History, Philosophy and Theory of the Life Sciences

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Life and Evolution

Latin American Essays on the History and Philosophy of Biology

Springer

Chapter 10
Laws, Models, and Theories in Biology: A Unifying Interpretation

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10.1 Introduction

Three metascientific concepts subject to philosophical analysis are law, model, and theory. Throughout the twentieth and twenty-first centuries, three general conceptions of scientific theories can be identified: the "classical (or received)" view, the "historical (or historicist)" view, and the "semantic (or model-theoretic)" view.

For the *classical view*, in its most general approach, theories should be represented as deductively or axiomatically organized sets of statements. Laws, on the other hand, are an essential component of these: they constitute the axioms by means of which they are metatheoretically represented (Carnap 1939, 1956). In the beginnings of the classical view, models were conceived as marginal phenomena of science (Carnap 1939). Subsequent authors (Braithwaite 1953; Nagel 1961) strive to incorporate the models into the framework of this classical view and recognize their importance.

Historicist philosophers of science, with their alternative notions to the classical concept of theory (*pattern of discovery* in Hanson 1958, *ideal of natural order* in Toulmin 1961, *paradigm* or *disciplinary-matrix* in Kuhn 1970, *research program* in Lakatos 1970, and *research tradition* in Laudan 1977), let shine a certain conception about the laws different from the classical one. At the same time, alternative proposals to the classical one developed, which highlight the function of models in

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L. Baravalle, L. Zaterka (eds.), *Life and Evolution*, History, Philosophy and Theory of the Life Sciences 26, https://doi.org/10.1007/978-3-030-39589-6_10

scientific practice (Achinstein 1968; Hesse 1966; Harré 1970), as well as investigating what role analogies and metaphors play in the construction of models (Black 1962; Hesse 1966) or of other components, linked to these, raised by historicist philosophers, such as exemplars (Kuhn 1970).

At the present time, the importance of models in scientific practice is being emphasized. The *semantic view*—which deals with the subject matter of models within the framework of a general conception of scientific theories—is being imposed as an alternative to the classical and historicist views of scientific theories,[1] and *model views* of science are being developed—which deal with questions of the relationship between models and experience and between models and general theories independently of a general metatheory of science (Cartwright et al. 1995; Morrison 1998, 1999; Cartwright 1999; Suárez and Cartwright 2008).

According to the semantic view of theories, concepts relative to models are much more fruitful for the philosophical analysis of theories, their nature, and function than concepts relative to statements; the nature, function, and structure of theories can be better understood when their metatheoretical characterization, analysis, or reconstruction is centered on the models that they determine and not on a particular set of axioms or linguistic resources through which they do it.[2] Therefore, the most fundamental component for the identity of a theory is a *class* (set, population, collection, family) *of models*. With the emphasis on models, one might think that not only can the term, or the concept, of "law" be disposed of[3] but also that the issue of laws should not be discussed. However, models must be identified in some way. And in the *semantic view* this is usually done through the laws or principles or equations (what they are called is the least important issue) of the theory to which they belong (thus, models would constitute the semantic or model-theoretic counterpart of such laws or principles or equations). On the other hand, for *model views*, models do not form part of theories (in some usual, encompassing sense of the term), and they are independent—"autonomous"—with respect to them. Yet, models would also be represented, or be identified, by means of principles, equations or laws, although not universally so.

The aim of this article is to present the explication of the concepts of law, model, and theory, and of their relationships, made within the framework of Sneedian or metatheoretical structuralism and of their application to a case from the realm of biology: population dynamics. The analysis carried out will make it possible to support, contrary to what some philosophers of science in general and of biology in

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[1] "Over the last four decades, the semantic view of theories has become the orthodox view on models and theories" (Frigg 2006, p. 51).

[2] This idea has been developed in different particular ways, giving rise to different approaches, variants, or versions, which despite their differences constitute a family, the *semantic family*. For a characterization of this family, and of some of its members as well as a reference to many of them, see Lorenzano (2013) and Ariza et al. (2016).

[3] For skeptical positions about any notion of law and the substitution of the term "law" by other notion, such as "(fundamental) equations" or "(basic) principles," see Cartwright (1983, 2005), Giere (1995), and van Fraassen (1989). By the way, Carnap himself had already considered the possibility of dispensing with the term "law" in physics (Carnap 1966, p. 207).

particular hold, the following claims: (a) there are "laws" in biological sciences, (b) many of the heterogeneous and different "models" of biology can be accommodated under some "theory", and (c) this is exactly what confers great unifying power to biological theories.

To begin with, the structuralist explication of the metascientific concepts of law, model, and theory and their application to population dynamics[4] will be presented successively.

Next, the relevance of the previous analysis to the issues of the existence of laws in biological sciences, the place of models in theories of biology, and the unifying power of biological theories will be stressed. Finally, the chapter will conclude with a discussion of the presented analysis.

10.2 The Concept of Law from the Point of View of Metatheoretical Structuralism[5]

In scientific as well as in philosophical literature, many authors speak not just plainly about *laws* but about *natural* laws, or laws *of nature*, on the one hand, and about *scientific* laws, or laws *of science*, on the other hand, too. Such expressions, besides, are commonly used as if the expressions belonging to one pair were interchangeable with the expressions belonging to the other pair, i.e., as if they were synonymous or had the same meaning. However, we consider it convenient to distinguish the first pair from the second one since they correspond to different approaches or perspectives (e.g., Weinert 1995). The first pair corresponds to an approach of an *ontological* kind—corresponding to how things themselves are—while the second one corresponds to an approach of an *epistemic* kind—centered in what we know.

Some philosophers have argued that a philosophical treatment of laws should be given only for the laws of nature and not for the laws of science. While others consider it more appropriate to refer to the laws of science than (only) to the laws of nature because, in any case, it is the laws of science that would provide important keys to understanding what a law of nature is.

In what follows when we speak about laws, we will be talking about *scientific* laws, or laws *of science*, and not about *natural* laws, or laws *of nature*.[6]

At least as of 1930 the problem of what a law is, i.e., the problem of finding the necessary and sufficient criteria or conditions which a statement should satisfy in order to be considered or in order to function as a law, is discussed.

According to the classical view (Hempel and Oppenheim 1948), a *law* is a true *lawlike* statement that has the following properties: it is universal with an unlimited

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[4] The analysis of population dynamics is based on Díaz and Lorenzano (2017).

[5] See Balzer et al. (1987) for a complete and technically precise presentation of this metatheory.

[6] For a more extensive discussion about the nature of laws as well as an analysis of natural laws within the framework of metatheoretical structuralism, see Forge (1986, 1999) and Lorenzano (2014–2015).

or at least unrestricted scope of application; it does not refer explicitly or implicitly to particular objects, places, or specific moments; it does not use proper names; and it only uses "purely universal in character" (Popper 1935, sects. 14–15) or "purely qualitative" predicates (Hempel and Oppenheim 1948, p. 156).

