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Interdisciplinary Public Health Reasoning and Epidemic Modelling: The Case of Black Death

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With 79 Figures

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To my little daughter, Maria-Stephania, who is doing what many of us fail to do--constantly looking at the world with fresh eyes--wishing her to realize her own legacy with a winged heart.
GC

For Lucila with all my love.
RAO

To my wife Leslie, for her love and support.
MLS

To my parents Po-Lung Yu and Lung-Gan Wang, for their love and support.
HLY

To my lovely daughter Erika
LLW

Preface

> If you want to achieve something, if you want to write a book, paint a picture, be sure the center of your existence is somewhere else and that it's solidly grounded; only then will you be able to keep your cool and laugh at the attacks that are bound to come."
>
> *P. Feyerabend*

This is a book about interdisciplinary public health reasoning and epidemic modelling, in general, and the study of the infamous 14th century AD Black Death disaster, in particular. We focus on the intellectual context in which epidemic modelling takes place, in a way that accounts for the present-day interdisciplinary and multicultural trends in scientific inquiry. Like most scientific fields, public health research defines itself based on knowledge, which raises serious epistemic and cognitive issues. Therefore, we maintain that for public health modellers to function in an often complex environment, they should be aware of the divergent conceptions of knowledge and the technological changes that these imply, the multiple sources of information commonly available and their reliability, the different styles of thinking adopted by the disciplines involved, and the importance of developing sound interdisciplinary knowledge integration skills.

A unique feature of the book is that it takes the reader through all four major phases of interdisciplinary inquiry: adequate conceptualization (in terms of metaphors, methodology, epistemic rules, and argumentation modes), rigorous formulation (involving sophisticated mathematical models), substantive interpretation (by means of correspondence principles between form and meaning), and innovative implementation (using advanced systems technology and multi-sourced real world databases).

If the interdisciplinary effort is going to succeed, it must be based on critical intelligence and take place at a research grassroots level rather than at an institutionalized level. Critical intelligence and new ideas cannot be developed in accordance with the dictates of an institution or the established "elite" that is usually behind it. Instead, some level of detachment is necessary to allow creativity to flourish and to gain a new perspective. A case in point is that, despite pompous institutional announcements, genuinely interdisciplinary environmental health research is often confused with cosmetic pseudo-interdisciplinarity that has a superficial and *ad hoc* interdisciplinary character, allowing disciplinary business to proceed as usual.

In view of the above considerations, our discussion of a synthetic public health paradigm and its implementation in the case of the Black Death epidemic is by no

means "the complete story". It is rather "a call for research" in the field of disease modelling that ought to include new ways of thinking and interdisciplinary perspectives. Our research approach in this book is to open possibilities for consideration. The proposed theses and ideas are launched for exploration, and we do not pretend that we have demonstrated decisively that they are the best ones possible. In a similar vein, our criticism of existing paradigms and competing approaches is not intended to refute them conclusively. Rather its goal is to open scientific space in which new perspectives and ideas concerning a synthetic epistemic paradigm can breathe and grow.

The research presented in this book was supported in part by a grant from the National Institute of Environmental Health Sciences[1]. We are grateful to NIEHS, although one should not necessarily hold the institute responsible for the views expressed in the book. We are indebted to Mr. Christopher Windolph for his editorial acumen. He did a superb job, and if the text does not possess an Apollonian perfection of form, it is due to the interdisciplinary nature of the subject and the limitations of the authors. We also express our appreciation to Dr. Alexander Kolovos for reviewing the final copy of the book and Mr. Ulrich Schirov for his voluntary research on Black Death at his state of Mecklenburg-Vorpommern (Germany).

We would like to thank Drs. Jiu-Chiuan Chen and John Chasteen for their valuable comments and criticism. The criticism is welcomed and not feared, because one should be assured that the centers of our gravities are outside our professions. More to the point, every researcher must possess enough reserves of humor. Let us not forget that in life and in scientific inquiry there are significant parallels between the Ha-ha! and the Aha! experience. In the end, some subjects are so serious that one can only joke about them.

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E.M. Cioran

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Note:

The following notation is used throughout the book:

- **Section A** denotes section A of the same chapter.
- **Section II.A** denotes section A of Chapter II. This notation is used when we refer to a section that is from within a different chapter.
- **Fig. 3** denotes the 3rd figure of the same chapter.
- **Fig. II.3** denotes the 3rd figure of Chapter II. This notation is used when we refer to a figure that is from within a different chapter.
- **Table 3** denotes the 3rd table of the same chapter.
- **Table II.3** denotes the 3rd table of Chapter II. This notation is used when we refer to a table that is from within a different chapter.
- **Eq. (3)** denotes the 3rd equation of the same chapter.
- **Eq. (II.3)** denotes the 3rd equation of Chapter II. This notation is used when we refer to an equation that is from within a different chapter.
- **Ziegler (1969: 127-128)** denotes that the reader is referred to pages 127-128 of Ziegler (1969).

Chapter I – Toward an Interdisciplinary Methodology

> "Lacking the role of criticism, science would be reduced to a witches' sabbath of adventurous ideas."
> *E. Mach*

A. Concerning the Current Paradigm—In Search of Bohemians

Public health is viewed as the science and practice of protecting and improving the health of a human population, as by preventive medicine, health education, control of communicable diseases, application of sanitary measures, and monitoring of environmental hazards. Within this framework, the term "epidemic" is usually applied to the occurrence and space-time evolution of a disease (infectious or non-infectious) in a human population. Generally speaking, the aims of *epidemic modelling* are to understand, control, and when possible prevent the distribution of disease in the population. Epidemic modelling may address questions related to the factors that influence or determine this distribution, including the cause of the disease (genetic trait, environmental exposure, life style, etc.). In the case of environmental effects, epidemic modelling is closely related to human exposure-health impact research. Another group of questions may be concerned with the rate of disease transmission within the population, the geographical evolution of the epidemic, a description of the contact process, or the distribution of mortality and other epidemic variables[1].

