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Transfer and templates in scientific modelling

Wybo Houkes^a and Sjoerd D. Zwart^{a,b}

^a Philosophy & Ethics, Eindhoven University of Technology

^b Philosophy, Delft University of Technology

To contact the authors, please write to: Philosophy & Ethics, School of Innovation Sciences, Eindhoven University of Technology, Den Dolech 2, NL-5600 MB, Eindhoven, The Netherlands; e-mail: w.n.houkes@tue.nl; s.d.zwart@tudelft.nl.

Keywords

Scientific modelling; template; knowledge transfer; technology diffusion; Lotka-Volterra equations; computational model

Abstract

The notion of template has been advocated by Paul Humphreys and others as an illuminating unit of analysis in the philosophy of scientific modelling. Templates are supposed to have the dual functions of representing target systems and of facilitating quantitative manipulation. A resulting worry is that wide-ranging cross-disciplinary use of templates might compromise their representational function and reduce them to mere formalisms. In this paper, we argue that templates are valuable units of analysis in reconstructing cross-disciplinary modelling. Central to our discussion are the ways in which Lotka-Volterra models are used to analyse processes of technology diffusion. We illuminate both the similarities and differences between contributions to this case of cross-disciplinary modelling by reconstructing them as transfer of a template, without reducing the template to a mere formalism or a computational model. This requires differentiating the interpretation of templates from that of the models based on them. This differentiation allows us to claim that the LV models of technology diffusion that we review are the result of template transfer – conformist in some contributions, creative in others.

1. Introduction

An intriguing feature of the process of scientific modelling is that some of its products may be applied across scientific disciplines. Harmonic-oscillator models, for instance, are seemingly applied wherever there is scientific work to be done. Still, not all models are migratory. The Nambu-Jona-Lasinio model, for instance, hardly sees any application outside of quantum field theory. The evaluation of modelling efforts in different contexts of application warrants further analysis – which minimally requires a clear identification of what is transferred between such contexts.

Recently, *templates* have been proposed as an illuminating or appropriate unit for analysing modelling practices (Humphreys 2002, 2004; Knuuttila 2009, 2011; Knuuttila and Loettgers 2012, 2016). Examples of templates include sets of differential equations, such as the Lotka-Volterra equations, and modelling methods, such as agent-based modelling, that can be applied across disciplines. At first glance, templates are therefore plausible candidates for what is transferred in practices of cross-disciplinary modelling;¹ and providing insight into such practices seems one, natural way for template-centred analyses to prove their merits. However, there is a tension in (applications of) the notion of template with regard to one of the central philosophical issues about models, namely that concerning representational content. This tension is directly related to the dual functions of templates that is signalled by Humphreys (2004, p.95) and discussed in more detail in Section 2. On the one hand, templates are used to represent specific target systems, such as diatomic gases or insect swarms, and on the other hand, they should facilitate quantitative manipulation. The worry is that wide-ranging computational performance might compromise the representational function of templates by reducing them effectively to computation-enabling formal structures. Thus, illuminating cross-disciplinary modelling practices

as transfer of templates might have the side-effect of making unclear how templates can fulfill all of their envisaged functions.

In this paper, we show that there is added value in reconstructing cross-disciplinary modelling as transfer of a template rather than as use of different computational models that share a computational form; but that such a reconstruction involves suitably developing the notion of a template. Central to our argument is the analysis of the application of the Lotka-Volterra equations to processes of technology diffusion. In Section 3, we review pioneering and more recent papers in this case of cross-disciplinary modelling, and we present a selection of shared features as well as differences between these modelling efforts. In Section 4, we restructure and extend Humphreys' (2004) conceptualizations of templates. In particular, we show how the interpretation of templates is different from that of the models based on them. This differentiation allows us to distinguish different forms of transfer, which we call 'conformist' and 'creative'. In Section 5, we go on to show that our case of cross-disciplinary modelling can be analysed as involving template transfer; that such an analysis illuminates similarities and differences between the reviewed contributions; and that both conformist and creative transfer are exemplified in our case study. Section 6 concludes and identifies some limitations of our reconstruction and ways of developing it.

2. The multi-functionality of templates

Templates were proposed by Paul Humphreys (2002, 2004) and advocated by others (e.g., Knuuttila 2009, 2011; Knuuttila and Loettgers 2012, 2016) as valuable units of analysis in the philosophy of science, partly to emphasize the importance to science of broadly applicable computational techniques and the "outcome-orientedness" of

scientific modelling. On the basis of a range of examples, including the heat/diffusion equation and normal distributions, Humphreys argues that some items constructed by scientists see widespread use primarily because of their computational tractability. These templates are often sets of differential equations “together with the appropriate boundary or initial conditions types” (p.102/3),² on which more application-specific computational models are based. Templates, however, are claimed to have at least a dual functionality: they serve both to facilitate computation and to represent target systems (p.95). In the terminology introduced by Michael Weisberg (2007), templates should allow scientists to combine representational fidelity – faithful rendition of target systems – with dynamical fidelity – accurate, numerical descriptions of the behaviour of the target systems. Simultaneously, templates such as fitness landscapes and Poisson processes need to be distinguished from the models based on them: models are “too specific to serve in the roles played by templates” (p.58), and are frequently based on templates that were originally constructed in other contexts of application.

