Interdisciplinarity "In the Making": Modeling Infectious Diseases

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The main contribution of this paper to current philosophical and sociological studies on modeling is to analyze modeling as an object-oriented interdisciplinary activity and thus to bring new insights into the wide, heterogeneous discourse on tools, forms and organization of interdisciplinary research. A detailed analysis of interdisciplinarity in the making of models is presented, focusing on long-standing interdisciplinary collaboration between specialists in infectious diseases, mathematicians and computer scientists. The analysis introduces a novel way of studying the elements of the models as carriers of interdisciplinarity. These elements, being functionally interdependent building blocks, evolve during the modeling work and carry the disciplinary tensions in the process. This shows how the long and challenging process of defining and reformulating the object of research is crucial for understanding the dynamics of interdisciplinarity in the making.

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1 Introduction

Modeling complex, dynamic phenomena, such as bacterial behavior and contagiousness in the population requires expertise from various disciplines. How can one study modeling in relation to interdisciplinary research activities? This paper develops a way of studying the "interdisciplinarity in the making" through the building and using of a set of infectious-disease models in multidisciplinary research collaboration. I will argue, on the basis of an empirical analysis that interdisciplinary research is bound to its object, in accordance with which it can develop and evolve or cease. Infectious-disease modeling is thus a fruitful example in that one needs to know in detail the fine-grained features of the bacterial behavior as well as the appropriate method for its modeling. How are these pieces of knowledge brought into the model? What kind of process is needed to develop object-oriented interdisciplinarity in modeling?

So far, studies on modeling have been restricted to models within an established, scientific field such as physics or economics. Although they have emphasized the differences in modeling collaboration within these fields, the specific question of interdisciplinarity has not been taken into closer analysis (e.g., Morgan and Morrison 1999, Merz 1999). A further step towards understanding models and modeling within a variety of disciplines was taken in Bailer-Jones (2002), who conducted an interview study concerning researchers' own thoughts of models in the sciences. However, her focus was on the different conceptualizations of models, not on the nature of interdisciplinary modeling. Correspondingly, the current literature on forms of disciplinarity has focused on defining and locating the various forms of multi-, inter-, and transdisciplinarity (Thompson Klein 1990), relating these notions to science policy strategies (Gibbons et al. 1994), or examining interdisciplinary practices on a general, organizational level (Weingart and Stehr 2000). Neither approach, in its current form, is capable of answering the question of what is interdisciplinarity in modeling in the context of complex phenomena such as infectious diseases.

I will approach these questions with reference to a study of infectious disease modeling that took place in long-standing research collaboration between the National Public Health Institute, the Rolf Nevanlinna Institute[1] and Helsinki University of Technology during 1994–2004. The main task within this INFEMAT project was to build infectious-disease models and develop the corresponding modeling methods for

1. The Rolf Nevanlinna Institute has been part of the Department of Mathematics and Statistics at University of Helsinki since 1.1.2004.

Haemophilus-Influenzae type b related datasets. The emphasis was on public-health interests, such as vaccination planning.

My answers to the questions lie in the analysis of the "built-in" interdisciplinarity of a set of Hib-related models developed in long-standing multidisciplinary research collaboration. I will apply Latour's (1987, p. 7) appealing metaphor of "science in the making," which is a contrast to the "ready-made science." Generally speaking, he means that science has a dual nature—the side that knows and the side that does not know yet. In other words, my interest is to study the side of interdisciplinarity, which "does not know yet"—which does not carry ready-made definitions or categorizations. My main contribution is to study the different forms of interdisciplinary expertise in long-standing research collaboration by analyzing the *elements* of the models as *carriers of interdisciplinarity.* This means that I will turn to the functionally interdependent building blocks of infectious-disease models and examine how they evolve, develop and carry the disciplinary tensions during the modeling project. I will argue that the 'making' covers the long-standing, somewhat slow formation of object-oriented[2] interdisciplinarity, which is a combination of skill and know-how. The emergence of interdisciplinarity is partially located in the object of research, and more specifically in the elements of the models. This is a new way of approaching the subject of interdisciplinarity in science, and it sheds light on the question of how to organize, manage and sustain interdisciplinary research. I use the term interdisciplinarity throughout the paper to refer to the challenge of overcoming disciplinary boundaries within a joint modeling project.

The structure of the paper is the following. In section 2 I introduce the current discussion on interdisciplinarity in science and justify the study of its emergence in the making. I also describe the *elements* of models and relate them to the general discussion on model studies. My focus is on the *life span* of infectious-disease models and on their *functionally interdependent* elements in relation to the multidisciplinary expertise brought in by the modelers. I analyze the elements of these models in sections 3–6 in terms of the form of disciplinarity in each phase of the project. Section 7 ends the paper with a discussion of the development of *object-oriented interdisciplinarity* in the broader framework of the discourse of disciplinarity.

2. Object-oriented interdisciplinarity applies the activity-theoretical supposition that human activity is always object-oriented, i.e., all activities we are engaged in have a certain goal and outcome, which motivate and guide the activity, and the development of tools (or alternatively sign systems) used in it (e.g., Engeström, Miettinen and Punamäki 1999).

2 The use of life-span of models in analyzing interdisciplinarity in the making

In order to relate the analysis of modeling as an interdisciplinary research activity to the broader framework of analysis on interdisciplinarity in science, I will first introduce the current discourses and then show how I intend to apply and expand it to cover the microlevel analysis of interdisciplinarity in the making.