In certain circumstances, a temporal distinction could be made between epidemic modelling occurring *before* the event (when certain measures may be taken to avoid a disastrous outbreak), *during* the event (in which case, there is the possibility of "on-line" intervention, effective containment of the epidemic, etc.), and *after* the event (in which case, understanding the space-time distribution character-

[1] While "epidemic" focuses on phenomena in the distribution of disease in space-time, "epidemiologic" refers to things pertaining to the study of such phenomena. Today the discipline of epidemiology is often understood to include the study of non-epidemic diseases, so things that are epidemiologic could pertain to epidemiology without pertaining to epidemics (Savitz, 2004).

istics of the specific disease can provide valuable knowledge concerning future outbreaks of the disease or about other kinds of epidemics).

For modelling purposes, epidemics may be categorized in different ways. One categorization distinguishes between two kinds of epidemics of communicable disease (Haggett, 2000: 11-12): (*a*) The *propagated* epidemic, which results from the chain transmission of some infectious agent. Transmission may occur directly from person-to-person (e.g., measles), or indirectly via an intermediate vector (e.g., malaria) or a microparasite. In some situations, transmission takes place through humans (e.g., typhus fever), whereas in some others the parasite survival is independent of man (e.g., bubonic plague). (*b*) The *common-vehicle* epidemic that is due to the dissemination of a causative agent. The epidemic may result from a group of individuals being infected from a common medium (e.g., water or food) that has been contaminated by a disease-causing organism (see, e.g., the cases of cholera and typhoid). In fact, as a result of the emerging environmental pollution problems and their health effects, many epidemiologic techniques have been extended and applied to study the effects on human population health of physical, chemical, and biological agents within the environment. This effort led to the development of the discipline of *environmental epidemiology* (e.g., Terracini, 1992; Moeller, 1997). By examining specified populations exposed to a variety of ambient environments, the general goal of environmental epidemiology is to investigate exogenous determinants of disease distributions and clarify the relationships between physical, chemical, or biological factors and human health.

Discussions of the current *paradigm*[2] of epidemiology can be found, e.g., in Gordis (1996), Rothman and Greenland (1998), and Rothman (2002). Basically, this paradigm provides little motivation for directing research toward seeking basic knowledge. Instead, it encourages research activities that are built mainly on the discipline's empirical basis. Its focus is *technical* practices rather than *theoretical* achievements[3]. Moreover, part of the difficulty of the current epidemiologic paradigm is that it persists in talking about modern interdisciplinary problems in an outmoded vocabulary. These are crucial elements of the current paradigm, because they may indicate a culture that equates *intellectual* debate with the banal exchange of technical opinions. Such a paradigm, of course, may be the influence of a predominantly anti-intellectual climate characterizing many institutional and social environments nowadays (see, e.g., Furedi, 2004, and references therein). Intellectuals, people who *wonder* (i.e., practice theoretical thinking, search for meaning and truth, seek to improve the ways of scientific reasoning, and try to build new concepts and models), are often considered pariahs and ir-

---

[2] Generally, the term "paradigm" is used to describe a particular way of looking at things. The paradigm includes a set of theories, techniques, applications, and instrumentation together (Christakos *et al.*, 2002: 13).

[3] Unfortunately, as many junior faculty members will admit, those who are proactively accepting the “brute force” application of new technologies in epidemiologic problems are much more likely to get federal research support than those who are interested in a theoretical type of work.

relevant. Thus, it is hardly surprising that theoretical modelling in epidemiology and public health often falls victim to this climate.

In the current paradigm, public health data gathering and processing avoids facing the fact that innovative experimentation and observation are theory laden, i.e., they are not possible without strong theoretical support and interaction between different *modes of reasoning*. This was a hard-learned lesson in a recent case of grossly inaccurate health effect estimates that resulted from the "brute force" implementation of commercial statistical packages without a deeper understanding of the underlying assumptions and theoretical parameters (see, Knight, 2002; Revkin, 2002). As a matter of fact, it is theoretical knowledge--and not just observation or data gathering--that *distinguishes* humans from other animals and that is responsible for major advances in the history of mankind (Tomkinson, 1999). Given the strong historical evidence about these matters, it is safe to predict that a continuing backlash against intellectuals cannot be without repercussions in the future of epidemiology and public health, among other fields.

The gap between data gathering and theoretical thinking is, indeed, widening[4]. In his study of the plague in 17th century AD Italy, Cipolla (1981: 14) maintains, "Paradoxically as it may sound, the lesson of history is that all too often people find it easier to manipulate the facts to fit their theories than to adapt their theories to the facts observed". In "Epidemiology Faces Its Limits", Gary Taubes warned that modern epidemiology was reaching a crisis point and was in danger of becoming a "pathological science" because it had devolved into a data dredging exercise, mindlessly searching an ever-expanding pool of danger for marginally significant associations unpredicted by any *a priori* hypothesis (Taubes, 1995). Also, Phillips *et al.* (2004) emphasized the need for greater perspective and innovation in epidemiology, pointing out that "the desire for new information means that the health science literature is overwhelmingly devoted to reporting new findings, leaving little opportunity to improve the quality of the science" and that "current discussions of advanced statistical methods, the nature of random error, sensitivity analysis and uncertainty quantification, and proper interpretation of results, to name just a few, show that most current epidemiologic research uses methodology[5] in need of improvement".

In view of the profound asymmetries of the current paradigm, new ways of thinking are needed to establish an improved public health methodology based on

---

[4] It seems that data gathering often seeks isolation, avoiding interaction not only with theoretical knowledge but with crucial developments in different disciplines as well. Moreover, it is not uncommon that the inability of data gathering to produce the necessary experimental results lies behind an institutionalized agenda aiming at preventing theoretical thinking from developing improved models that could lead to deeper understanding of the epidemic system and the associated human health risks. This agenda may serve someone-sometime-somewhere, but it is profoundly against scientific progress in the global effort to fight disease.