Despite successive and renewed efforts there is not a satisfactory adequate set of precise necessary and sufficient conditions as a criterion for a statement to be considered a "(scientific) law."[7]

The discussions in the field of general philosophy of science have also been held, and have taken place, in the special field of philosophical reflection on biology and its different areas such as classical genetics, population genetics, evolutionary theory, and ecology, among others.

Some authors deny the existence of laws in biology in general, and in ecology in particular. Two main arguments have been put forward against the existence of laws in biology. The first one is based on the alleged locality or non-universality of generalizations in biology (Smart 1963); the second one is based on the alleged (evolutionary) contingency of biological generalizations (Beatty 1995).

At least three responses to these arguments can be found. The first one consists in submitting them to a critical analysis. This approach is chosen by Ruse (1970), Munson (1975), and Carrier (1995), among others. The second one is to defend the existence of laws, or principles, in biology but arguing that they are non-empirical, a priori. This strategy is followed by Brandon (1978, 1981, 1997), Sober (1984, 1993, 1997), and Elgin (2003). The third one is to defend the existence of empirical laws, or principles, in biology but arguing for a different explication of the concept of law or of non-accidental, counterfactual supporting, generalizations (Carrier 1995; Mitchell 1997; Lange 1995, 2000; Dorato 2005, 2012; Craver and Kaiser 2013). Our proposal will be of this third kind. But in such a manner that it will allow to consider "theoretical pluralism," "relative significance" controversies and some kind of contingency as not exclusive of biology (agreeing with Carrier 1995 on this) and to understand better the role played by different laws or lawlike statements of different degrees of generality in biology (capturing some of the points made by Ruse 1970 and Munson 1975) as well as the "a priori" component pointed out by Brandon, Sober, and Elgin.[8]

With respect to the existence of laws in ecology in particular—and taking into account the classical proposal of differentiating between two types of genuine laws: on the one hand, laws of unlimited, unrestricted scope or *fundamental laws* and, on the other, laws of limited, restricted scope or *derivative laws* that would *follow* from more fundamental laws (Hempel and Oppenheim 1948, p. 154)—we must distinguish the claim that there are no laws in ecology at all, which is hardly tenable given at least the so-called "Malthus law" of exponential population growth (Ginzburg 1986; Turchin 2001; Berryman 2003) and the more asserted and discussed claim

[7] See Stegmüller (1983) and Salmon (1989) for an analysis of the difficulties of the classical explication of the notion of scientific law.

[8] For a more detailed discussion of the two first kinds of responses, see Lorenzano (2006, 2007, 2014–2015), Díez and Lorenzano (2013, 2015).

that there are no fundamental and/or general nomological principles in ecology (see e.g. Peters 1991; Lawton 1999).

Ecologists and philosophers of ecology have taken part in the debate, resulting in a large number of publications on the subject. Following Linquist et al. (2016), we can distinguish three main reactions to the denial of the existence of fundamental laws in ecology in a similar way as we did in the case of biology in general: either to take issue with the kind of evidence used to justify Lawton's skeptical claims (Linquist 2015) or to cite examples of candidates for laws (Murray Jr. 1979, 1992, 1999, 2000, 2001; Turchin 2001; Berryman 2003; Ginzburg and Colyvan 2004), or to reject the concept of law that Lawton and other skeptics employ (Cooper 1998; Colyvan and Ginzburg 2003; Lange 2005). Our position will be, again, of this last kind. And, once more, in such a way that it will allow to understand better the role played by different laws or lawlike statements of different degrees of generality in ecology.

With respect to the non-universality of biological generalizations, we contend that universality is a too demanding condition. What matters is not strict universality but rather the existence at least of non-accidental, counterfactual supporting, generalizations, which we take as uncontroversial present in biology, though generally more domain restricted and ceteris paribus than in other areas of science such as mechanics or thermodynamics.

As many philosophers of biology and of physics, we also accept a broader sense of lawhood that does not require non-accidental generalizations to be universal and with no exceptions in order to qualify as laws.

This minimal characterization of laws as counterfactual-supporting facts is similar to the one defended in Dorato (2012), and it is also compatible with some proposals about laws in biology in particular, such as the "paradigmatic" (Carrier 1995) and "pragmatic" (Mitchell 1997) ones.

Whether one wants to call these non-accidental, domain restricted, generalizations "laws" is a terminological issue we will not enter here. What matters is, tagged as one wills, that these non-accidental generalizations play a key role in biology in general and in ecology in particular. We will show that in the case of population dynamics (**PD**).

Within the structuralist tradition, when dealing with the subject of laws, discussions, even from their beginnings with Sneed (1971), though not with that terminology, focus on those scientific laws which, starting with Stegmüller (1973), are called "fundamental laws" of a theory.

However, accepting the problems for finding a *definition* of the concept of a law, when the criteria for a statement to be considered a fundamental law of a theory are discussed within the framework of metatheoretical structuralism, one tends to speak rather of "necessary conditions" (Stegmüller 1986, p. 93), of "*weak* necessary conditions" (Balzer et al. 1987, p. 93), or, better still, only of "symptoms", some even formalisable (Moulines 1991, p. 233), although

> in each particular case of reconstruction of a given theory, it seems, as a general rule, to be relatively easy to agree, on the basis of informal or semi-formal considerations (for example, on its systematizing role or its quasi-vacuous character), that a given statement should be taken as the fundamental law of the theory in question (Moulines 1991, p. 233).

On the other hand, metatheoretical structuralism draws a distinction between the so-called *fundamental laws* (or *guiding principles*) and the so-called *special laws*. This distinction, which will be developed later, elaborates the classical distinction between two kinds of laws with different degrees of generality in a different way as well as the Kuhnian distinction between the symbolic generalizations — "generalization-sketches" (Kuhn 1974), "schematic forms" (Kuhn 1974), "law sketches" (Kuhn 1970, 1974) or "law-schema" (Kuhn 1970) — and their "particular symbolic forms" (Kuhn 1974) adopted for application to particular problems in a detailed way.[9]

Very briefly, five criteria can be mentioned as necessary conditions, *weak* necessary conditions or "symptoms" for a statement to be considered a fundamental law/guiding principle in the structuralist sense:

1. Its *cluster* or *synoptic character*. This means that a fundamental law should include "*all* the relational terms (and implicitly also all the basic sets) and, therefore, at the end, *every fundamental concept* that characterize such a theory" (Moulines 1991), "several of the magnitudes," "diverse functions," "possibly many theoretical and non-theoretical concepts" (Stegmüller 1986), "almost all" (Balzer et al. 1987), "at least two" (Stegmüller 1986).
2. To be *valid in every intended application*. According to this, it is not necessary that fundamental laws have an unlimited scope, apply every time and everywhere, and possess as universe of discourse something like a "big application," which constitutes an only one or "cosmic" model, but it rather suffices that they apply to partial and well-delimited empirical systems: the set of intended applications of the theory (Stegmüller 1986).[10]
3. Its *quasi-vacuous character*. This means that they are highly abstract, schematic, and contain essential occurrences of **T**-theoretical terms, which in a structuralist sense are terms whose extension can only be determined through the application of a theory's fundamental law(s)[11] so that they can resist possible refutations, but which nevertheless acquire specific empirical content through a non-deductive process known as "specialization" (Moulines 1984).
4. Its *systematizing* or *unifying role*. Fundamental laws allow including diverse applications within the same theory since they provide a guide to and a conceptual framework for the formulation of other laws (the so-called "special laws"), which are introduced to impose restrictions on the fundamental laws and thus apply to

[9] On the other hand, the expressions "fundamental law" and "special law" are not used here in Fodor's sense (Fodor 1974, 1991)—the former for laws of basic or fundamental sciences, the latter for laws of special sciences—but rather in the sense used by structuralists, i.e., for different kinds of laws within a theory.