Given the transfer of, for instance, fitness landscapes from evolutionary biology to a broad variety of social sciences (as reviewed in Gerrits and Marks 2015), the distinction between application-specific models and more flexible or ‘portable’ templates is intuitively appealing. Yet it is difficult to see how templates can be distinguished from models on the one hand and purely formal objects on the other, so that they are genuinely different units of analysis; and how they realize the dual functions of facilitating computation *and* representing the world while being transferred between contexts of application.

To bring out this difficulty, we consider in more detail how Humphreys describes the representational role of templates and the computational models based

on them.³ Notably, unlike Humphreys, we do not distinguish between theoretical and computational templates in our discussion, in light of the argument of Knuuttila and Loettgers (2012, Section 3). Our term ‘template’ refers indiscriminately to both.

Humphreys argues that the template, on which computational models are based, is accompanied by a set of construction assumptions, which are made with respect to a specific context of application on the basis of subject-specific knowledge. These assumptions provide the template with an intended interpretation and an initial justification. The construction assumptions are accompanied by an ontology: a set of objects, properties and relations “represented” (p.78) or “used” (p.79) in the template. Other construction assumptions are idealizations, approximations, abstractions and constraints, which may enable computational tractability. Furthermore, templates come with a correction set, which anticipates on the need for adjustment by specifying ways in which elements of the construction assumptions may be modified or relaxed, primarily to improve dynamical fidelity. Like the construction assumptions, the correction set connects the template – at least initially – to a particular application area or set of target systems.⁴

That a template has such components as construction assumptions and correction sets distinguish it from “a mere piece of formalism” (p.80) and underlines its representational function; but also blurs the distinction with the models based on it: these models are said to also have construction assumptions and correction sets as constitutive elements – in addition to “syntactic objects” such as differential equations that provide the basic computational form of the model (p.103). If templates are not identical to such syntactic objects, they become difficult to tell apart from models.

The transfer of templates in cross-disciplinary modelling accentuates the problems regarding their representational role. In using templates or computational

models that were constructed in one disciplinary context – which we shall call the ‘source’ context – in another, ‘recipient’ context, scientists need not be guided by commitments to strong similarities between the ontologies of target systems. Rather, cross-disciplinary applications may involve a *change* of ontology (p.79) and templates may be applied to systems or phenomena that, in the extreme, “seem to have nothing in common ‘physically’” (Humphreys 2002: S4). This suggests that, even if a template realizes its dual functions in the source context, the realization of its computational function after transfer might interfere with its representative function in the recipient context. More specifically, it raises the question to what extent cross-disciplinary modelling efforts can be usefully analysed as applications of one template that grounds different application-specific computational models, where both template and models are partly characterized in terms of an intended interpretation. Templates, in other words, appear to be conceptual hybrids, combining functions that are also – and perhaps better – served by other items. Highlighting their representational function might make them indistinguishable from models, which makes it difficult to claim that one object is applied in different contexts; whereas describing the computational function of a single template as enabling dynamical fidelity in different contexts may make it difficult to maintain that this single template is more than a mere formalism.

Given these difficulties, one might have doubts whether templates are indeed useful units of analysis, i.e., whether there is added value in reconstructing cross-disciplinary modelling as transfer of a template rather than as, say, use of different computational models that share a computational form characterized by a set of differential equations. Through analysing a case of cross-disciplinary modelling, outlined in the next section, as transfer of a template, we aim to dispel these doubts.

3. Case study: modelling technology diffusion with Lotka-Volterra equations.

In this section, we review one case of cross-disciplinary modelling, namely the application of Lotka-Volterra (LV) equations to processes of technology diffusion. After a necessarily brief introduction of the LV equations, our review first outlines the background and main motivation for modelling technology diffusion with the LV equations; then we present the main similarities and differences between the earlier pioneering work; and finally we identify some additional features that come to light in recent applications.

The LV equations, independently formulated by Alfred Lotka in 1910 and Vito Volterra in 1925, are coupled non-linear differential equations. The general form of these equations is:

$$\frac{dx_i}{dt} = x_i \left(b_i + \sum_{j=1}^m a_{ij} x_j \right), \quad i = 1, 2, \dots, m$$

The LV equations play a recurring role in the philosophical literature, to illustrate a broad variety of features of, and positions concerning, scientific modelling. Humphreys (2004, p.63), for instance took them as illustration of a theoretical rather than computational template, given their general analytical intractability and cross-disciplinary use. Knuuttila and Loettgers used them to demonstrate the dynamics of the distinction between theoretical and computational templates, given their enhanced (computational) tractability since the 1970s (2012, Section 3). Weisberg (2007) analysed Volterra's and d'Ancona's use of the LV equations in terms of a three-stage (construction-analysis-coordination) procedure that distinguishes scientific modelling

from other forms of scientific reasoning. Scholl and Rz (2013) rather reconstruct Volterra’s use as an incomplete trajectory from how-possibly to how-actually explanations. Knuuttila and Loettgers also have contrasted Volterra’s construction with Lotka’s to bring out the partial fit of modelling to the three-stage procedure and the modellers’ outcome-orientedness (2012, 2016). Furthermore, Weisberg and Reisman (2008) take Volterra’s work to show the role of robustness analysis, whereas others draw on LV equations transfer to another domain of application to show the context-dependence of robustness analysis (Houkes and Vaesen 2012).

