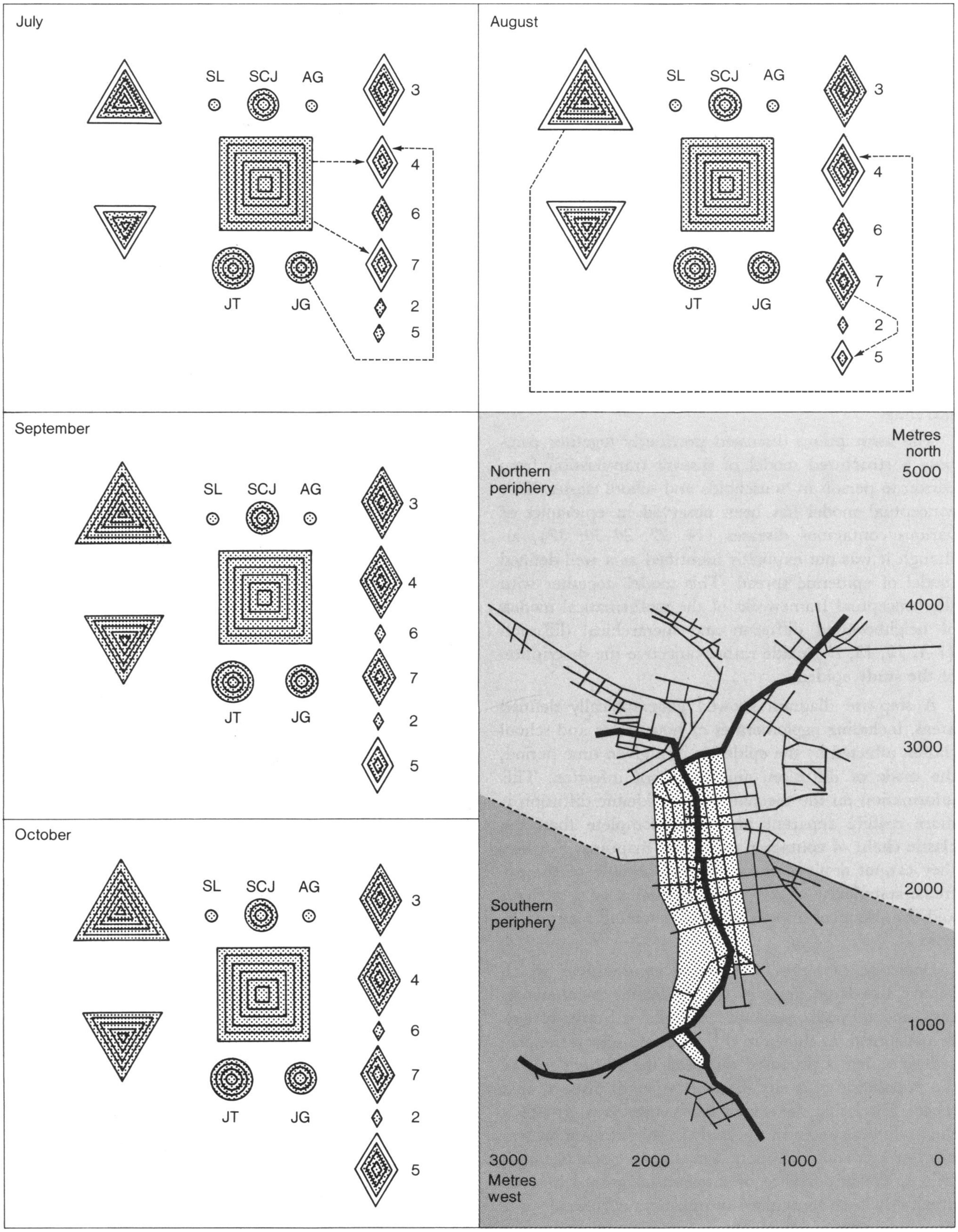
In addition to being reasonable, the assumptions made for the procedure we propose closely correspond to reality according to ample empirical evidence. In effect, the given references support assumptions basic to the conceptual model: (*a*) persons with variola minor introduced the disease into the affected households and school classes, not persons with subclinical infection (*18–23*), (*b*) those persons with the introductory cases were infected outside their social groups (*18–20, 22*), (*c*) introduction of variola minor provoked a within-household outbreak which proceeded without further dependence on happenings in neighboring or distant social groups (*20, 22, 24–32*), (*d*) variola minor was introduced into schools on various occasions and it either did or did not provoke further cases (*15, 16, 21–23*)—no school group larger than a class was the setting for a defined chain of contagion (*15, 16, 21*); (*e*) the epidemic consisted of the summation of smaller, almost independent outbreaks occurring in sub-areas: the household dwellings and the classrooms. These outbreaks were out of phase but interacted, for brief periods, during the between social group spread (*15, 16, 18, 20–23, 26–32*)—(*f*) the epidemic spread through the county as a diffusion process similar to, if not identical with, the adoption of an innovation (*1, 3, 5–13, 17, 22, 33, 34*).