Current literature conceptualizes the heterogeneous phenomena of multi-, inter- and transdisciplinarity in three contexts: studies on rhetorics in science (e.g., Ceccarelli 2001), science-policy approaches (e.g., Gibbons et al. 1994), and organizational studies of science and its practices (e.g., Weingart et al. 2000).

Firstly, interdisciplinary research is understood in terms of the use of rhetorical devices in the emergence of new disciplines. Ceccarelli gives the specific example of how textual tools, i.e., scientific articles and monographs, bridge two separate disciplines combining them in one, novel field of study and thus inspiring interdisciplinarity. There are, at least two sub-themes related to the rhetoric in the scientific analysis of interdisciplinarity: the differentiation—integration process of science and the discourse on the unity of science. On the one hand, disciplines may split into subdivisions, which could eventually become separate disciplines or lead to the emergence of "interdisciplines," covering a wide range of interactions—from informal research groups to well-established communities (Berger 1972 paraphrased in Klein 1990, p. 43). This, in general terms, reflects the institutionalization of science and its simultaneous specialization, which implies the emergence of new special fields of study. On the other hand, as Weingart (2000) pointed out, the discourse on interdisciplinarity was previously bound with the debate on unity of science, which ranges from the logical positivist ideal of reductionism in science to the rather recent discussion on the concept of consilience in sociobiology (e.g., Segerstråle 2001). Even though, according to Weingart, the link between interdisciplinarity and the ideal of unity has been broken, it is useful to bear in mind this ontological aspect, which is present in the concept of interdisciplinarity.

From the rhetoric of interdisciplinarity, one could turn to the second perspective, namely its science-policy-related uses. The growing interest in categorizing and defining different forms of interdisciplinary research on the science-policy level has led to conceptual and organizational analysis promoting a 'vocabulary of interdisciplinarity' for various uses in science policy and administration (Thompson Klein 1990, 1996). The policy-oriented analysis of interdisciplinary research aims at relating multidisciplinarity to the very locus of scientific practices (Weingart 2000), or even at replacing the 'old-fashioned' Mode-1 science with Mode-2 knowledge production, which is inevitably transdisciplinary (Gibbons et al. 1994, pp. 4–5). Within this discourse, transdisciplinarity consists of developing a distinct problem-solving framework, new theoretical structures, and research methods or modes of practice to facilitate problem solving. The aim is to foster closer interaction between knowledge production and a succession of problem contexts. Weingart (2000, pp. 40–41) builds a link between interdisciplinarity and innovation, reflecting the promise of progress that was once given to the "unity of science ideal." Included in innovation policies (Miettinen 2002), interdisciplinarity is bound up with broader societal activities addressed to universities.

With regard to the third aspect, "practicing interdisciplinarity,"[3] special attention has been given to disciplinary structures and their role in research activities, as reported in studies on the formation of a local research program (in Saari and Miettinen 2001). Early reactions to this development are presented in Knorr Cetina's analysis of *transepistemic areas of research* (Knorr Cetina 1982, p. 117), which could be read as a predecessor of the discourse. These arenas involve a mix of persons and arguments that do not fall naturally into the category of relationships pertaining to science, or into other specialized categories. This is echoed in Lenoir's argument that disciplines are the structures in which skills are assembled, intertwined with other diverse elements, and reproduced as coherent ensembles suitable for the conduct of stable scientific practice. These skills form the set of unarticulated, non-verbal skills, competence in manipulating both simple and complex instruments and calculation skills (Lenoir 1993, pp. 79–80).

What is problematic in these categorizations of disciplinarity? I would like to put forward two points. Firstly, this group of heterogeneous, independent accounts of disciplinarity in science ignores the core of research, the research object, which is an inseparable part of the research activity. Secondly, they have neglected the processual, "not yet seen" nature of interdisciplinarity in the making. These shortcomings, I suggest, can be overcome by analyzing the lifespan of interdisciplinary modeling in relation to the functioning of models as objects of research.

The life span of scientific objects was brought under closer scrutiny by Daston (2000). She suggests that analyzing the life span of objects not only gives us insight into their social construction, but also shows the deeply interrelated character of the object in question and its uses, applications and the social aspirations reflected in it. By reconstructing the life span of models, one learns how they gradually turn into research objects

3. The title of the Weingart and Stehr 2000 edition.

within interdisciplinary research work. My analysis applies the idea of studying the development of interdisciplinarity in the construction of research objects. Miettinen (1998) highlighted this by emphasizing the importance of studying the construction of epistemic objects as the "simultaneous development of an artefact and a network of actors mobilizing the relevant knowledge and expertise by collaboration." This is also reflected in Callon's (1980) early analysis of a fuel-cell research program, in which the simultaneous process of setting research questions and mobilizing social actors resulted in a "socio-logic of research." My analysis thus considers models as an object of activity, and as tools and instruments in activity. The object defines the activity, it expresses its purpose and motive society, and it also carries the use of research results outside the original community (e.g., Miettinen 1998, Saari 2003, Tuunainen 2001).