Our goal is not to explicate or resolve the apparent tensions between these discussions. Rather, we note that they have focussed mostly on the construction of the LV equations and their context of application in population biology, in “the most common models for the dynamics of population numbers in ecosystems” (Hofbauer and Sigmund 1998: xxv). Discussions in the philosophy of modelling have led to significant insight into these contexts and their complications. We only employ the uncontroversial fact that the LV equations have been used to great effect in population biology; and that, in this context, the various terms of the LV equations have a well-established interpretation: in the general form stated above, the x_i are the numbers or densities of m populations or species; the b_i are intrinsic growth or decay rates of these populations; and the ‘interaction parameters’ a_{ij} “describe the effect of the j -th upon the i -th population, which is positive if it enhances and negative if it inhibits the growth” (Hofbauer and Sigmund 1998: 42). Of specific interest to our purposes are the competitive Lotka-Volterra (LVC) equations for two populations, whose interaction parameters a_{12} and a_{21} are both negative, i.e., who negatively affect each other’s densities x_1 and x_2 .

We focus on applications of the LV equations outside this biological context, in order to analyse the role of templates in cross-disciplinary modelling. For this purpose, we review how the equations have been used to model the diffusion of technological innovations. This context of application is relatively well-established, with exploratory and theoretical papers published in the 1980s and 1990s, as well as recent more empirically oriented work. As we shall argue in Section 4, it shows how on the one hand templates rather than mere coupled differential equations are transferred between contexts of applications; and on the other hand how the shared template differs, in its interpretation, from the application-specific models based on it. One consequence of our argument is a differentiation of forms of transfer in this recipient context of application, bringing out its heterogeneity. Our review therefore highlights aspects of several seminal and recent papers, illustrated by representative quotes, instead of focusing in depth on one particular research effort.

The diffusion of technological innovations – mobile phones, ballpoint pens, corn seeds – is a complicated process, influenced by consumer preferences, advertising campaigns and government regulations, among many other factors. However, it has been widely observed that, after a technology has captured a small but significant market share, its diffusion pattern – in terms of market share or cumulative number of adopters – follows a sigmoid curve: after rapid initial diffusion, a period of slower diffusion follows until the market is saturated, market share stabilizes or starts to decrease, and there are no new adopters (see, e.g., Mahajan and Peterson 1985; Rogers 2003, Chs 6 and 7). Accurately predicting this diffusion pattern on the basis of past performance is of obvious commercial interest: it might allow early identification of market failures, established products, and products that have exhausted their market

potential. Many broadly used models for such ‘technology forecasting’, such as that of Fisher and Pry (1971), are phenomenological, i.e., they fit a sigmoid curve to relevant data without deriving the expression explicitly from theories about underlying mechanisms. The considerable predictive success of these models has led to different lines of further research: one in which existing phenomenological models are hybridized to improve predictive power,⁵ another in which models are constructed on the basis of conjectures about underlying mechanisms. One such attempt follows a suggestion by Fisher and Pry that the diffusion of innovations can be understood as, primarily, an emerging technology *competing* against an incumbent technology, or one technology *substituting* another. Other attempts, not considered here, derive expressions from assuming that obsolescence or word of mouth are the underlying mechanisms.

The transfer of LV equations to this domain fits the search for explanatory supplements to existing predictive models. Typically, the latter are criticized because “[t]he mechanism of adoption is not explicit” (Bhargava 1989: 325), but none of the papers reviewed here claims that transfer increases predictive power over the best forecasting models. Instead, the merits of the LV models are presented as involving “clearly defined assumptions about the nature of technological growth” (Porter et al. 1991: 197) or “capable of providing a good understanding of the root mechanisms of technology advancement” (Farrell 1993: 177). This explanatory aim, often phrased in terms of mechanisms, is the first similarity between the papers included in the review.

A second similarity is the narrative used to motivate or frame the transfer of the LV – or often, more specifically, the LVC – equations (Bhargava 1989: 319-320; Farrell 1993: 64-68; Modis 1997: 109; Pistorius and Utterback 1997: Appendix). This narrative is often presented right after indicating the shortcomings of the

phenomenological models, and immediately before stating the equations in their standardized form. It starts by likening the diffusion of a single technology to a process of growth up to a maximum carrying capacity, governed by the sigmoid Pearl-Verhulst curve.⁶ Then, it notes that a better understanding of the diffusion process is obtained by considering how growth may be affected by other technologies, like the growth of a biological population is affected by that of other species. Finally, it is stated that in ecology, the effects of these mutual interactions are represented by the LV equations, which may therefore be transferred to the context of technology diffusion. In this way, the solutions of the LV equations are implicitly, and sometimes explicitly, taken to be ‘generalized Pearl-Verhulst curves’ and the parameters and variables in the equations are interpreted in terms of “technological populations”, “growth rates”, and perhaps most colourfully “the number of units of the competing technology that is inhibited from existing by the existence of one unit of technology i ” (Morris and Pratt 2003: 105). This same paper contains a telling, brief example of the guiding narrative, worth quoting in full:

“Forecasting technological substitution requires a model that generates intuitive understanding of the factors affecting substitution, but that also has good predictive ability. Many ... models exist ..., that, although often quite effective, model only the invading competitor whose population is increasing, and ignore the declining competitor, thus failing to model the fundamental process driving substitution. The Lotka-Volterra competition (LVC) equations, a set of coupled logistic differential equations, model the interaction of biological species competing for the same resources and can also model parasitic and symbiotic relations. The LVC equations model both the emerging

and declining competitors, allowing intuitive understanding of the factors driving substitution.” (Morris and Pratt 2003: 103)

A third and final feature is that many papers do not explicitly discuss the tractability of the LV equations. The absence of closed-form solutions and availability of numerical solutions is noted in the paper that was just quoted; the others show at best tacit appreciation of tractability concerns. Still – moving gradually from similarities to differences between the reviewed papers – most of the explorative papers do use the LV equations for purposes in which tractability matters. Farrell (1993) uses specific closed-form solutions, themselves transferred from a textbook on mathematical ecology, to derive interaction parameters for specific historical datasets. Modis (1997) and Pistorius and Utterback (1997) identify different “modes” of interaction between technologies, using ecological terminology (predator-prey, symbiosis, etc.), on the basis of the values of the interaction parameters a_{ij} – albeit without giving guidelines for estimating these parameters. Another characteristic application is a comparison of one or more phenomenological models with the LV equations – leading to claims that the former are “special cases” of the latter (Bhargava 1989: 325), or that the latter “reasonably mimic” the former without achieving “arbitrarily close fit” (Morris and Pratt 2003: 103; 132).

The most salient difference between the papers lies in how far, in terms of presentation of the model and results derived from it, they stray from the population-biological context of application. We discuss two in which the divergence is most striking.

One innovative application involves studying the effects of a sudden *change* in the mode of interaction (Modis 1997: 113-117). This deliberately takes studies of the

behaviour of the equations into less familiar territory – one in which rabbits and foxes could switch to symbiosis overnight.⁷ The ground for this shift in studied behaviour is prepared by explaining the various terms in the LV equations as measuring “the ability to attack, counterattack, or retreat” (Modis 1997: 109), followed by qualitative, generic descriptions of “business *strategy and tactics* of attack and counterattack” such as “[u]nder attack, the defender redoubles its own efforts to maintain or improve its position” (ibid.: 110; emphasis added). After this, advertising strategies are explicitly coupled to the interaction parameters in the LV equations – and we find striking but relatively well-contextualized phrases such as “independent *advertising* messages according to the *biological* model” (ibid.: 114; emphasis added).

Another innovative application is found in Saviotti and Mani (1995). The paper starts by noting the utility of biological analogies for understanding technology. Yet instead of the logistic/inhibited-growth narrative used in the other explorative papers, it frames the LV equations as an alternative to another, more complicated set of equations (ibid, Section 3). These are meant to capture the microeconomic mechanisms behind technology substitution: a set of three equations with an elaborate, detailed interpretation in terms of obsolescence, learning-by-doing, purchase of intellectual property rights and other factors that have no obvious counterpart in ecology. The behaviour of these equations is not studied, apart from a qualitative reconstruction of various modes of competition (perfect, monopolistic, Schumpeterian and inter- and intra-technological), familiar from the economic literature. Subsequently, the LV equations are introduced, as an “aggregate representation” or “macro-model” (ibid, Section 4.1) of technological change, with reference to their similar status for ecological change. After some manipulations, counterparts of the microeconomic model are sought – especially of the parameters

corresponding to the distinction between inter- and intra-technological competition; and the behaviour of the manipulated (difference) equations is simulated to derive a relation between technological variety and the relative strength of modes of competition, along with the conditions under which the relation holds.

In closing, we highlight some relevant features from two recent applications of the LV equations to a specific process of technology diffusion: the shift from fixed-line voice communication to mobile telephony, in South Korea (Kim, Lee and Ahn 2006), and the Czech and Slovak Republics (Baláz and Williams 2012). Firstly, both applications present the LV equations through heavy use of ecological terminology such as “species”, “growth”, “reproduction” and “mortality”. Secondly, they adopt an explicit identification of the mode of interaction between fixed-line and mobile-phone technologies, framed in ecological terms: the technologies are predators competing for the same prey, namely consumers. Thirdly, both papers notice the difficulties in assigning values to virtually all parameters in the LV equations: the reproduction rates or ‘logistic’ parameters, carrying capacities, interaction parameters, and – for one paper – the mortality rates. One paper presents estimates of the various parameters based on the dataset, notes that no statistically significant value can be obtained for one interaction parameter, and concludes that “it is reasonable to assume” that its value is zero (Kim, Lee and Ahn 2006: 180). The other interestingly uses mortality rates of human consumers as a “meaningful” approximation of the mortality rate of technologies (Baláz and Williams 2012: 395), notes that unlike for biological systems, no “direct observations and/or laboratory experiments” (ibid: 401) can be used for data collection, and then uses substantial background knowledge concerning the communication market and consumers to assign values to the reproduction rates and interaction coefficients. In both papers, the asymmetry in interaction parameters –

roughly: mobile phones strongly inhibit the growth of fixed-line phones, whereas the latter have a weak or no inhibiting effect on the former – is presented as the main result.