[5] In general, methodology refers to concepts and ideas about when and how to use various methods to develop knowledge and solve problems, and about what each method really *means* (underlying conceptions, presumptions, normative rules, reasoning modes, etc.); (see, Christakos *et al.*, 2002: 189).

genuine interdisciplinary interactions and intellectual exchanges. Indeed, we now have the opportunity to study infectious and other onset diseases in a more substantive and rigorous manner. The following is a brief summary of certain significant limitations of the current epidemic paradigm that a new methodology should take into consideration in the new Conceptual Age[6]:

a. Little attention has been given to the *interdisciplinary* nature of epidemic research and development. In this manner, important sources of knowledge available in the physical and life disciplines are ignored at the cost of profoundly inadequate epidemic and human exposure studies. The *status quo* of disciplinary attitudes needs to change in the current epidemic research paradigm so that interdisciplinary *knowledge integration* becomes a genuine scientific inquiry and not a cosmetic process having a superficial and *ad hoc* interdisciplinary character allowing disciplinary business to go on as usual.

b. The fundamental *spatiotemporal* character of an epidemic under conditions of uncertainty has been mostly neglected. Intrinsically spatiotemporal phenomena, like disease propagation, are often modelled with "aspatial" and "aspatiotemporal" theories. Mathematically rigorous and epidemically meaningful stochastic tools (e.g., spatiotemporal random field theory) have been ignored in favor of deterministic methods and classical statistics techniques that neglect vital cross-correlations and laws of change on space-time manifolds[7]. This neglect has resulted in unsatisfactory analyses of major issues such as space-time prediction of disease distribution, epidemic explanation, and causation. Holmes (1997: 111), e.g., poses the plausible question: "A key question is to what extent do we lose insight or are quantitatively misled by modeling the intrinsically spatial process of disease spread with nonspatial theory". In the present book we go beyond that and argue that the process is fundamentally spatiotemporal, i.e., it develops within a composite space-time domain.

c. The solution of mathematical models of epidemics has been viewed as a purely *ontologic* affair that focuses on abstract and dry formulas, whereas crucial factors—such as modes of perception and reasoning, and their integration—are neglected. Thus, what the current perspective is missing is that these models are imperfect constructs of the human mind, often they do not account for essential site-specific knowledge, and they constitute an uncertain representation of reality. Since public health research defines itself based on

[6] We are certainly aware of the difficulties that such a view will be probably confronted with. The majority of professional scientists are strongly committed to the paradigm of their subject. But, as Ziman (1991: 90) maintains, "…there is a price to pay for this commitment. Each generation of scientists gives too much credence to its own paradigm. By his education, and by participation in 'normal science', the average research worker is heavily indoctrinated and finds great difficulty in facing the possibility that his world picture might be wrong".

[7] Although the discussion focuses on infectious diseases and acute onset diseases following point exposures, even chronic disease modelling (e.g., childhood leukemia) could benefit considerably from stochastic space-time analysis (say, advanced clustering techniques).

knowledge, the solution of an epidemic model is likely to be more realistic if its derivation invokes *epistemic cognition*[8] notions and insights concerning the validity and legitimacy of knowledge (e.g., what are the "grounds of knowledge", what the mind considers to be the goal of a solution of a public health problem, or how it reaches this solution). Also, since the solution of an epidemic model often refers to the future, it should account for the fact that the future is accessible neither observationally nor physically, but only cognitively (the future is ontologically nonexistent).

d. In many cases of public health research, the emphasis is solely on *data gathering*[9] (experimental, observational, surveillance, etc.) and the black-box operation of the *techniques/instruments* employed for this purpose, without any appreciation of the kind of substantive *theoretical* modelling that underlies these techniques/instruments and gives voice to the data. In fact, there is nothing inspiring or intellectually satisfying in the flood of undigested data, mistaken for knowledge in the current paradigm[10]. Public health researchers become data managers (and guardians), and in order to work efficiently, they often use tools that they do not understand. Naturally, issues linked to the question of the *reliability* of the generated information naturally arise in this context. Moreover, in epidemic sciences with little theoretical modelling basis, the *indetermination* principle[11] can cause considerable problems.

An in depth study of the above limitations of the current epidemic paradigm could potentially produce a paradigm change in certain constructive ways. In view of this possibility, we find it reasonable and timely that the goal of the present book be twofold:

i. Bring to the fore a significant challenge in public health research, namely, the possibility of developing a *synthetic epidemic paradigm* (SEP) that provides an integrated methodology able to account for the major issues *a-d* above in a mathematically tractable and epidemiologically thoughtful fashion. Key concepts and tools are needed to open new areas of epidemiology to detailed understanding in an integrated manner. The SEP should play a creative role in

[8] The term "epistemic" refers to the construction of models of the processes (perceptual, intellectual and linguistic) by which knowledge and understanding are achieved and communicated. In the epistemic cognition framework, the contribution of cognition is to identify basic knowledge-assimilation, belief-forming and problem-solving processes, which are then examined by means of the evaluative standards of epistemology. The meaning of these terms will be clarified further in subsequent sections.

[9] Data gathering but not sharing might be closer to the mark (see, also, Section B.a below).

[10] Unfortunately, the dictum that "data do not speak for themselves, and when they do they tell different stories, depending on the audience" has gone unnoticed in these cases. Directly relevant to the Black Death study of this book, is the remark of a medieval scholar: "Medieval data are like children; they do not talk to strangers."

[11] Indetermination principle: Every set of data can be associated, in principle, with an infinite number of possibilities. Thus, sound theoretical modelling is needed to eliminate all but a few meaningful choices.

this context, containing novel ideas as well as concrete suggestions on how existing ideas fit into new frameworks.

ii. Implement SEP in the case of the major 14th century AD *Black Death* epidemic. Although this epidemic has been a major disaster in human history (in terms of the mortality it caused and the speed with which it spread), and as such has been discussed extensively in the literature, neither rigorous modelling of its main epidemic features nor systematic mapping of its space-time evolution exist (including mortality maps, space-time correlation functions, areal spread and epidemic velocities). The SEP can produce useable models of the way the epidemic propagated through geographical space and time. Since Black Death had grave societal, public health, and financial effects (Fig. 1), the study of these models can offer valuable insight about these effects, as well as about similar effects of potential contemporary epidemics[12].