The assumptions that introduction into households by adults and preschool children correspond to neighborhood (household-to-household) diffusion and that introduction by school children was hierarchical diffusion were strongly based on the following evidence: (*a*)

Social, geographic, and temporal features of the flow of variola minor through Bragança Paulista County, from the onset of the epidemic in November 1955 to its peak in June 1956. Map (lower right) shows Bragança Paulista's streets. The city core is the dotted



area; the main street (thick line) was the major artery of traffic from which the four most important highways (two on the northern end and two on the southern end) radiated.



the fieldwork and reconstruction of the chain of contagion clearly showed that variola minor spread only in the household and the school class (*14–16, 23*), since no other social group (asylum, jail, factory, office, or shop) was the site of an outbreak; (*b*) painstaking investigation of the contacts of an adult or preschool child who had an introductory case with those who had previous cases usually disclosed repeated visits to patients or receiving visits of patients, (*c*) since the disease spread in schools, school attendance by pupils having subsequent cases at home constituted examples of household-to-school class (hierarchical) diffusion, and (*d*) the probabilities of school children having been infected through casual contacts in streets and playgrounds, for instance, are scanty. In this regard, in one of the most severe epidemics of smallpox on record, Barry (*35*) noted that the risk of fully susceptible persons in households was at least eight times greater than the risk of contacts with those who were infected at work or while traveling.

The assumptions discussed previously together compose a structured model of disease transmission from person to person in households and school classes. This conceptual model has been observed in epidemics of various contagious diseases (*14, 22, 24–30, 32*), although it was not explicitly identified as a well-defined model of epidemic spread. This model, together with the conceptual frameworks of the mathematical models of neighborhood diffusion and hierarchical diffusion (*1–4, 12, 13, 17*) made rather objective the description of the study epidemic.

A stepwise diagram showed geographically defined areas, including agglomerates of households and school classes, affected by the epidemic in a given time period, the mode of diffusion, and source of infection. This information on the mechanism of epidemic diffusion is more readily apparent and more complete than the classic chain of contagion or of spot mapping. Further, they cannot depict large epidemics because of the extreme complexity of the resulting chains or spot maps and the practical impossibility of detecting many large links.

Detection of large links (small communities which behave like large units of the epidemic) is inherently easy, and they represent real, well-defined units of epidemic spread, as shown in this study. In effect, the procedure which is proposed disclosed the distinct role of the population of a city subdivision, rural district, or a school. Disclosing the role of these large social groups is the preliminary step in the study of the intimate mechanism of epidemic diffusion. Yet, save for school populations, the importance of large social groups has not previously been recognized in epidemic diffusion.

The procedure also indirectly disclosed the roles of smaller social groups (households and school classes) and even of individuals (those with introductory cases) of a certain social status (school attendance). The effects of social and geographic factors on the pattern of an epidemic are not apparent in the classic chain of contagion, and spot maps must restrict in space or time the data they show to yield fairly clear representations. Previous attempts at graphic representation of epidemic diffusion in time and space (*34–36*) neither followed the conceptual framework of a mathematical model nor provided insights into the mechanism of spread. In effect, they were entirely intuitive and arbitrary and dealt only with general space-time aspects.

It thus seems that a hitherto unused procedure is available to study epidemic diffusion, provided that easily obtained data of fundamental importance are collected. Besides, the procedure facilitates the application to epidemiology of the numerous developments of diffusion theory which are being used in geography, sociology, ecology, and economics (*1, 3–6, 17, 33*). Furthermore, by bridging the gap between the intuitive and formal approaches, a more reliable and deeper insight into the mechanism of the diffusion of epidemics can be obtained. These insights may lead, in turn, to improved mathematical modeling which has not made practical progress despite its potential advantages.

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SYNOPSIS

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Concepts used to analyze sociological, geographic, and economic processes were adapted to an examination of the diffusion of contagious disease. The example used in applying these concepts was an epidemic of variola minor which continued for 12 months in an area of 1,006 square kilometers centered on the city of Bragança Paulista, Sao Paulo State (Brazil). A graphic procedure is proposed that depicts aspects of the epidemic flow of person-to-person transmission.

Spatial, temporal, and sociological characteristics of the epidemic flow are disclosed in sequential diagrams. They represent geographic areas as well as schools and agglomerates of households affected by the epidemic at a given time, the mode of diffusion, and the source of the infection.

The procedure yielded indirect evidence of the role of school pupils as introducers of variola minor into households and school classes. All subdivisions of the city, six of the seven rural districts, and four of the five elementary schools were affected through hierarchical (between-areas) diffusion. Subsequently, there was neighborhood (within-area) diffusion, and this resulted in new interactions between areas.