4. Cross-disciplinary modelling as transfer of templates.

To apply the notion of template to the case study, we first restructure and extend Humphreys' (2004) conceptualizations. We limit our reconstruction to templates that consist of differential equations together with boundary or initial conditions.⁸ To distinguish such syntactic objects from mere pieces of formalism, and avoid what Humphreys calls the *detachable interpretation view* (2004, p.80), we claim that some terms of such syntactic objects have an intended intensional interpretation. For instance, the typical interpretation of the LV template, t refers to time. Moreover, the elements of each x_i -set are taken to mutually “inhibit” or “enhance” each other’s “growth” in a sense that leaves open the precise mechanism at work and objects involved (e.g., predation among fish species, depletion of molecules in autocatalysis, free-market competition between technologies), while typically still describing some of these mechanisms in generic terms (e.g., mutualism, predation, competition). In this sense, the LV-template is characterized by a ‘thin’ intensional interpretation of a set of coupled differential equations; we take this to be part of the construction assumptions of a template as described by Humphreys (2004). We will refer to this intensional interpretation of a template T by In^T .

To explain how (different) models may be developed on the basis of a (shared) template, and how the interpretations of these items are related, we draw on Contessa's (2007; 2011) interpretational conception of epistemic representation. On Contessa's conception, a user adopts a so-called “analytic interpretation” of a model

M in terms of a target system S by identifying a nonempty set Δ^M of relevant items (objects, properties, relations and functions) in the model and a set Δ^S of relevant items in the target system; and by maintaining that every item in Δ^M denotes one and only one item in Δ^S , and that every item in Δ^S is denoted by one and only one item in Δ^M .⁹ We call Δ^M the ‘denoting’ set and Δ^S the ‘denoted’ set.

To analyse cross-disciplinary transfer, we distinguish the template T from models Ma and Mb that are based on T ; and we distinguish two target systems, Sa and Sb , studied by (communities of) users Ua and Ub who work in separate disciplinary contexts. The users adopt analytic interpretations of their models: Ua interpret Δ^{Ma} in terms of Δ^{Sa} ; and users Ub interpret Δ^{Mb} in terms of Δ^{Sb} , where in principle the denoting sets may be different. Moreover, both Ua and Ub adopt an intensional interpretation of template T ,¹⁰ which is possibly but not necessarily the same. Furthermore, we assume that users Ub know that models Ma , based on T , have been used successfully by users Ua in their context of application, so that the latter is plausibly labelled as the ‘source’ context, and that of Ub as the ‘recipient’ context – without thereby claiming that Ua are similarly aware of the efforts of Ub . Here, we follow Knuuttila and Loettgers’ (2016) emphasis on the outcome-orientedness of modelling efforts.¹¹

On this reconstruction, a template has an intensional interpretation In^T that may be shared across contexts of application. Yet in both contexts the template is developed into different ‘vehicles of representation’, among other things by adding different analytic interpretations.¹² Users Ub should adopt an analytic interpretation in terms of their target system of interest Sb ; they cannot, given the differences in target system, adopt the analytic interpretation adopted by Ua in terms of system Sa . Yet they can transfer template T that users Ua developed into Ma and analytically

interpreted in terms of Sa . This involves more than using the same differential equations; Ub retains at least a part of the intensional interpretation In^T adopted by Ua in the source context. If so, their modelling efforts involve transferring a template. In such transfer, Ub need to develop T into a model Mb , minimally by identifying a denoting set Δ^{Mb} and denoted set Δ^{Sb} .

This reconstruction of cross-disciplinary modelling does not require that template T is itself an epistemic representation of Sa for Ua or of Sb for Ub . Rather, in template transfer, In^T must play a role in adopting the analytic interpretation of Mb based on T , e.g., in identifying elements of the denoted set. The analysis of the case study below will allow us to clarify this requirement.

By distinguishing the intensional interpretation of a template from the analytic interpretation of computational models based on the template, we can distinguish cases of template transfer in cross-disciplinary modelling from mere use of the same formalism. Closer attention to the use of vehicles of representation in cross-disciplinary modelling allows us, in addition, to distinguish various forms of template transfer – and we take this distinction as at least one way in which templates have added value as units of analysis in the philosophy of scientific modelling.

In general, as stated above, analytic interpretations in different contexts by different users will concern different denoting sets.¹³ Now models, in virtue of being epistemic representations, allow users to perform specific inferences from the model to the target system. Such ‘surrogate reasoning’ (Swoyer 1991; Contessa 2007) involves inferences from elements of the denoting set Δ^M to elements of the denoted set Δ^S ; in slightly different terms, from behaviour of the model to behaviour of the target system.¹⁴

In some cases of cross-disciplinary modelling, users Ub might focus on behaviour B_{Sb} of their target system of interest that is highly similar to behaviour B_{Sa} that was successfully modelled by Ua . In this case, in their analytic interpretation of Mb , users Ub may deliberately – or at least effectively – maximize the overlap between Δ^{Ma} and Δ^{Mb} . We call such forms of transfer ‘conformist transfer’. In conformist transfer, it is *as if* a computational model is transferred rather than a template.

Conformist transfer allows – indeed might be arranged by modellers so as to allow – what one might call ‘surrogate reasoning by analogy’. Here, behaviour B_{Sb} of a system Sb is inferred from behaviour B_{Ma} of a model Ma , where models Ma and Mb share a template T ; and Δ^{Ma} is taken to display sufficient overlap¹⁵ with denoting set Δ^{Mb} of model Mb . Thus, in a hypothetical case of cross-disciplinary modelling, modellers might seek to explain a power-law distribution in individual wealth by transferring a percolation template that has been developed by other modellers into a model that explains a power-law distribution of outgoing hyperlinks on the World-Wide Web – by identifying in their model’s denoting set Δ^{Mb} the counterparts of elements in the latter model’s denoting set Δ^{Ma} .