Figure 1. One of the effects of the Black Death epidemic was the frequent use of extremely morbid imagery in art. Death incarnate made many appearances in paintings of the period, like the apocalyptic composition of Pieter Bruegel's "The Triumph of Death". Death--a skeletal figure on an emaciated horse at the center of the painting--is the leveler. Its legions and horsemen--all skeletons--drive humanity toward the final trapdoor (Roberts-Jones and Roberts-Jones, 2002).

[12] Today, many experts believe that the majority of infectious diseases have not gone away, but lie in wait until their chance comes. The re-emergence of Black Death several times in the past is an example of this situation.

But before we start our long promenade through the methodological and empirical affairs of public health interdisciplinarity, we briefly introduce our readers to some technological, intuitive, intellectual, and philosophical features that should be incorporated into an SEP.

A main characteristic of SEP should be the *innovative description* of the composite geographical and temporal distribution of a disease (propagation characteristics, space-time correlation structure, etc.). The description should be the product of a sound theory of knowledge rather than an *ad hoc* combination of purely empirical techniques (pattern fitting, etc.). This kind of description can generate valuable information that would optimally allow containing the epidemic spread (by means of control strategies, infection breaks, isolation, or eradication), assessing potential socioeconomic effects, etc. Furthermore, in the case of environmental epidemiology, the adequate description of the geographical and temporal distribution of the exposures (toxic chemicals, radioactive materials, etc.) to which the population has been subjected is a crucial component of any modelling study. As Moeller (1997: 39) has pointed out, "Regardless of the complexity, valid environmental monitoring measurements and accurate estimates of exposures are essential if confidence is to be placed in the associations that are developed between exposures and observed adverse consequences to human health."

Another characteristic of SEP is that it should be *flexible* and *versatile*. It could rely directly on measurable infection parameters, environmental quantities and health variables (incident rate, mortality, contaminant concentration, infection agent and path, etc.) and the models relating them; it may utilize a group of epistemic vectors drawn from interdisciplinary areas of human thought and experience; or it may involve a complete causal chain based on a certain course of events. In the latter case, the chain may start with ambient sources of environmental risk (e.g., contaminated water or air pollution), followed by population exposure to environmental risk factors and health damage, which can result in an epidemic[13].

The SEP focus should not be limited to the implementation of computational technologies (informatics, sophisticated numerical schemes, etc.) with experimental techniques. The use of these valuable technologies should not be a cut-and-dry subject but an *intellectual* effort in a conceptually sound and creative background context. Sound interdisciplinary knowledge is the result of the careful integration of the underlying concepts and critical reasoning modes, and not merely the integration of the vast sequences of numbers generated by the computational technologies[14]. In a similar vein, SEP should seek a balance between *form* and *substance* that accounts for the facts that humans can develop sophisticated formal tools because they possess very effective capabilities to construct meaning and

[13] In this case, the SEP description of the epidemic would depend on the environmental chain of events that precedes it.

[14] Noticeably, recent publications (e.g., Kanehisa, 2000) emphasize the critical role of conceptual links between different disciplines toward understanding basic principles of life vs. informatics technologies that merely cope with the vast amount of data generated by the genome projects.

that the correlation of form and meaning is a highly desirable feature of creative thinking.

When disciplinary boundaries are successfully crossed, new arrangements are emerging. The SEP could confront the challenge by adopting a change from the traditional view of a human health community consisting merely of experts with their technological tools and specialist interpretations, to a new view of a community possessing an *epistemic culture* that is certainly run on expert processes and systems epitomized by science, but which is also structured into various areas of life and their concepts of theory and practice. This raises the issue of the transition of the contemporary public health community to a knowledge community, of which epistemic culture is a structural feature. One of the real consequences of such a culture underlying SEP is that it would be preferable to debate about hypotheses before debating about results. It is a common practice that different teams of public health scientists are brought together at the final stage of their research projects in order to debate their results and attempt an "after the event" dialogue that focuses mostly on rhetoric and has little effect on scientific progress[15]. On the contrary, in the SEP context these research groups will have to debate their hypotheses and resolve the relevant issues (theoretical, experimental, institutional, social, etc.) at the early research stages.

As we mentioned in the Preface of this book, our discussion of the SEP and its application in the Black Death situation is by no means "the complete story". It should be rather viewed as "a call for research" in the field of public health research, in general, and epidemic modelling, in particular, which should include novel ways of thinking and rational interdisciplinary perspectives. As a matter of fact, the above considerations seem to point toward the creation of a Bohemian style of an epidemic modeller[16]. According to the *Bohemian Manifesto* (Stover, 2004; 11): "Bohemians start movements. They break the rules, set the trends. Bohemians change thinking and sometimes they write manifestos. Bohemians cross cultures and integrate mantras, philosophies, substances and clothing seamlessly into everyday life. Bohemians tenderly and violently create new work and change paradigms." What could be closer to the mark in the emerging Conceptual Age?

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[15] This kind of a "dialogue" is certain to fail, as the aftermath of the World Trade Center (WTC) disaster amply demonstrated (Dalton, 2003): Two groups of researchers came to diametrically opposing conclusions concerning how much of the lower Manhattan pollution could be ascribed to the WTC-generated plume and how much was native. Typically, such cases are characterized by: (i) the lack of understanding of the different scientific theories underlying the instruments used, thus leading to contradictory interpretations of the measurements obtained; (ii) the unwillingness to share information obtained by the different groups at the early stages of the research; and (iii) the subsequent absence of constructive criticism, knowledge reliability assessment, and methodology evaluation (all of which constitute violations of fundamental principles of scientific reasoning). Issues such as i-iii should have been dealt with at an early stage of the WTC study and not at the late stage of presenting the final results.

[16] This would be a Ha-ha! or an Aha! moment.