What, then, are these models? I refer to all models in the scope of this analysis as *a set of Hib-related models*[4]. In general terms, they are probabilistic models of the bacterial pathogen *Haemophilus influenzae type* b, which can cause severe or life-threatening diseases such as *meningitis, epiglottitis, arthritis, pneumonia* and *septicaemia,* especially among infants and children. However, these severe conditions are rare due to the proper coverage of Hib-vaccinations, which started in the mid-80s. These models were built in a longstanding research project[5] called INFEMAT. Researchers from the Department of Vaccines at the National Public Health Institute (KTL), the Biometry research group at the University of Helsinki, the Rolf Nevanlinna Institute (RNI)[6], and the Multimedia Laboratory of Helsinki University of Technology (HUT) all participated in the project. The aim was to enhance understanding of the dynamics of Hib infection and assess its persistence in a population (Auranen 1996, p. 2235). A further objective was to "develop methods for the analysis of Hib infection and the effect of different intervention strategies" (Research Plan 1994).

The modeling of this challenging and multilayered phenomenon required the skills, know-how and expertise[7] of people from different fields of study in the problem-solving phase. The researchers brought their pro-

4. During the project, a total of 15 models were built. Most of them were of Hib-related research questions, but methods of modeling other bacterial agents or chronic disease were also developed. The focus here is only on Hib-models.

5. The fine-grained nuances of the fields of expertise are not fully expressed in this list. However, I have decided to classify the participants' fields of expertise according to their disciplinary background: infectious-disease specialists have a background in medicine, and mathematicians, although crossing the boarder with applied statistics, are trained in mathematics.

6. RNI became part of the Department of Mathematics and Statistics on 1.1.2004.

7. In this article, I talk about expertise in its general meaning, not as proposed in the debate launched by Collins and Evans (2002).

fessional expertise from the fields in which they had successfully conducted their scientific work. The computer scientist from HUT provided experience in visualization techniques and virtual life modeling. The mathematics and statistics expert, who was particularly well-versed in Bayesian probability theory and event-history analysis, and familiar with the wide range of studies on mathematical modeling brought in the expertise on probabilistic modeling required to study the fragmented data and master the uncertainties. Hib diseases, the bacteriology of the pathogen and the development and testing of Hib vaccines were the fields of expertise of the infectious-disease specialists at KTL: it was their solid knowledge of the phenomenon that motivated them to launch the project in the first place. The project researchers included two research pairs: one infectious-disease specialist (Aino) was married to the computer scientist (Tapio), and later on the junior researcher in biometry (Kari) worked in a pair with the junior infectious-disease specialist (Tuija).

I will call these pairs *dyads* in the analysis, a concept that comes from Vera John Steiner (2000), who studied the work of research teams. She describes dyadic collaboration as close, family-like teamwork, arguing that complementarity of disciplinary knowledge and personal resources are crucial for elements, and are closely related to the object of the activity (2000, p. 40).

Table 1 summarizes the researchers' disciplinary backgrounds. Throughout the analysis, I understand multidisciplinarity as a form of coordinated[8] research activity in which actors from different fields share but a rather loose research area or field of interest rather than a defined research object while remaining bound to disciplinary conceptualizations in their activities. By interdisciplinary research, I refer to the form of research collaboration in which the shared object is defined and new tools and practices for collaboration are developed. Disciplinary conceptualizations do not dominate, and researchers are willing to work towards a mutual understanding of the research object (e.g. Thompson Klein 1990). Thirdly, I use the concept interdisciplinarity to refer to the challenging, sometimes tensional, long-standing research activity within which researchers struggle to overcome their disciplinary ways of modeling and put their efforts into jointly defining and working on a shared research object.

As objects of activity, models function in multiple ways in the processes of building and using them. This functioning is acknowledged and ana-

8. Coordination is based on the rule-bound division of labour, in other words, it is the "normal, scripted flow of interaction" in which actors follow their roles. (e.g., Engeström et. al. 1991).

Table 1. The disciplinary backgrounds of the researchers: the information includes the field of expertise (senior researchers) or experience from previous studies and research activities (junior researchers).

Researcher and organization	Disciplinary background	Field of expertise/ previous studies
Elja/RNI	Professor in mathematics and statistics	Bayesian inference, probability theory
Kari/RNI and KTL	M.Sc. in mathematics	Studies in physics, mathematics and statistics
Jukka/RNI	M.Sc. in mathematics	Studies in applied statistics
Martin/visitor	PhD in mathematics and biology	Mathematical modeling of biological phenomena
Tapio/HUT	Professor in computer science	Simulation techniques, virtual life modeling
Aino/KTL	PhD in epidemiology, medicine	Hib epidemiology
Pirjo/KTL	Professor emerita in epidemiology, medicine	Hib epidemiology, public-health studies, Hib vaccines
Tuija/KTL	Lic. Med. in epidemiology, medicine	Studies in public health, minoring in STS

lyzed in Morgan and Morrison (1999), who propose that models as "autonomous agents," i.e., partially independent of the theory and the world, could be considered "investigative instruments" in science, which means studying their uses and applications, or their mediating roles in research work (ibid., pp. 10–11). In order to find out how models function as objects of interdisciplinary research work, I focus on how they are formed through the construction of their elements, their building blocks. This approach is motivated by Boumans' (1999) analysis of the construction of small-business-cycle models as a process of integrating and molding a set of heterogeneous ingredients, such as metaphors, mathematical formulae, policy views, and theoretical assumptions. I consider the construction of a set of Hib-related models by analyzing their basic "building blocks," their *elements.* I argue that by analyzing these shared "building blocks," which can be identified in each model and modeling phase, one is able to learn how models (i.e., their elements) facilitate the formation of *object-oriented interdisciplinarity.* This is crucial because the model building involves simultaneous research on modeling methods, simulation techniques, data analysis and explorations in infectious-disease epidemiology. Examining the elements makes it possible to come up with a processual description of each specific practice of model building.