[10] The validity of laws can be regarded as *exact*—and thus as *strict* or non-interferable laws—or, rather, to the extent that they usually contain not only *abstractions* but also various *idealizations*, as *approximate*, as already pointed out by Scriven (1959) and more extensively by Cartwright (1983)—and so as non-strict or *interferable* laws, and compatible with various specific treatments of this situation, such as those referring to ceteris paribus clauses (Cartwright 1983), "provisos" (Coffa 1973 and Hempel 1988), or "normicity" (Schurz 2009).

[11] For more on the structuralist **T**-theoretical/**T**-non-theoretical distinction, see Sect. 10.3.

particular empirical systems (Moulines 1984).[12] It is clear that the distinction between fundamental and special laws is relative to the considered theory.

5. To possess *modal import*. Fundamental laws express non-accidental regularities, are able to give support to counter-factual statements (if they are taken "together-with-their-specializations" within a theory, in the sense that we will introduce later of theory-net), even when they are context-sensitive and with a domain of local application, and that, in its minimal sense, instead of attributing *natural necessity*, *necessity of the laws* is attributed, and, in that sense, they should be considered as *necessary in their area of application*, even when outside such an area it does not need to be that way (Lorenzano 2014–2015; Díez and Lorenzano 2013).

Fundamental laws/guiding principles are "programmatic" or heuristic in the sense that they tell us *the kind of things* we should look for when we want to explain a specific phenomenon. But, as said before, taken in isolation, without their specializations, they say empirically very little. They can be considered, when considered alone, "empirically non-restrict." In order to be tested/applied, fundamental laws/guiding principles have to be specialized ("concretized" or "specified"). These specific forms adopted by the fundamental laws are the so-called "special laws."

It is worth emphasizing that the top-bottom relationship established between laws of different levels of generality is *not* one of implication or derivation but of *specialization* in the structuralist sense (Balzer et al. 1987, Chap. 4): bottom laws are specific versions of top ones, i.e., they specify some functional dependencies (concepts) that are left partially open in the laws above. That is the reason why they are called "*special* laws" instead of "*derivative* laws" like in the classical view of laws according to which the laws with a more restricted or limited scope are assumed to be logically derived or deduced from the fundamental laws. Actually, "special laws" *are not derived* or *deduced literally* from the fundamental laws (at least are not derived or deduced *only* from them) without considering some additional premises. Formally speaking, the specialization relation is reflexive, antisymmetric, and transitive and does not meet the condition of monotonicity.

When the highest degree of concretization or specificity has been reached, i.e., when all functional dependencies (concepts) are completely concretized or specified, "*terminal* special laws" are obtained. This kind of special laws, proposed to account for particular empirical situations, can be seen as particular, testable and, eventually, refutable hypotheses to which to direct "the arrow of *modus tollens*" (Lakatos 1970, p. 102).

10.2.1 Laws in Population Dynamics

Population dynamics is a part of population ecology that studies the variation in the number of individuals in a population over time. Although during the nineteenth century it began with the works of Malthus and Verhulst, we can affirm that it had

[12] By saying it in a model-theoretic way, fundamental laws determine the whole class of models of a theory while special laws determine only some of them, which constitute a subclass of the class of models.

its formal beginnings in the first decades of the twentieth century, when the ecologists adopted a vision centered on populations, by means of which they tried to explain using mathematical equations their behavior over time. In this way the most important developments of population dynamics have been made when the equations of competition and predation of Lotka (1925) and Volterra (1926), and the curves of Pearl (1925), among others, were added to the exponential equations of Malthus (1798) and the logistic equation of Verhulst (1845). These authors sought to determine how the number of individuals or size of the population was modified based on certain characteristics of the species and factors external to the population.

Population dynamics (**PD**) studies the changes in population size over time. It is about populations, defined as the set of organisms of the same species that inhabit a given area, whose sizes (N), i.e., the number of individuals, change (ΔN) over time (from t to $t + 1$) (i.e., from N_t to N_{t+1}). It talks about *populations* (*POP*)—*organisms* (O), or, better, sets of organisms $Pot(O)$ belonging to the same species which make up *populations*, where **pop** symbolizes a population (**pop** $\subseteq Pot(O)$) and *POP* the set of populations such that **pop** $\in POP$—and of the size of populations (N) that changes (ΔN) over time (from t to $t + 1$) (i.e., from N_t to N_{t+1}), depending on the demographic processes (DP) of birth (B), death (D), immigration (I), and emigration (E).

The connections between its different components can be graphically represented in the following way (see Fig. 10.1):

Population dynamics (**PD**) intends to account for changes in population size over time, i.e., for organisms that make up a population in which a set of demographic processes occur (birth, death, emigration, and immigration) that determine that the size of the population is modified in a given interval of time.

Examples of cases of closed populations (i.e., of populations in which neither immigration nor emigration occur) are the following:

1. The post-glacial expansion of *Corylus avellane* population in Nortfolk, UK
2. The decrease of the population of North Atlantic northern right whale (*Eubalaena glacialis*)
3. The post-glacial expansion of *Pinus sylvestris* population in Nortfolk, UK
4. The fluctuation of the Australian sheep bow-fly (*Lucilia cuprina*)
5. The growth of adult carob trees (*Prosopis flexuosa*) population

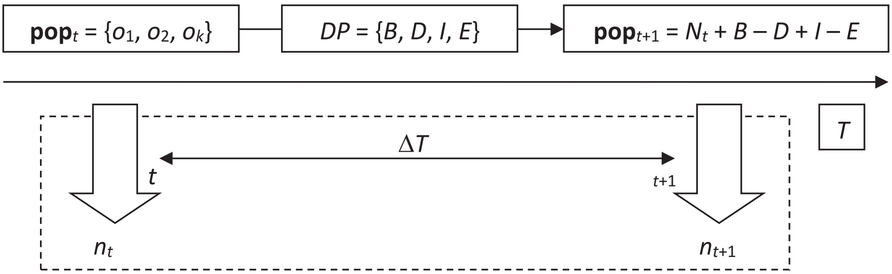

Fig. 10.1 Connections between different components of population dynamics

6. The competitive system of the species *Drosophila willistoni* and *D. pseudo-obscura*
7. The interspecific competition between juvenile *Hobsonia florida* (*Polychaeta*, *Ampharetidae*) and oligochaetes
8. The cycling of predator and prey populations of the Canada Lynx (*Lynx canadiensis*) and its principal prey, the snow-shore hare (*Lepus americanus*)

For every specific case ecologists have to postulate *specific* biotic and other *population factors*[13] that act together with specific demographic factors as well as the specific manner of their combination in the *rate of population change*[14] that accounts for the observed (or estimated) change in population size.