B. Methodological and Empirical Issues of Interdisciplinary Epidemic Research

In the context of scientific development, public health scientists try to make sense of the real world by developing a set of *mental* frameworks about it. A fundamental constituent of such an effort is the establishment of an adequate *methodology*, i.e., a coherent step-by-step procedure for thinking critically about scientific development and acting upon it. Methodological standards act like teachers: they give marks to one's epidemiologic theories. Although a considerable deal of *ad hoc* interdisciplinary activity may be happening on an everyday basis (e.g., in the form of complimentary health professions and skills within a common space, partnerships, or as a management tool), no systematic methodological framework exists for integrated epidemic modelling in a realistic space-time domain under conditions of multi-sourced uncertainty. As a result, even with a group comprised of the best experts, there is no guarantee for a successful public health outcome (i.e., the sum total of competencies is not necessarily competence). Edward Bender, an expert on artificial intelligence, notices (Bender, 2000: 192), "One approach to inaccurate estimates is to consult several experts and then create a reasonable compromise based on their estimates".[17]

In the meantime, the number of interdisciplinary research cases continues to grow at an increasing pace. The need to develop integration frameworks incorporating individual- and population-level dynamics of a disease, as well as within-host dynamics, has been emphasized in recent studies (Grenfell *et al.*, 2004). Panels of experts acknowledge that the environment plays a contributing role in the etiology of most diseases (e.g., reproductive, immune competence, pulmonary/cardiovascular, cancer, or neurodevelopment), and urge that (DHHS, 2003), "the long-term improvement of public health requires an interdisciplinary approach that integrates biomedical, geochemical and engineering sciences." While numerous techniques of cluster detection exist in the epidemiologic literature, a sound interdisciplinary methodology is not yet available (Millikan, 2004). The need for an interdisciplinary approach in the context of the genome project is emphasized by Kanehisa (2000: 19-23): "The genome certainly contains the information on the building blocks, but it is premature to assume that the genome also contains the information on how to connect or relate the building blocks… the information in the genome is not sufficient to make up life… The ultimate objective of post-genome informatics is therefore to unite life and matter and to establish a grand-unification theory of the physical and biological worlds". Decision-makers who need to combine information from different disciplines agree that "there is no commonly accepted methodology for combining multiple expert judgments" (Webster, 2003: 4). The National Institute of Health proposed its Roadmap initia-

[17] Many speak of the growing problem of experts who are no longer able to understand one another and communicate effectively. Disciplinary territoriality, ignorance of basic findings in scientific domains other than one's own, and occasional arrogance, all contribute to this lack of understanding between experts.

tive in 2003 as "an integrated vision to deepen our understanding of biology, stimulate interdisciplinary[18] research teams, and reshape clinical research to accelerate medical discovery and improve people's health." At the same time, the development of a genuinely interdisciplinary public health approach is necessary, especially since information processing sciences give rise to new objects of study, new instruments of collective practices, and new forms of human interactions (Web forums, etc.), which challenge disciplinary boundaries. In his book *How Scientists Explain Disease*, Paul Thagard studies the three major kinds of explanations of the development of scientific knowledge--logical, cognitive, and social[19]--and comes out in favor of the view that health scientists will have to bring these three schemas together to form an integrated explanation of scientific change (Thagard, 1999: 4): "But we can appreciate science as a product of individual minds *and* as a product of complex social organizations. Not only can we see cognitive and social explanations as providing complementary accounts of different aspects of science, but we can also look for ways of integrating those explanations, bringing them together into a common approach."

As far as Black Death is concerned, the interdisciplinarity of the various information sources (documents, accounts, reports, etc.) has been noticed, although its impact has not been adequately assessed (Bleukx, 1995: 72). This is not a small matter, since the case of Black Death is unique in the sense that it deeply affected life at all levels--social, economic, demographic, political, religious, and artistic.

a. Quis Custodiet Ipsos Custodies?

We have already said that the development of an SEP aiming at the integration of different life support fields across space-time for public health purposes will have to deal with the salient methodological and empirical aspects of interdisciplinary sciences. But the outcome is certainly worth the effort, in our view. A broadly conceived SEP would bring data and explanation into a coherent whole, merge cross-disciplinary dynamics and logics of inquiry, and offer opportunities for space-time epidemic prediction, infection risk assessment, health policy and damage control. E.g., in order to identify infectious agents and toxicants, assess factors that may affect their transmission, transport, and bioavailability, and determine the critical pathways resulting in exposures to human populations, SEP needs to rely on a synthesis of methods and tools utilized by biomedical, ecological, toxicological, and biological specialties. Although SEP provides an integrated public health modelling methodology that is generally applicable, for illustration

[18] Although in this initiative interdisciplinarity seems to be conceived as the integration of data and techniques from different disciplines rather than conceptual frameworks and thinking modes.

[19] According to logical explanations, new knowledge derives logically from previous knowledge; for cognitive explanations the growth of knowledge derives from the mental structures and procedures of scientists; and in social explanations factors such as the organization, power relations, social connections and interests of scientists are used to explain scientific change.

purposes its implementation in this book involves the specific case of the Black Death epidemic. This epidemic has been studied in the past by different disciplines, which have missed important parts of the picture and did not come together to form a coherent whole.

Naturally, the development of an SEP should reside on *organized connectedness* between the various scientific disciplines involved in a public health study. Many names have been given to the making (or finding) of such connections: integration, organization, patterning, development of schemata. These connections may apply to processes, objects, symbols, ideas, and actions. Moreover, the SEP requires the consideration of certain conceptual and technical products (e.g., models, algorithms and computer codes, and experimental techniques) developed during cross-disciplinary research. In this respect, the study of the elements that contribute to the segregation of science into isolated units called *disciplines* can provide valuable guidance in one's effort to successfully integrate these units in the human health context. The SEP should also account for the fact that most of the public health processes and disease variables involved in cross-disciplinary integration vary across space and time. In addition to efficiently coordinating events and processes, the *space-time* domain of SEP may provide the means for establishing connections between different disciplines.