I use the term element[9] here to refer to the elementary constituents of models that are important for their functioning, and are interdependent in the way that a change in one element cannot to be ignored and might require some changes in another. The three identifiable elements in all the Hib-related models are 1) modeling methods, 2) substantial knowledge of infectious diseases and 3) data. What is characteristic of these elements is that they all are dependent on the expertise brought into the model by a researcher or a network of researchers. In other words, the expertise is built into the models through the construction of the elements, and at the same time, as the modeling proceeds, new skills and know-how are learned in the process. These elements can be described as follows.

The element of modeling methods consists of a set of mathematical and statistical models and sub-models, which are applied according to both Bayesian and frequentist principles.[10] The sub-models include spatial models, hierarchical models, stochastic[11] and probabilistic models and simulation models. This element also covers computer-intensive methods[12] and simulation techniques.

The element comprising substantial knowledge of infectious disease is, in other words, the epidemiological model, which consists of a set of background assumptions concerning the behavior and the transmission of the bacterial pathogens. This element, in general terms, covers what was the basic epidemiological model consisting of a loose set of background assumptions about the behavior and transmission of Hib pathogens. In other words, the changes in the carriage states of Hib, the difficulties in estimating Hib carriage, and the fact that Hib infection does not result in life-long immunity nor does it leave any marker with the individual, were

9. Throughout this article, the term element should be understood as a general building block of Hib-related models. When these elements are analyzed on a more detailed level, it is possible to specify properties that could later be integrated into a new model.

10. The main difference between the frequentist and Bayesian approaches lies in their way interpreting probability. The frequentist probability of "x happening" is the proportion of these happenings in a large set of trials, whereas Bayesians consider probability as a personal, subjective opinion of how likely the "happening" would be. The personal view changes as evidence, through data, accumulates (Leino 2003, p. 26).

11. Stochasticity means that the model has a probability pattern that can be analyzed statistically.

12. Computer-intensive methods are statistical methods in which the computer is a vital tool in performing the inference, such as Markov Chain Monte Carlo methods.

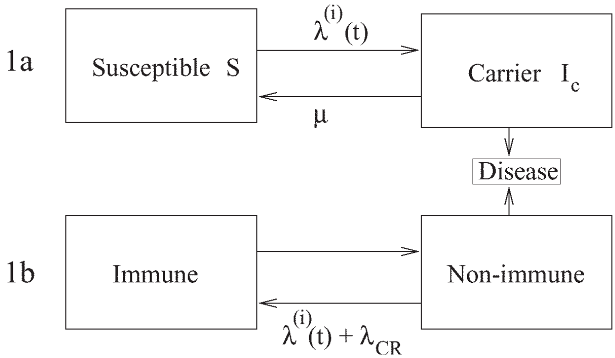

Figure 1. Illustration from an unpublished manuscript (Auranen et al., 2003): a simplified picture of an epidemiological Hib model. The main blocks (1a) are "susceptible" and "carrier," two alternating states of usually asymptomatic infection. In addition, each individual is either "immune" or "non-immune" against disease (1b). The disease develops occasionally in non-immune carriers. Parameters λ and μ describe the different probabilistic rates of acquiring and clearing carriage.

demanding features (Leino 2003). The following figure of the simplified structure of a Hib model clarifies this.

The data element is the set of epidemiological data covering databases from previous studies on pathogens collected by KTL, and datasets from collaborators in the project. Data set I was collected as part of a risk-factor analysis of invasive[13] Hib disease in Finland during 1985–1986, just before the Hib vaccination program was launched. Data set II was collected in the United Kingdom during 1991–1992. The data on Hib carriage were collected from infants and family members when the infant was six, nine and twelve months of age (Auranen et al. 1996, p. 2237). These two datasets carried the two aspects of Hib studies. The first one represented historically conducted studies on Hib and comprised data that needed to be reanalyzed using the new, more efficient modeling method. The second set brought into the project an important collaborative relationship with a British research group lead by Dr. Marina Barbour.

In the following analysis, these elements are examined in relation to the emergence of object-oriented interdisciplinarity in the different phases of the INFEMAT project. The analysis is based on different types of data,

13. Invasive Hib diseases can be life-threatening for children: such diseases include *meningococcus, epiglottitis* and *pneumonia.*

ranging from interviews to documents and archived data, and ethnographic field notes, and transcripts of the meetings held during 2001–2004.[14] The main aim is to study how the elements function as carriers of interdisciplinarity throughout the project.

3 Constructing the Good-night-kiss model: professional expertise as a starting point for collaboration

The life span of the set of Hib-related models can be divided into four phases, characterized by the main research goals. The aim in the first phase was to construct the first, simple transmission model, the so-called Good-night-kiss model (GNKM). In the second phase, the emphasis was on developing modeling methods for a variety of infectious and chronic diseases, and thus building a family of models. The focus shifted in the third phase to the epidemiological questions that were to be solved, and in the final phase, the previously built models served as a basis for studies on public-health.