This means that in order to account for the observed (or estimated) change in population size, the following parameters have to be specified:

(i) Types and numbers of components of the *rate of population change* (*RPC*) acting together (i.e., types and numbers of demographic processes (*DP*) and of population factors $((F_i)_{i \leq k})$), and
(ii) (a) The specific mathematical form assumed by *RPC* and (b) the specific mathematical form assumed by the equation in which all basic concepts occurred (being it continuous, discrete, exponential, linear, logistic, etc.)

Thus, ecologists propose equations, which contain these two types of specifications.

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[13] There are different ways of classifying the different types of factors that affect demographic processes. For instance, Krebs (2008) distinguishes two types of factors, external and internal, while Berryman (2003) distinguishes three types of factors, biotic, genetic, and abiotic. We follow this tripartite distinction but with a slightly different denomination. So, members of the set of population factors $((F_i)_{i \leq k})$ are the so-called set of *environmental factors* (F_{amb}) (such as physical and chemical conditions of the environment and resources), set of *genetic factors* (F_{gene}) (related to genetic properties of the distinct individuals that place them in different classes with respect to age, sex, or size), and set of *biotic* (or *biological*) *factors* (F_{bio}) (variables or "parameters" like carrying capacity, competition coefficient, capture efficiency, and conversion efficiency of predator, which measure the biotic interactions such as predation, parasitism, and intra- or interspecific competition). While the extension of the concepts environmental and genetic factors can be determined independently from population dynamics, and thus are **PD**-non-theoretical, the extension of most of biotic factors can only be determined by means of **PD** and in that sense a subset of them are **PD**-theoretical.

[14] The rate of population change (*RPC*) is a functional whose domain is the set of demographic processes (*DP*), the size of the population (N_t), and the whole of population factors $((F_i)_{i \leq k})$ in an instant of time (*T*), and its co-domain is the set of real numbers: $RPC: DP \times N_t \times (F_i)_{i \leq k} \times T \rightarrow \mathrm{R}$. It is definitely a **PD**-theoretical concept: its extension can only be determined by applying the very same **PD**.

The following are the specifications introduced to account for the above examples and the respective equations to which they give rise[15]:

1. The post-glacial expansion of *Corylus avellana* population is (i) not affected by population factors and (ii) has no population limitations of continuous and exponential variation: $dN/dt = (b - d) \cdot n_t$ (Bennett 1983).
2. The population of the North Atlantic northern right whale is (i) affected by genetic factors and has a (ii) continuous and exponential variation: $dN / dt = [\ln \sum_{x=0}^{k} b(x)d(x) / G] \cdot n_G$ (Caswell et al. 1999).
3. The post-glacial expansion of *Pinus sylvestris* population in Norfolk, UK, is (i) affected by environmental and biotic factors and has (ii) carrying capacity and continuous logistic variation with linear dependence between b, d and N_t: $dN/dt = [(b - d)(1 - n_t/K)] \cdot n_t$ (Bennett 1983).
4. The population of Australian sheep bow-flies is (i) affected by environmental and biotic factors and has (ii) carrying capacity and continuous logistic variation with linear dependence between b, d and the population size in an instant of time previous to t: $dN/dt = [(b - d)(1 - n_{t-\tau}/K)] \cdot n_t$ (Nicholson 1957).
5. The population of adult carob trees is (i) affected by environmental and biotic factors (carrying capacity and critical population size) and follows (ii) carrying capacity and continuous logistic variation with non-linear dependence between b, d, N_t and C: $dN/dt = [(b - d)(1 - n_t/K)(1 - C/n_t)] \cdot n_t$ (Aschero and Vázquez 2009).
6. The competitive system of populations of species *Drosophila willistoni* and *D. pseudoobscura* is (i) affected by environmental and biotic factors and has (ii) carrying capacity and continuous logistic variation with linear dependence between b, d and N_t: $dN/dt = [(b - d)(1 - n_t/K)^{\theta}] \cdot n_t$ (Gilpin and Ayala 1973).
7. The interspecific competition between populations of juvenile *Hobsonia florida* and oligochaetes is (i) affected by biotic factors (populations of other species with carrying capacity and competition factors) and follows (ii) carrying capacity and continuous logistic variation with dependence on b and d with N_{t1}, K_1, N_{t2} and α: $dN_1/dt = (b_1 - d_1)[(K_1 - n_{t1} - \alpha n_{t2})/K_1] \cdot n_t$ (Gallagher et al. 1990).
8. The cycling of predator and prey populations of the Canada Lynx and its principal prey, the snow-shore hare is (i) affected by biotic factors (populations of other species with capture efficiency and conversion efficiency of predator) and follows (ii) exponential continuous variation and therefore demographic pro-

[15] It is worth noting in relation to the equations mentioned in these examples that different authors usually designate the same base sets or functions of population dynamics by different terms and symbols. For N and the demographic processes (b, d, i, and e) its use is generalized and uniform, but for the population factors there is much diversity of terms and symbols between the different authors, especially in what we label the "rate of population change" (and symbolize by *RPC* instead of by r as in Turchin 2001, p. 19) as well as in the presentation of the so-called "Lotka-Volterra equations." This generates the coexistence of different terminology and symbology for the same factors or rates and the erroneous impression that the concepts are different as well as the distinct formulations of the equations in which they occur. In order to avoid this impression and ambiguity we have unified the use of terms and symbols.

cesses without dependence on population size: $dN/dt = [(b - d) - \alpha P] \cdot n_t$ (for prey) and $dN/dt = [(-d) + \beta V] \cdot n_t$ (for predator) (Gotelli 2001).

In the terminology of metatheoretical structuralism each specific equation, which applies to a particular case, should be considered a *special law*; moreover, to the extent that all concepts are completely concretized or specified, each equation should be seen as a *terminal* special law.

In all these cases, it happens that the value of the *rate of population change* (*RPC*), calculated out of the values of chosen types and numbers of *population factors* ($(F_i)_{i \leq k}$), multiplied by the size of the population at instant t (or initial instant) (N_t) matches or fits (exactly or approximately) with the values of the changes in population size over time (ΔN).