Besides, the need for a close *collaboration* between theory and experiment/observation is an inescapable necessity. By arbitrarily isolating phenomena for experimentation, one seeks to give them a beginning and an end. Yet phenomena are no more isolated in nature than are notes isolated in a melody, which is why theoretical modelling is the soul of science. When theory and experiment/observation are well-balanced and work in concert, progress is made by means of an public health research program that manages careful shifts from empirical investigation to explanatory theory, from ontologic description to epistemic interpretation, and from epidemic prediction to confirmatory evidence. In the end, the question "Quis custodiet ipsos custodies"[20] has a deeper meaning in the context of a scientific inquiry aiming at a realistic representation of the epidemic system that can best serve the needs of public health. The current public health paradigm that allows the practice of "data gathering but not sharing" serves neither the ultimate goals of scientific research nor the long-term interests of the public that finances it. The institutional encouragement of a misguided experimental culture that systematically avoids any constructive criticism by means of theoretical thinking and critical intelligence should be reconsidered.

Data sharing and scientific criticism can drastically prevent the data gathering process from heading into a blind alley. As Lewis Thomas has remarked (Thomas, 1995: 91): "If the funds for a particular research project are coming in over his head in cascades, the scientist may be misled into thinking that he is on to a good thing, no matter what his data show… If he is in possession of sophisticated instruments of great power, and if he is being assured that whatever other new instruments he can think of will be delivered to the door of his laboratory tomorrow, he may find it difficult to stop himself on a dead road of inquiry, even if he knows

[20] "Who will observe the observers?"

it to be dead. I have long believed that there is no scientist alive whose career could not be terminated by an enemy, if the enemy were capable of increasing the laboratory's budget by ten fold or any-fold overnight and, as well, assuring access immediately to any instrument within reach of the victim's imagination". If Thomas is right, there seem to be cases in which the research administration and bureaucracy system seriously corrupt scientific inquiry.

The rush to collect data before the phenomenon is sufficiently understood is the approach of Deweyan pragmatism, which seems to be a dominant worldview in modern America. For Dewey's pragmatism, human action precedes the invention of human forms of thought needed to satisfy the needs of the action. In this case, reality is expected to adapt itself accordingly (of course, there is no historical evidence that reality has made any such commitment to pragmatists--on the contrary). Besides, pragmatists would be surprised how hard it can often be to translate an action into an idea. Deweyan pragmatism is strongly opposed by the Aristotelian worldview. For Aristotle, human thought always precedes human action: first grasping the appropriate facts of reality in an adequate thought mode, on the basis of which the goals and the necessary course of action are set.

The main objectives of SEP should include the development of integrated epidemic *systems*[21] for innovative problem solving and inquiry, and the advancement of public health interdisciplinary efforts to join communities of scholars from a range of disciplines. The SEP, of course, assumes that practicing scientists and scholars and public health research administrators are interested in creating and working in environments that help researchers traverse intellectual, cultural, and organizational boundaries. Remarkably, rather obvious connections with other disciplines are not always adequately appreciated in the context of an epidemic study. Human exposure-health effects is one of these disciplines. The linkage between epidemiology and human exposure-health effects is undoubtedly very strong, especially when the cause of the disease is environmental exposure[22]. As a matter of fact, serious challenges emerge from attempts to link epidemiology-relevant research taking place in a range of scientific disciplines. One of the chief issues is that researchers from different fields approach health problems with different conceptual tools and methodological orientations. No systematic framework exists to synthesize the diverse reasoning modes and knowledge sources of scientists working, e.g., in the fields of infection analysis, environmental transport, contaminant bioavailability, physiological compartmental systems, biochemical transformations, demography dynamics, and population risk assessment, in a way that is more than juxtaposition, more than laying one discipline along side another. At the same time, important notions, such as "exposure", may not be well under-

[21] Generally, a system is viewed as a collection of related elements organized according to a plan and forming a unity. In the case of epidemics, the system may include the infection agents, the exposure pattern, the population (infecteds, susceptibles, removed, etc.), the medium within which an epidemic may propagate, lines of infection, contact processes, as well as their relations and interdependencies in a space-time domain.

[22] In some cases, this strong linkage makes the two disciplines essentially indistinguishable (Haining, 2003).

stood (conceptually and operationally), or their meaning may differ from one discipline to another. In the end, one should not forget that what can count more in these cases is integration of concepts rather than data.

Concerning the public's preparation for future epidemics, a serious effort is dedicated to combining and communicating information from different disciplines to *decision-makers*. Such an effort gives rise to a number of challenges, as well. Due to other non-epidemiologic factors at play (economic growth, technological change, climate variations, etc.), one cannot rely only on past disease data to predict future epidemic distributions; decision-making can be aided by calculating how epidemic uncertainties change with new interdisciplinary knowledge and how they impact potential choices; although certain types of epidemiologic data are often too sparse, valuable information can be transferred from other disciplines, assuming that adequate techniques become available for this purpose; biases exist in the way the human brain forms judgments under conditions of uncertainty, and these biases may be of different kinds depending on the discipline; and there is currently no established methodology for combining multiple expert judgments, especially when these come from various disciplines.

The above are some of the interdisciplinarity issues that deserve to be studied in a wider SEP context. Such a study can potentially produce a paradigm change in certain ways. Next, with the reader's permission, we will make a modest attempt to investigate a few of these ways.

b. Crossing Disciplinary Boundaries

As already mentioned, a number of cases exist in public health, in particular, and in life sciences in general, in which researchers have been actively engaged in endeavors that take them across disciplinary boundaries (e.g., White *et al.*, 1998; Christakos and Vyas, 1998; Pennington *et al.*, 2001; Pybus *et al.*, 2001; Serre *et al.*, 2003; BenMap, 2003; Law *et al.*, 2004). In special circumstances, it may be possible to apply a kind of an isolation condition claiming that the properties of the components of the structured whole can be identified by studying them when they are not incorporated into the structured whole. Their behavior in the structured whole can be then derived from this condition plus statements describing the organized structure in which they are bound and the prevailing epidemic conditions. In the most interesting situations, however, a connection condition applies, in that it is impossible to understand how the components function when bound into structured wholes by simply studying their properties in an isolation condition[23]. These situations are ripe for investigation by those interested in the process of interdisciplinary public health inquiry.

[23] The paramount importance of the connection condition is also demonstrated in the case of the genome project. As was mentioned above, while the genome contains the information on the building blocks of life, it is unlikely that it contains the information on how to connect or relate the building blocks.