In other forms of cross-disciplinary modelling, which can still be reconstructed as template transfer, users Ub deliberately diverge from the analytic interpretation of Ma in adopting an analytic interpretation of their model Mb , so that the latter model may serve their own purposes. In such ‘creative’ transfer,¹⁶ they might explicitly acknowledge that there are mismatches between the denoting sets Δ^{Ma} and Δ^{Mb} given underlying differences in target systems or differences in epistemic purposes. Yet they may retain elements of the intensional interpretation of the template T on which both Ma and Mb are based.

Creative transfer does not support surrogate reasoning by analogy; but in many cases of cross-disciplinary modelling, modellers might describe, explain or calculate system dynamics by focusing on behaviour of their own model that is *unfamiliar* or *irrelevant* in the source context, i.e., behaviour that the model developed from the template in the source context was never shown to exhibit. In many cases, this might involve a different way of developing the model on the basis of the template, e.g., through different additional idealizations and approximations. In other cases, creative transfer could involve modifications of the differential equations that constitute the template, e.g., through adding extra terms. Even here, there may still be similarities in the intensional interpretations of the template in both contexts of application – so that the case is still plausibly analysed as transfer of the template.

5. Template transfer in models of technology diffusion

We now turn to an analysis of the case study presented in Section 3. Our central claim is that the LV models of technology diffusion that we review are the result of the transfer of a template – conformist in some contributions, creative in others. In all cases, the template retains its intensional interpretation, which refers to populations of competing or otherwise interacting entities. Still, developing a technology-diffusion model on the basis of the template requires a new analytic interpretation, in terms of competing technologies or firms within a specific market segment. Our analysis focuses on the similarities and differences identified earlier.

A first similarity is the use of LV models for explanatory purposes. This mainly serves to contrast these models with available phenomenological models, used for forecasting market shares and sales volumes. This aligns the aim with the similarly

explanatory aim of LV modelling practices in population biology, and also prepares the ground for the motivational narrative.

This narrative is a second similarity. It frames the use of the LV equations as modelling species whose growth rates are affected by their mutual interactions, in contrast to the uninhibited or intrinsic growth modelled by the Pearl-Verhulst equation. This is most often tied to the fundamental, generic mechanism of competition that is supposed to drive technology diffusion, as in the contrastive description quoted earlier: where other models “model only the invading competitor whose population is increasing, and ignore the declining competitor”, the LV equations “model both the emerging and declining competitors, allowing intuitive understanding of the factors driving substitution” (Morris and Pratt 2003: 103). This narrative thus does more than motivate the application of a set of coupled differential equations: it presents what it takes as the typical interpretation of parameters and variables in the source context, in terms of “populations”, “intrinsic/inhibited growth rates”, “competition” and so forth; and it does so to show which fundamental process is captured by the (interpreted) equations. Its typical narrative structure, which frames the LV equations as modified logistic or Pearl-Verhulst curves, even follows that in textbooks on the source (i.e., population-biological) context of application; it reflects, for instance, the order of presentation by Hofbauer and Sigmund (1998), who devotes a chapter to the logistic equation before chapters on various forms (predator-prey, two-species competition, and general multi-species) of the LV equations. On our account, this amounts to retaining the intensional interpretation In^{LV} of the LV equations. This allows reconstructing the case as transfer of the *LV-template* rather than application, in a new context, of the *LV equations*.

The lack of explicit concern for tractability, which is shared by several papers that we reviewed, is partly connected to the first two features. Sometimes, transfer of the LV template is only presented as serving the purpose of understanding or explaining processes for which dynamically faithful phenomenological models are already available. In this context, tractability need not to be the prime motivation for transferring a template: irrespective of tractability, the interpreted equations provide some intuitive understanding of a fundamental process, i.e., they are supposed to have some representational fidelity – for instance in a mapping of the signs of the interaction parameters to mechanisms such as pure competition and mutualism (Modis 1997: 111). Still, most contributions derive from the LV template some conclusions regarding technology diffusion, i.e., they engage in surrogate reasoning. Yet these conclusions often amount to derivation of logistic growth models as a special case (Bhargava 1988) or approximate fitting to historical datasets that show a “typical bell-shaped growth and demise” (Farrell 1993: 172). These conclusions are based on behaviour of the equations that is familiar from the source context. The identification of qualitative modes of interaction, for instance, is a result that is itself directly transferred from population biology. The reversion of the LV equations to various phenomenological models is not, but closely resembles the familiar result of deriving the Pearl-Verhulst curve as a special case. In at least one case, the conformism of the transfer is further emphasised by aligning the notation with ‘textbook’ biology, and asserting that “[t]he mathematics of Lotka Volterra is dealt with” in this textbook (Farrell 1993: 169; referring to Pielou 1969). Understandably, tractability is not a major concern if the central result of cross-disciplinary modelling is to infer behaviour B_{sb} that is roughly similar to behaviour B_{sa} familiar from another context of application.