So far, we have identified some of the different equations or special laws that have been proposed in population dynamics.

In order to try to identify some fundamental law/guiding principle in population dynamics, the strategy we will use is to ask what all the different equations/special laws of **PD** have in common.

It is worth noting that the key metatheoretical question is not "from what fundamental laws or general principles or equations are all specific equations or special laws of **PD** deduced?" but "what do all specific equations/special laws of **PD** have in common?"

Answering this question is not only a feasible task; it will also shed light on the relationship between laws of **PD**, and moreover, as we shall see later, on the relationship between models of **PD**, and **PD** as a theory, in the sense of a theory-net, and on the unifying power of **PD** in particular and of theories in general.

One might respond to this question by denying that there is one particular feature (or set of features) that all equations/special laws of **PD** share and argue that the case of ecological laws is analogous to Wittgenstein's games (1953, § 66 and ff.): what ties different equations/special laws together and what makes them belong to **PD** is some kind of family resemblance between them rather than the existence of a fixed set of shared features, providing necessary and sufficient conditions for membership to them.

However, this answer begs another question because we still want to know in what sense the different equations/special laws of **PD** are similar to each other.

It seems unlikely that the desired similarities can be read off from the mere appearance of them, and this is all that the Wittgensteinians can appeal to. Moreover, what matters is not that they are similar to each other in appearance but rather that they share certain structural features: the equations/special laws of **PD** possess the same structure (of the same logical type), meaning that they all are specifications/specializations of one and the same fundamental law/guiding principle of **PD**, respectively. And thus, as we shall see later, they form a theory or, better, a theory-net, the theory-net to which they all belong.

In specific **PD** applications only specific laws or equations appear, and that is all that we have in standard textbooks. However, we would like to suggest that they are specific versions of a general, fundamental law or a guiding principle for the application in question. Nevertheless, in contrast to other empirical theories like those that belong to physics such as classical particle mechanics or thermodynamics,[16] the fundamental law/guiding principle of **PD** is not "observed" in the standard literature, but it is only "implicit" there. Thus, population dynamics (**PD**) is guided by a general guiding principle implicitly presupposed in specific applications. Roughly, this fundamental law/guiding principle (**PDGP**) states the following:

PDGP: The change in the size of a population in a given time interval is due to the presence of a set of (types of) demographic processes (birth, immigration, death, emigration), i.e., demographic functions, and of a set of (types of) population factors (environmental, genetic and biotic), i.e., population factors, such that the observed (or estimated) change in the size of the population in a certain period of time corresponds to the product of the rate of population change multiplied by the size of the population at the beginning of the time interval.

All interconnected concepts of **PD** can be graphically depicted as follows (see Fig. 10.2, where besides the components already present in Fig. 10.1 appears a symbolic representation of the set of (types of) population factors (F_i) at the top and of the fundamental law/guiding principle of **PD** (**PDGP**), in which also occurs the concept of rate of population change (*RPC*), at the bottom):

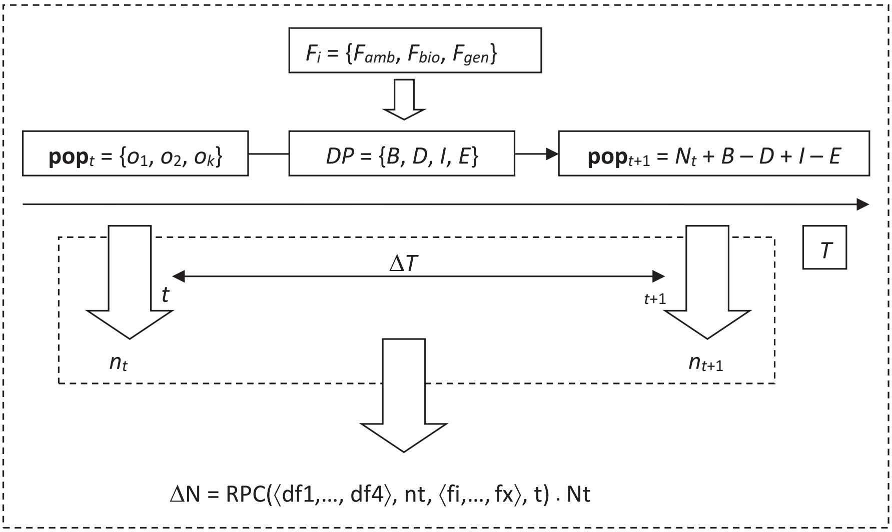


Fig. 10.2 Graphical depiction of the elements of PD

[16] For an analysis of these theories from a structuralist point of view, see among others Balzer et al. (1987).

As mentioned before, fundamental laws/guiding principles are programmatic/heuristic in the sense that they tell us *the kind of things* we should look for when we want to apply the theory to a specific phenomenon. In the case of **PD** fundamental law/guiding principle, its heuristic character can be read as follows:

PDGP: When population size changes over time, look for (types of) biotic and other population factors (environmental and genetic) that acting together with (types of) demographic processes (natality, immigration, mortality, emigration) in the rate of population change, which, multiplied by the population size at the initial time, "match"/"fit" the observed (or estimated) change in population size.

As we already mentioned, in every specific case ecologists have to look for specific biotic and other population factors that act together with specific demographic factors and discover the specific manner of their combination in the rate of population change that accounts for the observed (or estimated) change in population size.

This means that **PD** fundamental law/guiding principle guides the process of specialization, since, as we saw before, in order to obtain special laws that account for the observed (or estimated) change in population size, (i) types and numbers of components of the rate of population change (*RPC*) that act together (i.e., types and numbers of demographic processes and of population factors), and (ii) (a) the specific mathematical form assumed by *RPC*, and (b) the specific mathematical form assumed by the fundamental law/guiding-principle (being it continuous, discrete, exponential, linear, logistic, etc.) have to be specified.

10.3 The Concept of Model from the Point of View of Metatheoretical Structuralism

The use of the term "model" is not restricted to scientific contexts. On the contrary, it is used in all kinds of everyday situations, being used, moreover, as much to refer to the thing "painted" or modeled as for the "painting" or model of some original. In the sciences it began to be used towards the end of the nineteenth century, through the allusion to "mechanical models" or, with different terminology, "mechanical analogies", proposed and discussed, among others, by Maxwell (1855, 1861), Thomson (1842, 1904), and Boltzmann (1902) and Duhem (1906), or, in the context of German physics, where the term "Bild", in singular, or "Bilder", in plural was usual (Helmholtz 1894; Hertz 1894; Boltzmann 1905, who discussed the "models" and developed a "Bild conception" of physics in particular and of science in general).