It is a well-known fact that major scientific progress often comes from researchers who have crossed conventional disciplinary boundaries, and who had no established authority in the particular discipline. Generally, cognitive reasons that motivate crossing disciplinary boundaries include the recognition that either the public health problem of interest cannot be adequately studied within one discipline, or the problem requires--by its nature--the synthesis of knowledge sources from different scientific disciplines. Epidemic prediction across space-time, e.g., entails blending information from the fields of mathematics, systems engineering, molecular biology, toxicology, climate change, and demography (Christakos and Hristopulos, 1998). Also, Pybus *et al*. (2001) developed a model that builds a bridge between the disciplines of population genetics and mathematical epidemiology by using pathogen gene sequences to infer the population dynamic history of an infectious disease. Several other examples can be found in the relevant literature.

Albert Einstein famously said, "The significant problems we face cannot be solved at the same level of thinking we were at when we created them". Indeed, the reader may agree that, it is not unusual to find out that a public health problem cannot be solved with the same kind of thinking that gave rise to that problem. Therefore, of considerable interest is the development of a paradigm that merges intellectual discourse, ideas, and techniques from different disciplines to produce a new structure, which shows the influence of the ancestor ideas without being a mere "cut-and-paste" combination. In this context, adequate human health assessment is not achieved solely from knowledge of its component parts--it will emerge from the integrated whole. Subsequently, what one seeks from the integrated whole is sound epistemic ideals that can be expressed in terms of mathematical equations for theoretical modelling and applied technology purposes. More to the point, the SEP involves four major phases--adequate *conceptualization*, rigorous *formulation*, substantive *interpretation*, and innovative *implementation*--and every one of these phases requires a group effort of experts from different disciplines who share the integration goal of SEP[24].

c. Inter- and Intra-

If the development of SEP is going to produce rigorous rules for the integrated modelling of knowledge from different disciplines and levels of organization, it must rely on an adequate understanding of scientific intradisciplinarity and interdisciplinarity in an epidemic assessment context. One should point out that:

- *Intradisciplinarity* usually refers to integration activities between sub-fields of the same domain (e.g., genetic and molecular epidemiology; or obstetrics, gynaecology, and paediatrics).

[24] While they will not be discussed in due detail in this book, we are aware that when attempts to cross the disciplinary boundaries are successful, important sociological and political arrangements are emerging as well (Latour, 1988, Thagard, 1999).

- *Interdisciplinarity* involves the synthesis of different scientific domains (e.g., physics, cognitive science, toxicology, systems theory, and epidemiology).

It is worth noticing that, while intradisciplinarity is a rather familiar precept among most scientists, interdisciplinarity is not always a clearly understood and widely accepted concept. As a matter of fact, it is not uncommon for scientists to refer to the latter when what they really mean is the former.

First, for epidemic modelling purposes interdisciplinarity should not be viewed in the same context as the so-called *unification* of science, which refers to the pyramidal hierarchy that reduces one domain of science to another, seeking the unity of science and searching for the ultimate scientific truth (Galison and Stump, 1993). While many scientists oppose the idea of unification (for a variety of scientific, social, political, and economic reasons), the vast majority of them support the cooperation of different domains of inquiry.

Second, one may distinguish between interdisciplinarity producing a new discipline (e.g., biochemistry) and interdisciplinarity involving the *continuing interaction* of a variety of disciplines without leading to a separate discipline (e.g., evolutionary biology). In the former case a group of individuals coming together from different disciplines feed into the same research enterprise, whereas in the latter case individuals are able to successfully develop cross-disciplinary programs through their own research efforts (Bechtel, 1986).

Third, a distinction must be made between interdisciplinarity viewed as a merely *practical activity* happening on an everyday basis (e.g., studying the components of structured whole in isolation and applying arbitrary combinations to yield the final result) and interdisciplinarity considered for scientific research purposes. Interdisciplinarity is considered valid and even necessary in the context of pressing practical public health problems that need attention from experts from a variety of scientific fields to be dealt with effectively. For scientific research purposes, however, interdisciplinarity is usually handled with considerable caution. E.g., some scientists often argue that their discipline is either too incomplete or too non-reductively autonomous to be blended with another one. On the other hand, nothing will ever be attempted if all possible objections must be first overcome.

Fourth, genuinely interdisciplinary and innovative epidemic research should not be confused with *cosmetic* inderdisciplinarity, the latter having a superficial and *ad hoc* interdisciplinary character allowing disciplinary business to proceed as usual at the cheap price of some interdisciplinary rhetoric. E.g., the lack of genuine interdisciplinarity has often led to human exposure research that is based on poor interaction with physical sciences, even when it is obvious that the latter play a vital role in the causal chain leading to the disease.

d. The Interdisciplinarity Argument of SEP

Public health scientists have long struggled with conceptual and methodological issues occurring when the enormous variation of environmental data is juxtaposed with the biological, kinetic and infection processes leading to the generation and

spread of an epidemic across space-time. It seems natural that in the SEP context the interdisciplinarity argument is three-fold:

(*a*) On occasion, it is a fruitful approach to look at one discipline through the lens of another, thus revealing similar, analogical, or conflicting *patterns* between them. E.g., by using differential equations theory, epidemiologists may represent the disease distribution in an exposed population. Or by using models from stochastic physics, toxicologists can predict the fate of toxicants in the human body and make useful epidemiologic inferences.

(*b*) The network of interacting disciplines of space-time epidemiology should be *holistic*, i.e. considered as a whole. E.g., the biological and physiological characteristics of human populations must be blended with the physical, chemical, and biological properties of environmental media to obtain a better understanding of the factors that increase the risk of a disease becoming an epidemic.

(*c*) While disciplinary research concerns one level of reality, interdisciplinarity concerns the *dynamics* engendered by the action of several levels of reality at once. E.g., part of the task in achieving epidemic synthesis is to bring together analyses at different physical, biomedical, and demographic levels to provide a coherent account of a potential epidemic and to assess the factors that can improve scientists' ability to control an outbreak once it has begun.

Beyond the three-fold argumentation, an adequate SEP should account for the two processes operating in parallel:

(*i*) One aiming at increasing what we *know* (by means of experimentation, observation, surveys, computer simulation, theorization, etc.).