The challenge at the beginning of the project was to find the shared common ground that would form the basis of the interdisciplinary collaboration. The researchers described this as a "search for the common ground," in other words, finding the areas that would lend themselves to joint study in the course of building the first model. The starting point of the modeling collaboration seems to have followed the basic description of multidisciplinary coordination. The researchers brought into the project their special knowledge of the subject, but they did not have a defined, shared research object, merely a joint area of interest. The emphasis on the search for the common ground implies that the modelers tried to achieve somewhat more sophisticated forms of collaboration.

The first model, the Good-night-kiss model (GNKM), was reported in the first published article from the project, and it was built upon the idea of monitoring transmission rates within the family, the supposition being that the "potentially infectious contacts were good-night kisses among family members" (Auranen, et. al. 1996, p. 2250). The modeling-

14. In more detail, the data consist of i) lightly-structured interviews with the key actors between January 2001 and February 2004, ii) research plans, protocols and reports written to the project-financing bodies between 1993–1999 (the time period was limited by the availability of archived documents), iii) seminar presentations, manuscripts, and various research reports written during the project, availability being limited to the archived samples, iv) three dissertations written during the project, and v) ethnographic field notes and transcriptions of a series of 23 meetings between February 2002 and February 2004. Given the fact that I started the empirical research in January 2001, the interactive data (interviews, seminar ethnography) are limited to the latter part of the project. As an ethnographer, I attended regular meetings, most of which were held at the Department of Vaccines in KTL.

methods element consisted of a probability model for structuring the dispersion of Hib infection in a small population. The probability and computer-intensive methods used, were developed jointly. The idea of programming computer-based simulation software, a Simulator, based on the model, by applying visual computing techniques was realized to some extent, although it was not used due to technical instability. Within this element, the modelers in fact tried to manage the changes in carriage states (e.g., those between susceptibility and infection) and the spread of Hib carriage in a family (e.g., the contact structure of how the bacteria spread), which were not recorded in the data.

In order to model these characteristics of the infection, it was necessary to apply and develop the mathematical and statistical modeling expertise of the researchers at the Rolf Nevanlinna Institute, the RNI. The Institute is specialized in modeling physical phenomena such as electromagnetism but this expertise had to be "translated" into modeling biological and epidemiological phenomena. This "translation"[15] was facilitated by a visiting researcher from the University of Tübingen in Germany who, having degrees in both biology and mathematics, shared his know-how on modeling methods with the research group. According to him, "the strong expertise in various kinds of modeling techniques mastered at RNI needed to be converted into a new framework to accommodate bacterial pathogens." With his interdisciplinary research experience, he was able to act as an interpreter between the infectious disease specialists and the mathematicians.

The element of substantial knowledge of infectious disease was mainly the epidemiological sub-model. It consisted of a loose set of background assumptions about the behavior and transmission of Hib pathogens, and captured the know-how from previous Hib studies conducted by the senior infectious-disease specialists in the project. They had achieved a "considerable amount of knowledge about *Haemophilus influenzae type* b bacteria, Hib disease, risk factors for disease and its spread, the natural immunity against Hib diseases among infants and children, and the prevention of Hib diseases with vaccination" (RP 1994, p. 2). This knowledge was combined with the general epidemiological S-I-S model and formed the backbone of this element.

In this phase, the data element consisted of two data sets, from the KTL and from the UK. The KTL data in particular was to be fruitfully further analyzed using the new, more efficient modeling method. The second set brought into the project an important collaborative relationship with a

15. Notion used in Latour 1979.

British research group lead by Dr. Marina Barbour, and linked the Finnish group to the British tradition of infectious-disease studies.

Together, these three main elements were the building blocks of the Good-night-kiss model. In order to combine these elements into a sophisticated whole, the modelers applied their knowledge and expertise from the previous studies they had conducted within their disciplines.[16] I interpret this as the core of accumulated professional expertise. The know-how and skills acquired during the respective long research careers prepared the ground for developing a new approach to studying epidemiological questions. The knowledge of the senior infectious-disease specialist[17] in particular was helpful in focusing and reframing the project goal in the different phases of the research.

The senior researchers started to hand down their professional expertise to the junior researchers through the joint research work, in seminars, and in joint writing projects, for example. The international visiting scholar, who had been working on modeling biological agents, shared his special skills and knowledge with the researchers. The seniors had their slow-built, broad expertise in their specialties, whereas the juniors merely had disciplinary know-how from their previous studies and interests, which offered the potential to learn and develop new expertise. Thus, in the first phase, the professional expertise facilitated and guided the formation of the modeling project.

The researchers also began to write the first article, initially submitted for review at the end of 1994, and published in 1996. During the writing process, the statistical approach shifted as expertise on Bayesian inference was acquired, brought to the project by the senior researcher at RNI. The seminars, the joint writing processes and familiarization with the modeling literature created the basis of what I call object-oriented interdisciplinarity.

The GNKM as a simple transmission model and the modeling practices developed in the first phase paved the way for other models constructed during the project. The first jointly built model, GNKM, had different functions. First, it represented, on a minor scale, the project goal: to understand the dynamics of Hib infection. Second, it guided the choice of modeling method, technique and use of data. Third, it facilitated communication, serving as a “common ground” for researchers from different disciplinary backgrounds, and turned into the first shared object support-

16. Mathematics, statistics, epidemiology, computer science and biology.

17. Professor emerita, who was appointed Fellow of the Academy of Finland in 2003, which is the highest academic position in the country. She had had an internationally recognized career in Hib vaccination studies, and later on in designing vaccination programs.

ing the *interdisciplinarity* in the modeling. Finally, it functioned in later phases of the model building as a reminder to the researchers of their successful, joint effort.