Yet concluding that actual cases of technology diffusion show this behaviour requires developing an LV model for the diffusion context that is sufficiently similar to that for the source context. The recent application-oriented papers give more insight into how, in conformist transfer, the intensional interpretation In^{LV} of the template and the analytic interpretation of population-biological models Ma guide development of the LV model Mb . In both papers, attempts are made to estimate values for all parameters in the LV equations, where reading these parameters as, for instance, “reproduction rate” or “mortality rate” directly impacts the type of data that are considered as suitable. In one case, the desire to develop the model in parallel to the trajectory that would be followed in population biology leads to the claim that, unfortunately, no “direct observation and/or laboratory experiments” can be used (Baláz and Williams 2012: 401) – although it is not clear which experiments could even be meaningfully performed for the voice-communication technology that is the central topic of the paper. Similarly, the interpretation of the template here leads to a search for a “meaningful” approximation of the mortality rate of technologies. That this is found in the mortality of human consumers – which background knowledge concerning this context of application would not suggest as a reliable proxy – shows how developing a model may, in conformist transfer, be driven by a perceived need by users Ub in the recipient context to emulate both the intensional interpretation of their chosen template and the analytic interpretation of a model Ma developed in the source context. The conformity of the interpretation appears to play a more important role in such cases of cross-disciplinary modelling than the tractability of the template – to put it roughly: conformity ensures tractability with regard to the relevant behaviour.

This already in part addresses the central difference identified. Some papers apply the LV equations to emulate familiar behaviour – which may still be of significant interest in the recipient context. Other papers involve more creative transfer: although they may still be analysed as applying the LV template (rather than merely the equations), they develop models in order to study behaviour that is less familiar. We discuss the two examples that were reviewed in Section 3, which are distinct in their creative application.

Modis (1997) initially presents the LV equations in close conformity to their typical interpretation in population biology, including the identification of various modes of ecological interaction based on the signs of parameters. Unlike in other papers (e.g., Pistorius and Utterback 1997), this similarity of interpretations In^{LV} is not in itself taken as a significant result for the technology-diffusion context. Rather, it is noted that the processes that feature in In^{LV} , such as competition for scarce resources, involve *strategic* interactions in the context of technology management. Without (initially) modifying the LV equations, the interaction parameters a_{ij} are re-interpreted in such terms as “attacker’s advantage” rather than inter-species competition – where the former arguably refers to the level of individuals rather than populations. This shift in In^{LV} may still be compatible with ‘folk biology’, given the widespread use of teleological and strategic terms in biological modelling practices. In the present case, however, it leads to modelling processes in which the mode of strategic interaction undergoes a sudden change, in the form of advertising campaigns that involve counterattacks (“Their products are not good”) or defences (“You need our products”). The computational model Mb developed by Modis (1997: 113-117) is supposed to represent this process: for him, it is a relevant element of the denoted set Δ^{Sb} , and the LV model should allow surrogate reasoning concerning it. Thus, the

analytic interpretation of Mb involves a denoting set Δ^{Mb} that also denotes the ‘advertising’ processes in Δ^{Sb} : Mb is developed in a markedly different way than, to our knowledge, population-biological LV models. Its behaviour B_{Mb} is, finally, taken to have some bearing on the effectiveness of advertising strategies, so that Mb is claimed to be “a guide through effective genetic manipulations of the competitive roles in the marketplace” (ibid: 118).

Saviotti and Mani (1995) transfer the LV template only after constructing an elaborate micro-economic model, and present the template explicitly as an “aggregate” that may be used in a broad variety of contexts. Consequently, their interpretation In^{LV} of the template is, even while it features standard terminology such as “growth rates” and “intra-species competition”, partly determined by the interpretation of the more elaborate model (1995: Table 1) – although, the ‘folk ontologies’ of population biology and microeconomics appear to have blended into each other for these particular users: their interpretation of the microeconomic model already features a large number of population-biological terms such as “birth”, “environmental saturation” and “fitness”. Even so, they go on to develop a specific computational model based on the “aggregate” LV template and simulate its behaviour (ibid: 383-387). This involves the introduction of new technologies following a Poisson distribution, where the rate of introduction per time unit would be extremely high by biological standards.¹⁷ Results are then interpreted using a combination of economic and biological terms, such as “fitness”, “economic development” and “diversity” (ibid, Section 4.3). In this case, it is difficult to judge whether the computational model Mb is developed differently than population-biological LV models: there is, in contrast with Modis’ model discussed above, no element of the denoted set Δ^{Sb} that clearly falls outside the scope of sets Δ^{Sa} in the

source context. Minimally, however, even if the diffusion model Mb were developed like a biological model Ma , the behaviour B_{Mb} of the diffusion model that is studied by Saviotti and Mani has no B_{Ma} counterpart that would be of interest to population biologists, given the extreme values assigned to some variables.

For the purposes of our analysis, neither the details nor the plausibility of both of these modelling efforts matter; it should be clear that, even if the LV equations are used here in subtly reinterpreted – but still recognizably biologically inspired – forms, both Modis (1997) and Saviotti and Mani (1995) study the dynamics of LV models that, in relevant ways, do not resemble the dynamics of population-biological models as studied in that context of application. Thus, this case of cross-disciplinary modelling involves creative transfer of the LV template.