(*ii*) One aiming at rectifying the *logical geography* of the knowledge that we already possess. In this context one must be able to talk sense with concepts as well as to talk sense about them (i.e., to know by practice how to operate with concepts inside familiar fields, and to also be able to state the logical relations governing their use).

Bringing together diverse teams of scientists for brainstorming plays a crucial role in implementing the threefold epidemic argument and the two parallel processes above. Through collaboration, consensus building, regular and open communication, and expanding roles across discipline boundaries, the SEP team members could plan and provide synthetic epidemic science.

e. Integrating Modes of Reasoning

Reasoning plays a vital role in all forms of human activities. Nothing expresses the power of reason to transfigure human suffering better than a sentence from the classic French novel *La Princesse De Clèves*: "I told him that as long as his suf-

fering had had limits, I had approved of it and shared it; but that I would pity him no longer if he gave way to despair and lost his reason."[25]

It could be a constructive approach, indeed, that the SEP views interdisciplinarity as a *reasoning* process that entails rigorously formulated logical and cognitive mechanisms (scientific argumentation modes, conceptual metaphors, epistemic principles, mathematical techniques, etc.) in a composite space-time manifold (in which space and time are intimately connected). This proposition contrasts previous views of interdisciplinarity, such as the *ad hoc* multidisciplinary activity precept (i.e., studying the components of structured whole in isolation and applying arbitrary combinations to yield the final result), and the unification of science metaphysical construct (i.e., in the sense of the unity of science and search for scientific truth). Instead, the SEP should refer to a higher-level synthesis process, which defines the means, or the way of working and acting, that produces holistic, integrative knowledge.

The interdisciplinary genre of public health research is problem-centered, participatory, and could involve multiple stakeholders. SEP should contribute, e.g., to the emergence of a cognitive science of human health that involves the application of the science of the mind to epidemiologic ideas and methods. At the center of this effort is learning to *think about thinking* in an interdisciplinary arena. More to the point, the SEP will be confronted with different *modes of reasoning* (or *styles of scientific thinking*) including:

- The Taxonomic
- The Analogical
- The Mathematical
- The Statistical
- The Experimental

While being well aware that epidemic assessments resulting from each one of these different modes of reasoning are not necessarily consistent with each other (e.g., an epidemic assessment may be valid in terms of taxonomic but invalid in terms of analogical reasoning), SEP should nevertheless seek an appropriate integration of the component modes. By focusing on integrated modelling in the methodological sense, the term "integration" covers possible links that can be developed between different physical and life science disciplines, i.e., SEP will be viewed as disunified but interconnected seeking integrated (theoretical and empirical) links and laws. In this manner the SEP can include, e.g., many biological characteristics that link exposure with dose and subsequent disease.

f. The Role of Uncertainty

We cannot think of a better introduction to this section than by quoting Sir Arthur Eddington (1958: 1): "If 'to know' means 'to be certain of', the term is of little use to those who wish to be undogmatic." Indeed, for a variety of reasons dis-

[25] "Je luis dis que tant que son affliction avait eu des bornes, je l'avais approuvée, et que j'y étais entré; mais que je ne le plaindrais plus s'il s'abandonnait au désespoir et s'il perdait la raison" (Lafayette, 1980: 150).

cussed elsewhere (Christakos and Hristopulos, 1998; Christakos, 2001, 2003a), there is not logical certainty in public health sciences. Instead, uncertainty characterizes a plethora of phenomena, such as the space-time distribution of toxicants or the precise molecular effects of environmental factors in relation to the DNA of genes. The future spread and threat to human populations of known pathogens (linked, e.g., to malaria and AIDS) are highly uncertain, as is the case with yet to be discovered pathogens. Considerable uncertainty also characterizes the transmission process of pathogens among humans, their adaptability, the links between pathogen evolution and epidemic processes (within and among hosts), and the potential to infect humans of pathogens found in animals (Grenfell *et al.*, 2004).

Despite the crucial role that the term "uncertainty" plays in public health sciences, no clear insight is available that accounts for its essential conceptual and technical features associated with various scales and levels of organization (e.g., Wimsatt, 1976). In the view of many, it is the "model concept" that is the main source of uncertainty[26], whereas others are concerned with uncertainty introduced by empirical relationships. Actually, most of the natural variables and biomedical systems involved in cross-disciplinary integration are connected and vary in *synergy* across space and time, rather than being isolated and space-time separable, as is often assumed. The concept of synergy has connotations that may determine the meaning of uncertainty associated with the epidemic system. In view of the above considerations, one of the SEP priorities is to examine an *integrated uncertainty* framework through which cross-disciplinary epidemic research can proceed, uncertainty sources (conceptual, empirical, etc.) can be meaningfully interpreted and taken into account with rigor, and valid predictions can be made across space-time. In fact, how to develop and implement efficiently such an integrated uncertainty framework is one of the most important outstanding questions in current public health modelling, one that involves deep and challenging conceptual and methodological issues.

On occasion, exposure studies have used the *organization* inherent in *deterministic* mathematics to represent and predict the behavior of rather simple physical systems, but this approach has basically failed to provide predictive models in life sciences. Instead, the SEP view is that one cannot underestimate the importance of uncertainty in health studies, for its consequences transcend the domains of the two most significant constituents of scientific development: *explanation* and *prediction*. When uncertainty describes a state of incomplete knowledge (due, e.g., to poor understanding of the integrated behavior of bioavailability across disciplines, the factors affecting host susceptibility, intra- and inter-subject variability, biological noise, or mixtures of chemicals acting in synergy) it can serve an inspirational purpose, for it makes it possible to study the role of human conceptualization in creating empirical knowledge across different life support disciplines. Hence, the SEP view is that the rigorous study of epidemic systems should be based on the power of the *stochastic* mathematical theory (Chapter II) that accounts for various sources of uncertainty emerging from cross-disciplinary inte-

[26] E.g., uncertainty due to inadequate model structure (conceptualization) may be far more detrimental to its predictive ability than parameter and data uncertainty.