4 Developing the modeling methods

The emphasis in the second phase was on developing the modeling methods, in other words constructing the set of mathematical and epidemiological models, which reflected the active, heterogeneous modeling and simulating practices engaged in during 1995 and 1997. This meant that the joint efforts lost momentum to some extent and the researchers occasionally worked alone to test the models and make them fit with the data. The main difference from the first phase was that multiple models were under construction at the same time. This was a time of intense, personal work. Some researchers suggested that the initial goal of building a single model became fragmented in various sub-goals and models that were achieved, studied and constructed partly alone or only in the context of the researchers' home organization.

> Junior researcher: The starting point was to construct an epidemiological population-simulation model. During the project, this aim was spread out among smaller sub-projects. We took some questions and some data and started to construct a model for that setting.

In other words, the lack of a single, shared object of research in this phase turned the emerging interdisciplinarity into multidisciplinary coordination. This implies that change and development in various forms of disciplinary collaboration does not form a linear developmental trajectory (as also suggested in Thompson Klein 1990). Furthermore, the importance of the object of research, how it functions in the different forms of collaboration, becomes evident. Whereas the Good-night-kiss model functioned as a shared object and thus supported the short period of interdisciplinarity, its dispersion and the development of more specialized modeling methods did not sustain the emerging object-oriented interdisciplinarity but rather promoted multidisciplinarity.

Nevertheless, the joint seminars and reading groups continued. Mutual learning processes and joint writing were introduced as part of the daily research work. The senior researchers gave talks on their areas of expertise (including Hib studies, Hib vaccinations, statistical modeling of data and simulation techniques) in the seminars, and the junior researchers presented literature reviews of recent modeling methods in epidemiology, or jointly read the basic textbooks (e.g., Anderson and May, 1992: *Infectious Diseases of Humans: Dynamics and Control*; Becker 1989: *Analysis of Infectious*

Disease Data). Interestingly, the dispersion of the research goals was also reflected in the dispersion of the datasets. This was partly because the research was being conducted in pursuance of a PhD degree. In applied statistics, novelty on the methodological level is a major achievement in a doctoral dissertation, and this encouraged the junior researchers to start modeling various datasets on other pathogens and diseases, such as *pneumococcus, meningococcus, poliomyelitis* and *diabetes mellitus.*

How was this specialization reflected in the development of the models? The modeling methods dispersed along various developmental paths ranging from probabilistic modeling to simulation techniques, and encompassed a rich variety of spatial and hierarchical models, for example. This dispersal, which in fact led to the choice of the main modeling methodology, was not smooth or simple; on the contrary, disciplinary tensions arose in this phase.

The researchers needed to choose their main modeling method during the second period. This choice provoked discussion:

> Senior researcher: One problem or difficulty was that two the methods were not understood sufficiently; the simulations and Bayesian inference did not happily co-exist.

The senior researchers made the choice based on their professional expertise. The stronger research focus on Bayesian inference within applied statistics was understandable because there were two doctoral students of mathematics contributing to the modeling. Consequently, the choice was made in favor of Bayesian inference, thus furthering the development of stochastic modeling[18] instead of simulation techniques. This was not an "all or nothing" type of choice: both methods, Bayesian inference and simulation techniques, were developed during the project, and the Integrated model applies to both of them successfully. However, the situation was competitive before the various methods were considered to be complementary. The idea of the Simulator was realized during the specialization process. It was programmed by three engineering students majoring in computer science, who described the need to program it in their research plan: "Along with an infectious-disease model, we need a population model and a model of contact structure. The development of a system modeled in this way needs to be studied through simulations, because one cannot solve analytically the probability distributions used in the system."

The choice of modeling method and the specialization in simulation techniques seems to me to be a way of developing stronger disciplinary ex-

18. They applied Bayesian inference in the stochastic models.

pertise. This might have appeared to be a necessary phase in the creation of a collaborative base for interdisciplinary modeling.

A substantial knowledge of infectious diseases was needed to cope with the growing body of information on various diseases modeled during this phase, such as diabetes mellitus and poliomyelitis. This variance was also present in the data element: KTL had collected multiple databases on these diseases during the 1970s and 80s.

The striving for *object-oriented interdisciplinarity* was described as a "search for the subset of shared expertise." In their ongoing modeling activities the researchers faced the fact that they were not able to strictly describe and limit their joint area of study, but they certainly knew that they needed to find it and to depict it. By definition, the shared research object had a changing and dynamic nature: it had to be reconstructed in the face of new datasets, new methods, and new efforts to program the Simulator. As such, it offered a basis for a more detailed and integrated way of studying epidemiological questions.

5 Using mathematical methods to enhance and broaden the scope of epidemiological models

The third phase was that of applying the previously acquired expertise in order to answer more specific epidemiological questions. This refers to the iterative, mutually intertwined chain of building and using the models, which I call *tailoring.*[19] There was a shift from modeling the dispersed sets of specified models towards building new ones from the previous ones. A new doctoral student of medicine, Tuija, began her PhD research with the project at the beginning of 1998. She was working with one of the junior researchers from RNI, Kari, as if in a *dyad.* The basic framework of the INFEMAT modeling project supported the idea of complementarity in dyadic collaboration.