6. Conclusions

Humphreys' (2004) conceptualization of computational templates and their transfer between disciplines turns out to be, when suitably reconstructed, an effective instrument to analyse actual cross-disciplinary modelling efforts. Our reconstruction in Section 4 allows a systematic distinction between templates, which we take to be set of differential equations with a 'thin' intensional interpretation, from computational models, which have an analytic interpretation and are based on templates. This accommodates, as we showed in Section 5, several shared features of papers in which the Lotka-Volterra equations are applied to understand technology diffusion, primarily their main motivational narrative and the role of tractability concerns. Simultaneously, our reconstruction leaves room for dissimilarities in terms of presentation of the model and results derived from it. We account for this by distinguishing forms of template transfer, which differ in the conformity to a source

context of application and the inferences drawn from computational models: whereas ‘conformist’ transfer allows surrogative reasoning by analogy, more creative transfer involves studying model behaviour that is unfamiliar in or irrelevant to the source context. Even in creative transfer, however, modellers retain elements of the interpretation of the template, and therefore do not take it as a merely formal structure. We do not maintain that there is a clear demarcation between conformist and creative transfer, nor do we identify a point at which transfer becomes so creative that modellers are better taken as constructing a computational model ‘from scratch’ rather than developing it on the basis of a transferred template. Moreover, our reconstruction has several self-imposed limitations: we focus on templates that consist of differential equations together with boundary or initial conditions; and a single, albeit heterogeneous case of cross-disciplinary modelling. In this case, we discern two forms of template transfer; other cases may reveal more forms, or may present specific difficulties for a reconstruction in terms of any form of template transfer. Still, through our analysis of one case of cross-disciplinary modelling, we maintain to have shown to what extent such efforts are forms of template transfer.

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¹ Throughout, we use “cross-disciplinary modelling” without expressing commitment about which items (models, templates or other) are transferred.

² References in this section are to Humphreys (2004) unless noted otherwise.

³ Humphreys (2004) describes templates and models in different places: pp.78-79 presents the main considerations on templates, whereas those on computational models are found later (pp.102-103). We focus on this text rather than other discussions of templates in the philosophy of scientific modelling, as an illustration of the tension in the notion of template. The difficulty identified in our Section 2 is not specific to Humphreys’ text, or an artefact of its disconnected descriptions of templates and models.

⁴ “The correction set is also always subject-dependent and so, despite its flexibility, is the template itself. This is in part because of the *inseparability* of the template and its interpretation, in part because of the connection between the construction of the template and the correction set.” (Humphreys 2002: S10; emphasis added)

⁵ To give one example, Meade and Islam (1998) review twenty-nine phenomenological models and show that a combination provides a better fit to data sets than each of the individual models.

⁶ The nomenclature is revealing: ‘Pearl-Verhulst’ refers to the source context of population biology.

⁷ “In contrast to the jungle, a technology, a company, or a product does not need to remain prey to another forever. The competitive roles can be radically [sic] altered with the right decisions at the right time.” (Modis 1997: 112)

⁸ This excludes from our reconstruction some objects that Humphreys describes as templates, such as fitness landscapes.

⁹ Contessa (2007: 58) specifies these identifications in further detail, and distinguishes sets of relevant objects, properties and functions in both the vehicle and the target system.

¹⁰ Our distinction between the intensional interpretation of a template and the analytic interpretation of a computational model has interesting parallels with Weisberg’s (2012; Ch.4) distinction between the folk ontology that accompanies a model and its construal.

¹¹ “... because of the outcome-orientedness of modelling, modellers use well-known and tractable representational tools and computational methods whose behaviour and outcomes they are familiar with” (Knuuttila and Loettgers 2016: 23). As shall become clear, our reconstruction does not presuppose that modellers in the recipient context of application use templates to achieve *the same* outcomes.

¹² Developing a template into a model might also involve additional construction assumptions (e.g., more detailed, context-specific idealizations and approximations), an “output representation” (Humphreys 2004, p.103), etc. We largely ignore this aspect of the model-template relation and focus mainly on the differences in their interpretations.

¹³ Whereas analytic interpretations involve bijections between the denoting and denoted sets in each context of application, there will generally not be a bijection between both denoted sets, because normally In^T is too weak to induce a bijection between the denoting sets.

¹⁴ This formulation is meant to encompass, among others, the inference rules defined by Contessa (2007: 66), which concern the presence of objects in model and target, relations holding between these objects, and values of functions ranging over objects. We choose the term ‘behaviour’ partly in connection to Weisberg’s (2012: 7) characterization of computational models as “potentially stand[ing] in relation to computational descriptions of the behavior of a system” and Knuuttila and Loettgers’ (2016) description of modellers “determining”, “calculating” or “reproducing” system behaviour.

¹⁵ I.e., whether, for each element in Δ^{Ma} that features in the rules used to perform the surrogative inference in the source context, there is an element in Δ^{Mb} .

¹⁶ The conformist-creative distinction employs a positive analogy between templates and technical artefacts, both of which show gradations of creativity in their (respectively epistemic and more immediately practical) use; see Houkes and Vermaas (2010, Ch.2) for a corresponding discussion of the use of artefacts.

¹⁷ A variety of models are studied, which involve either 1 or 200 incumbent species, and introduction of 25 to 1000 emerging species for 5000 time units (Saviotti and Mani 1995: Table 2).