Its use, however, was not limited to the field of physics, but extended to other domains of science, being of central importance in many scientific contexts. But neither in colloquial contexts nor in the diverse scientific contexts is the term "model" used in a non-unitary way, but rather it is an ambiguous, multivocal or polysemic expression that expresses more than one concept. At the same time, as we pointed out, it must be taken into account that different terms, such as the mentioned

"Bild" or "analogy" as well, have been used to refer to models. The term model applies to a bewildering set of objects from mathematical structures, graphical representations, computer simulations, to specific organisms or objects. And the means by which scientific models are expressed goes from sketches and diagrams to ordinary text, graphics and mathematical equations – just to name some of them.

In biology in general and ecology in particular the term model is used in different ways, calling "models" different entities, whether the equations themselves, idealized representations of empirical systems, organisms or physical objects, among other things. Thus, in biology, for instance, it is standard practice to speak about the Lotka-Volterra model of predator-prey interaction or the double helix model of DNA or models organisms or models "in vivo" or "in vitro".

On the other hand, different authors have proposed different typologies and classifications (neither necessarily exhaustive nor, much less, exclusive) in order to analyze models and to understand their nature and function in science.

But although the literature in philosophy of science has concentrated mainly on the so-called "theoretical models" (Black 1962), not everyone agreed with the exact role that models played in the empirical sciences nor with their relevance for them, as well as with their relation with the laws and empirical theories and the eventual need to take them into consideration as components of the latter.

Nowadays, as it Jim Bogen states in the back cover of the book *Scientific Models in the Philosophy of Science* (Bailer-Jones 2009), "The standard philosophical literature on the role of models in scientific reasoning is voluminous, disorganized, and confusing."

Despite this, one of the axis already mentioned that would enable the organization at least part of such a literature, and with which the book ends, is what is identified as one of the "contemporary philosophical issues: how theories and models relate each other" (Bailer-Jones 2009, p. 208). On this issue, and regardless of differences in particular developments, we have to main positions: the aforementioned *model views*, for which models do not form part of theories (in some usual, encompassing sense of the term), but they are rather independent—"autonomous"—with respect to them, and the *semantic view*, for which the most fundamental component for the identity of a theory is a *class* (set, population, collection, family) *of models*.

But whether within model or *semantic views*, there is an attempt to understand not only what they are, but also how they work and even how models are constructed from detailed case studies belonging to different sciences.

Although other authors had already pointed out the importance of models in biology and had tried to analyze them (Beckner 1959; Beament 1960; Holling 1964; or later Schaffner 1980, 1986, 1993), Levins (1966) occupies a central place in the discussion about models and model building in biology in general and ecology. From then on his proposal about the existence of a three-way trade-off between generality, realism, and precision, such that a model builder cannot simultaneously maximize all of these desiderata, has been much discussed (e.g. Orzack & Sober 1993; Levins 1993; Orzack 2005; Odenbaugh 2003; Weisberg 2006; Matthewson & Weisberg 2009).

Returning to the issue of the relationships between models and theories, the discussion in ecology continues nowadays with authors who strongly criticize the discipline affirming that it is an accumulation of models without any connection (as in the case of Roughgarden 2009) but on the other hand many ecologists maintain the existence of a common core of biological assumptions (Cooper 2003; Levins 1993) and that the differences in different components result in a family of mathematical equations (or "models", as the ecologists call them) (Cooper 2003). The latter has led many authors to argue that theoretical unification in ecology is possible through an iterative process that includes recognizing similarities between ostensibly competing models (Cooper 2003; Lange 2005; Sagoff 2003), developing a common theoretical framework and constructing a new super model within that framework (Fox et al. 2011).

As would be expected, being a member of the semantic family, the structuralist view shares with all the other family members the fundamental thesis on the centrality of models for metatheoretical analysis. But, on the other hand, it can differ from other members of the semantic family in its characterization of the precise nature of these entities that are called models, although eventually sharing it with some of them.

A model, in its minimal informal meaning, is a system or structure which intends to represent, in a more or less approximative way, a "portion of reality," made up by entities of various kinds, which *makes* true a series of claims, in the sense that in this system "what the claims say occurs," or more precisely, the claims are true in this system.

Models are conceived as systems or structures, i.e., mathematical structures. In the standard version of metatheoretical structuralism, these structures are set-theoretical or relational structures of a certain kind,[17] constituted by a series of basic domains (sets of objects) and of relations (or functions) over them, i.e., as entities of the form: $\langle D_1,\ldots, D_k, R_1,\ldots, R_n\rangle$, where $R_j \subseteq D_{i1} \times \ldots \times D_{ik}$.) (the D_i's represent the so-called "base sets," i.e., the "objects" the theory refers to, its ontology, whereas

[17] In trying to be as precise as possible, metatheoretical structuralism prefers the use of (elementary) set theory—whenever possible—as the most important formal tool for metatheoretical analysis. However, this formal tool is not essential for the main tenets and procedures of the structuralist representation of science (other formal tools such as logic, model theory, category theory, and topology as well as informal ways of analysis are also used). Besides, there are also uses of a slight variant of Bourbaki notion of "structure species" in order to provide a formal basis of characterizing classes of models by means of set-theoretic predicates (Balzer et al. 1987, Ch. 1) and of a version of the von Neumann-Bernays-Gödel-type of language including urelements for providing a purely set-theoretical formulation of the fundamental parts of the structuralist view of theories (Hinst 1996). There is even a "categorial" version of metatheoretical structuralism that casts the structuralist approach in the framework of category theory rather than within the usual framework of set theory (see Balzer et al. 1983; Sneed 1984; Mormann 1996). The choice of one formal tool or another or of a more informal way of analysis is a pragmatic one, depending on the context which includes the aim or aims of the analysis and the target audience. Nonetheless, in standard expositions of metatheoretical structuralism, as well as in the presented here, models are conceived of as *set-theoretical structures* (or models in the sense of *formal semantics*), and their *class* is identified by defining (or introducing) a *set-theoretical predicate*, just as in the *set-theoretical* approach of Patrick Suppes (1957, 1969, 1970, 2002; McKinsey et al. 1953).

the R_j's are relationships or functions (set-theoretically) constructed out of the base sets).[18]

In order to provide a more detailed analysis of empirical science, metatheoretical structuralism distinguishes three kinds of (classes, sets, populations, collections or families of) models. Besides what are usually called (the class, set, population, collection or family of) "*theoretical* models" or simply (the class, set, population, collection or family of) "*models*"—also called (the class of) "*actual* models" in structuralist terminology—, the so-called (class of) "*potential* models" and (class of) "*partial* potential models" are taken into account.

To characterize these structuralist notions, two distinctions are to be considered: the distinction between two kinds of "conditions of definition" (or "axioms", as they are also called) of a set-theoretical predicate, and the distinction between the **T**-theoretical/**T**-non-theoretical terms (or concepts) of a theory **T**. According to the first distinction, the two kinds of conditions of definition of a set-theoretical predicate are (1) those that constitute the "frame conditions" of the theory and that "do not say anything about the world (or are not expected to do so) but just settle the formal properties" (Moulines 2002, p. 5) of the theory's concepts and (2) those that constitute the "substantial laws" of the theory and that "do say something about the world by means of the concepts previously determined" (Moulines 2002, p. 5).