The medical models were built on the mathematical and statistical models: the methodology developed was pushed further to address more sophisticated medical and epidemiological questions. This interaction was discussed as follows:

> Junior researcher: It is said that this is based on Auranen's model. In fact, in this (article) and in the first article, the results are based on the model published in Auranen's dissertation. We have started to use the model and to speculate about the results, and to write for

19. The current literature has kept these aspects separate, focusing either on building or on using models (e.g., Boumans 1999, Morgan 1999). It is thanks to a personal discussion with Prof. Mary Morgan that I was able to develop the concept of tailoring to describe the mutual, iterative process of using and applying models.

> the medical audience, which is how we came up with these predictions.

This quotation reveals the complementarity in the dyadic collaboration. The models were built upon each other. The ones that had previously been published (in Auranen 1999) offered methodological support, i.e., a mathematical and statistical basis, for the epidemiological models. Furthermore, the complementarity in skills, expertise and specialization that arose in the dyadic collaboration facilitated the tailoring. As the junior researcher in epidemiology (Tuija) said, the mathematician (Kari) was patient enough to teach her, to explain the principles of modeling, and to introduce the methods applied in the previously published models.

Questions of prediction in terms of epidemics, immunity and vaccination, and the transmission of a pathogen on the population level, were addressed in a set of models built during this phase. These models applied and broadened the methods used in previous mathematical models. The modeling methods, now comprising mathematical sub-models, functioned a basis for raising further, medically and epidemiologically informed research questions. The main emphasis, however, was on in-depth study within the element of substantial knowledge of infectious disease in terms of developing more detailed epidemiological models and extending the datasets used to form new databases within the data element.

Interestingly, the social setting of the project changed in the third phase, which naturally had an influence on the development of interdisciplinary expertise. The research group was bigger and worked together as a team at the beginning of the project. Dyadic collaboration became necessary during the third phase because of the changes in the basic structure of the group. One senior infectious-disease specialist left KTL in order to work in a pharmaceutical company, but she maintained her role as collaborator and supervisor of the project. At the same time, the biometry research group started to expand its research interests into other fields of study (e.g., modeling population genetics), and the senior researcher at RNI stayed more in the background, although he continued to supervise the modeling studies. The new smaller research team included a postdoctoral modeler and a doctoral student in epidemiology, who thus formed a strong, specifically dyadic collaboration unit. They also worked in close connection with the visiting senior researcher, who had been involved in the project since its beginning.

6 Integrating the previously built models and programming the Simulator

The final phase of the project incorporated the years of intensive work Tuija needed to finish her doctoral dissertation in epidemiology, and the building of the Integrated model and programming its computer interface. Efforts were directed towards integrating some of the previously built Hib-related models into a comprehensive integrated model, which was extended to facilitate individual-based simulations on a computer. In terms of the actual INFEMAT project, this phase was not covered by the original funding and the researchers kept up their joint efforts at the same time as new projects or settling down in new working environments. In my view, this long-term commitment to the project was important and vital in terms of achieving the new, possibly transdisciplinary goals set at the beginning.

Within the modeling methods the main effort was in combining the knowledge of and expertise in the previous mathematical and statistical models into this multi-layered simulation model. The development of computational tools[20] was also an important factor facilitating the research during this phase. Composing the Integrated model and its computer interface—the continuous struggle to integrate the properties from the previously built models and to test the results—was the core activity in this phase.

The substantial amount of knowledge gleaned from previous sub-models examining vaccination effects, herd immunity and the spread of epidemics was incorporated into one model focusing on the individual path with its prevailing risk of the infection. The data element applied, as a form of validation of the Integrated model, the datasets from the previously built INFEMAT models. At this stage, the model with its computer interface provided a basis on which it could produce its own 'datasets', thus creating 'model world' for examining questions, which were not tractable in the real data. The shared, well-defined research object, i.e., the Integrated model and its computer interface, supported the interdisciplinary modeling during this phase.

However, in achieving both aims of the project in the final phase, namely the PhD degree in medicine and the Integrated model with its computer interface, the Simulator, the researchers lost their "shared object" of sustaining their longstanding collaboration. They gathered for a brainstorming session in order to reformulate and renew their research object, to come up with new research problems, and to reprogram the Simulator for new applications. They did not, as a research group, find any opportunities to renew their research object. Moreover, due to the lack of project funding, their commitments to other organizations and research

20. Efficient personal computers modified into Linux cluster computers to widen computational capacity relative to supercomputers at a low cost.

projects appeared to be more appealing than the struggle to work for a new shared research object, and they decided to bring the INFEMAT project to a close.

7 Conclusions: a long way to object-oriented interdisciplinarity

Interdisciplinary research, whether seen as evolving through the rhetoric of science or in terms of its organization, can be properly understood in relation to its changing research object. To study this, I proposed a way of analyzing lifespan models in relation to emerging and changing interdisciplinarity in the making. By analyzing the elements of a set of Hib-related models it was possible to explore the changes in modeling collaboration in terms of the emergence of object-oriented interdisciplinarity. In the following, I will recap the findings and discuss them.

As shown in the findings, the development of the first model, the Good-night kiss, required new forms of collaboration within which the accumulated professional expertise of the senior researchers could have been transmitted to the young researchers. The constellation of the project in the beginning, described in terms of multidisciplinarity, reflected the difficulty of defining and starting to work on a shared research object. On the basis of their accumulated, professional expertise, the senior members managed to formulate a shared research problem, which resulted in the construction of GNKM. The GNKM functioned to overcome the difficulties and resulted in the emergence of object-oriented interdisciplinarity.

In the second phase, the goal of developing a single model dispersed into research on modeling methods. This lead to the construction of a family or set of models by applying different modeling techniques to describe, explain and predict the different characteristics of the phenomena. During this phase, the somewhat 'invisible' acquaintance with the novelties of modeling resulted in lonely, concentrated working practices. The researchers had to decide how to develop the modeling method, and the resulting tensional dispute weakened efforts to redefine a joint problem. The tensions and disputes—within which the choices and decisions concerning modeling methods were made—were incorporated into the development of the elements, which thus functioned as carriers of interdisciplinarity in the modeling. I have argued that the emerging interdisciplinarity, resulting in success in terms of building the Good-night-kiss model, reverted to multidisciplinary coordination due to the lack of a clearly defined shared object. This change is significant as it strengthens the observation that there is no linear development between the different forms of disciplinarity (cf. Thompson Klein 1990).

The third phase, which was the final INFEMAT-funded phase,[21] was characterized by joint, dyadic modeling work. The researchers started to move towards new applications in order to attract further funding, and the previous jointly-formed expertise, which was built upon the "common ground," started to develop into a new dyadic form. The dyad comprising the PhD researcher in epidemiology and the post-doc researcher in mathematics described their working practices in terms of 'family-likeness' and playfulness. This meant that they were able to work confidently with each other, and from time to time to share personal 'ups-and-downs' of their lives. Playfulness refers to their way of working with the models: they 'played' with them as they constructed possible worlds and tested their hypotheses in those 'model worlds'. This strengthened their mutual reliance on each other's expertise within the dyad.

In the final phase, the core collaboration relied on the two dyads, the mathematician and one infectious-disease specialist, and of the other infectious-disease specialist and the computer scientist, who were a married couple. The project goal was expanded during this phase: the idea of programming a Simulator to predict and model various pathogens was highlighted. The pace of the modeling practice increased in order to facilitate the completion of the dissertation in epidemiology. Moreover, the modeling methods and expertise gained in the project met with novel challenges: a new, global epidemic required urgent attention from the national public-health authorities, and the modelers tried to find answers to questions concerning the transmission and spread of this contagious virus.[22]

The dyadic expertise was strengthened during this phase. Even though the Integrated model was constructed in the joint meetings of the research group, the dyad of the medical PhD student from KTL and the statistician from RNI and KTL, gained international recognition through their work. The transition from the emerging object-oriented interdisciplinarity acquired during the project to *dyadic interdisciplinary expertise* was an invisible process. They told me that they thought they would learn more about modeling methods and the uses of models in medical research by participating in an international conference, but when they were there they noticed that many researchers referred to their work and publications, and acknowledged them as "the Finnish modelers."

However, once the Integrated model and its computer interface were in place and the practical goal of the PhD in medicine had been achieved, the collaboration ceased to exist in the same form as it had been in the INFEMAT project. There were efforts to continue, but they did not appear to be fruitful. On the administrative level in KTL, the modeling of

21. Funded by the original project.
22. The 2002 SARS epidemic.

infectious diseases had turned into the "tool" they had aimed at in the beginning of the project. But what was this tool? The analysis shows that the dyadic collaboration, especially that of the junior epidemiologist Tuija and the mathematician Kari with their new know-how and modeling skills, was an essential part of it. The long methodological stabilization process supported this dyadic collaboration. The pair had already started to work in European networks in order to further the development of their modeling studies. When the INFEMAT collaboration came to an end, they continued applying and studying further the usage and applicability of the novel methods. If we think of models as investigative instruments, or autonomous agents, as mentioned earlier, the importance of expertise diminishes. It was the complementarity of the dyads that played a major role in the formation of object-oriented interdisciplinarity. The Integrated model with its Simulator would not function at this stage as an independent modeling tool without the long-standing process of learning to model, learning to stand outside of disciplinary conceptualizations.

By novel, interdisciplinary expertise, I mean the smooth, even playful,[23] close, almost family-like[24] collaboration that led to high-class expertise in modeling. The object-oriented interdisciplinarity, as emphasized by the researchers, was supported by the complementarity of the dyad, and this strengthened and broadened the basis of the ongoing and new modeling work, and the expert work being done by the researchers. It is reminiscent of the long, piece-by-piece constructed joint forms of work and practices that support, sustain and develop interdisciplinary collaboration.

My argument is that the previous discourses have not produced a similar, detailed analysis of interdisciplinarity 'in the making'. The advantage of analyzing models and their functioning in science combined with the micro-level study of interdisciplinary modeling has been in opening up a novel perspective on one of the most challenging, current research phenomena. Understood as a complex, dynamic relation between expertise, collaboration and the research object, interdisciplinary research work appears to be fertile ground for scientific discovery.

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23. The researchers said of their dyadic work: "We were able to play with the models."

24. The closeness of the researchers was clear in the meetings, their problems in private life were shared, and others were sympathetic to changes in the schedule.

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