According to the second distinction, which replaces the traditional, positivistic theoretical/observational distinction, it is possible to establish, in (almost) any analyzed theory, two kinds of terms or concepts, in the sense delineated in an intuitive formulation by Hempel (1966, 1969, 1970) and Lewis (1970): the terms that are specific or distinctive to the theory in question and that are introduced by the theory **T**—the so-called "**T**-theoretical terms or concepts"—and those terms that are already available and constitute its relative "empirical basis" for testing—the so-

[18] In a complete presentation, we should include, besides the collection of so-called *principal base sets* $D_1,\ldots, D_j$ or $D_1,\ldots, D_k$, also a second kind of base sets, namely, the so-called *auxiliary base sets* $A_1,\ldots, A_m$. The difference between them is the difference between base sets that are empirically interpreted (the principal ones) and base sets that have a purely mathematical interpretation, like the set N of natural numbers, or the set R of real numbers (the auxiliary ones). Here, auxiliary (purely mathematical) base sets are treated as "antecedently available" and interpreted, and only the proper empirical part of the models is stated in an explicit way.

On the other hand, in philosophy of logic, mathematics, and empirical science has been intensively discussed what would be a better way of understanding the nature of sets occurring in the relational structures and of the models themselves. In relation to sets, according to the standard interpretation of "sets-as-one" (Russell 1903) or "the highbrow view of sets" (Black 1971) or "sets-as-things" (Stenius 1974) sets themselves, though not necessarily their elements which may refer to concrete entities, should be considered as abstract entities, while according to the interpretation of "sets-as-many" (Russell 1903) or "the lowbrow view of sets as collections (aggregates, groups, multitudes)" (Black 1971) or "sets-of" (Stenius 1974) sets have not to be interpreted that way. For theoretical models, even though they are usually considered as abstract entities, there is no agreement about what kind of abstract entities they are, i.e., what is the best way of conceive them—either as interpretations (Tarski 1935, 1936) or as representations (Etchemendy 1988, 1990), or as fictional (Godfrey-Smith 2006; Frigg 2010), or as abstract physical entities (Psillos 2011). However, due to space limitations, we will not delve into these issues.

called "**T**-non-theoretical terms or concepts," which are usually theoretical for other presupposed theories **T**′, **T**″, etc.

According to the standard structuralist criterion of **T**-theoreticity (originated in Sneed 1971 and further elaborated in detail in the Structuralist program; see Balzer et al. 1987, Ch. II), a term is **T**-theoretical (i.e., theoretical relative to a theory **T**) if *every* method of determination (of the extension of the concept expressed by the term) depend on **T**, i.e., if they are **T**-dependent, if they presuppose or make use some law of **T**; otherwise, a term is **T**-non-theoretical, i.e., if at least *some* method of determination (of the extension of the concept expressed by the term) *does not* presupposes or make use of some law of **T**, if it is **T**-independent.

Now we are in a position to characterize these structuralist basic notions:

1. The class of *potential models* of the theory $\mathbf{M_p}$ is the total class of structures that satisfy the "frame conditions" (or "*improper* axioms") that just settle the formal properties of the theory's concepts, but not necessarily the "substantial laws" of the theory as well.
2. The class of (actual) *models* of the theory **M** is the total class of structures that satisfy the "frame conditions," and, in addition, the "substantial laws" of the theory. If $A_1,\ldots, A_s$ are certain formulas ("*proper* axioms" or simply "axioms") that represent the laws of the theory, *models* of the theory are structures of the form $\langle D_1,\ldots, D_k, R_1,\ldots, R_n\rangle$ that satisfy the axioms $A_1,\ldots, A_s$. (And that is the reason why, as it was mentioned before, models may be considered the model-theoretic counterpart of theory's laws.)
3. The class of *partial potential models* $\mathbf{M_{pp}}$ are obtained by "cutting off" the **T**-theoretical concepts from the potential models $\mathbf{M_p}$ ($\mathbf{M_{pp}} := \mathbf{r}(\mathbf{M_p})$, where **r**, the "restriction" function, is a many-one function such that $\mathbf{M_p} \rightarrow \mathbf{M_{pp}}$). If potential models are structures of type x ($x = \langle D_1,\ldots, D_k, R_1,\ldots, R_n\rangle$), *partial potential models* $\mathbf{M_{pp}}$ are structures of type y ($y = \langle D'_1,\ldots, D'_j, R'_1,\ldots, R'_m\rangle$), where each structure of type y is a *partial substructure* of a structure x.[19] (And let us call a specific structure of type y, with specific instances of the **T**-non-theoretical concepts, a "*data model*" of **T**).

Now, let us identify all these kinds of models in population dynamics, starting with data models and then moving on to potential models first and then to theoretical models that result in successful applications to end with the classes of potential models, models, and partial potential models.

[19] A structure y is a *substructure* of another structure x (in symbols: $y \sqsubseteq x$) when the domains of y are subsets of the domains of x and, therefore, the relationships (or functions) of y are restrictions of the relationships (or functions) of x. A structure y is a *partial substructure* of x (also symbolized by $y \sqsubseteq x$) when, besides being a substructure of x, there is at least one domain or relationship (or function) in x that has no counterpart in y. The important thing is that the *partial* substructure y contains less components – domains or relationships (or functions) – than the structure x. Thus, structures x and y are of different logical types. If y is a *substructure* (either partial or not) of x, it is also said, inversely, that x is an *extension* of y.

10.3.1 Models in Population Dynamics

If the examples of closed population cases given above (in Sect. 10.2.1) are to be represented in the structuralist format, they should be conceived as *data models* of **PD**. That is, they should be conceived as structures of type y of partial potential models: $y = \langle O, T, <, N_t, B, D, E, I\rangle$, with specific values adopted by the concepts that occur there—organisms (O) belonging to the same species which make up populations; the size of populations (N) that changes (ΔN) over time (from t to $t + 1$), i.e., from N_t to N_{t+1}; and the demographic processes (DP) of birth (B), death (D), immigration (I), and emigration (E)—in each of the given examples. Structures of type y are used to represent in a model-theoretic, structuralist way those empirical phenomena that **PD** intends to account for—i.e., organisms that make up a population in which a set of demographic processes occur (birth, death, emigration and immigration) that determine that the size of the population is modified in a given interval of time, or changes in population size over time, for short—, which also constitute what allows us to test population dynamics, i.e., its "(empirical) basis of testing."

Let us consider the case of *Pinus sylvestris* in more detail though. The system under consideration is constituted by a set of organisms O of the same species (set of individuals of *Pinus sylvestris*).[20] They form the objects involved in this intended application. Thus, $O_h = \{o_1,..., o_n\}$ are the set of organisms in a determined interval of time, $\{t_n, t_{n+1}\}$. The population size is measured in t_n and in t_{n+1}, and its difference between the two instants of time (ΔN) is calculated; in this particular case, the population size is the estimated number of pollen grains accumulated in a sedimentary environment per unit area per unit time, i.e. the so-called "the pollen accumulation rate"; this value is 6.3 in t_n (where $t_n = 9{,}500$ B.P.), which changed to 49,000 in t_{n+1} (where $t_{n+1} = 9{,}000$ B.P.), giving a difference (ΔN) of 48,993.7 (where the unit of measurement used for the pollen accumulation rate is grains/cm^2 × year). Regarding demographic processes (DP) of birth (B), death (D), immigration (I), and emigration (E) what is important in this example is (1) the difference between birth and death ($b - d$), which is = 0.945 and (2) that $E = I = 0$. We can now represent the data model for the case of *Pinus sylvestris* for $\langle O, T, <, N_t, B, D, E, I\rangle$ with what one likes to explain, i.e., the changes in population size of 48,993.7 from t to $t + 1$, i.e., from N_t to N_{t+1} as follows: $\langle\{o_1,..., o_n\}$, 9,500; 9,000, {6.3; 49,000; 48,993.7}, {0.945}, {0}, {0}$\rangle$. Let us then call such a structure "the *data model* for **PD** of *population dynamics* of *Pinus sylvestris*," or $DM_{\mathbf{DP}}(PDP)$ for short.

And if we now want to represent in a structuralist format the different ways in which the given examples of cases of closed populations are accounted for by introducing types and numbers of components of the rate of population change (RPC) that act together (types and numbers of demographic processes (DP) and population factors ($(F_i)_{i \leq k}$)) and the specific mathematical form that the rate population change adopts in the respective equations, we should consider these first as "potential models" of **PD** that, by adding the specific equations, result then in "theoretical (or actual or

[20] In this work a palynological study of the expansion of *Pinus sylvestris* in the geological stage after the last glaciation is carried out. The pollen grains contained in each sample are taken as organisms of the population.

simply) models" of **PD** and lastly in successful applications. That is, they should be conceived as structures of type x of potential models: $x = \langle O, T, <, (F_i)_{i \leq k}, N, B, D, E, I, RPC \rangle$ that are extensions of the structures of type y, which contain, besides specific instances of the concepts occurring in these structures, also specific instances of the concepts of population factors ($(F_i)_{i \leq k}$) and of rate of population change (RPC), and where the different specific equations postulate a "match" or "fit" between the observed (or estimated) change in population size and the rate of population change, multiplied by the population size at the initial time; if the "match" or "fit" can be established, they result in successful applications (as they actually do in the treatment of the examples presented in Sect. 10.2.1).

Returning to the case of *Pinus sylvestris*, there it is hypothesized (i) that there is only one population factor involved in RPC: the carrying capacity or load capacity or the largest population size that a given environment can support indefinitely (symbolized by K; and if the population is $\mathbf{pop}_p$, it is symbolized by $K(\mathbf{pop}_p)$); in our case, where $\mathbf{pop}_p$ symbolizes the population of *Pinus sylvestris*, $K(\mathbf{pop}_p) = 47{,}018$ grains/cm^2 × year; and (ii) (a) the specific value calculated for RCP, which in this case is of 0.873 grains/cm^2 × year, and (b) that the population of *Pinus sylvestris* constitutes a case of continuously varying populations whose demographic processes are dependent on population size that does not remain constant over time and give logistic form: $dN/dt = [(b - d)(1 - n_t/K)] \cdot n_t$.

If we put all the information of (i) and (ii) (a) together, i.e., the specifications for the **PD**-non-theoretical as well as for the **PD**-theoretical concepts together, we obtain the following structure of type $x = \langle O, T, <, (F_i)_{i \leq k}, N_t, B, D, E, I, RPC \rangle$ for $\mathbf{pop}_p$: $\langle \{o_1, ..., o_n\}, \{9{,}500; 9{,}000\}, \{47{,}018\}, \{6.3; 49{,}000; 48{,}993.7\}, \{0.945\}, \{0\}, \{0\}, \{0.873\} \rangle$. Let us then call it "the *potential model* for **PD** of *population dynamics* of *Pinus sylvestris*," or $PM_{\mathbf{DP}}(PDP)$ for short.

If, in addition, it is required that this structure satisfies (ii) (b), i.e., the linear logistic equation $dN/dt = [(b - d)(1 - n_t/K)] \cdot n_t$, we obtain what we call "the *theoretical* (*actual* or simply) *model* for **PD** of *population dynamics* of *Pinus sylvestris*," or $TM_{\mathbf{DP}}(PDP)$ for short.

In a similar way, as in the case of the different equations/laws, one can ask now what all these data models, all these theoretical models and all these successful applications have in common. And the answer to these questions is straightforward, using the notions of class of partial models, of potential models, and of models introduced in the previous section.

What all these data models have in common is that they are specifications of partial potential models of **PD**; what all these theoretical models have in common is that they are specifications first of potential models of **PD** and then of models of **PD** that result in successful applications.

We will next identify such classes of types of models in **PD**, starting with the class of potential models, continuing with the class of models, and concluding with the class of partial potential models.

The class of *potential models of population dynamics* ($\mathbf{M_p}(\mathbf{PD})$) is constituted by the total class of structures that satisfy the "frame conditions" that just settle the formal properties of **PD**'s concepts but not necessarily the "substantial laws" of **PD** as well and for which it makes sense to wonder if they are actual models of **PD**.

We can put together all **PD**'s basic concepts in one structure *x*, which thus contains the "conceptual framework" of **PD**: $x = \langle O, T, <, (F_i)_{i \leq k}, N, B, D, E, I, RPC \rangle$, and then formulate the "frame conditions" (or "*improper* axioms") for **PD**'s basic concepts as follows (by means of the introduction or definition of the set-theoretical predicate "being a potential model of population dynamics"):

Definition 1
$\mathbf{M_p}$(**PD**):$x = \langle O, T, <, (F_i)_{i \leq k}, N, B, D, E, I, RPC \rangle$ is a *potential model of population dynamics* ($x \in \mathbf{M_p}$(**DP**)) if and only if

1. O is a non-empty, finite set ("organisms": variable o)
2. $\langle T, < \rangle$ is a dense linear order ("time": variable t)
3. $(F_i)_{i \leq k}$ a non-empty, finite set ("types of population factors": variable f_i)
4. N_t: $POP \times T \rightarrow \mathbb{R}$
5. B: $POP \times T \rightarrow \mathrm{N}$
6. D: $POP \times T \rightarrow \mathrm{N}$
7. E: $POP \times T \rightarrow \mathrm{N}$
8. I: $POP \times T \rightarrow \mathrm{N}$
9. RPC: $DP \times N_t \times (F_i)_{i \leq k} \times T \rightarrow \mathrm{R}$

The objects that occur in the predicate *may be interpreted as follows*:

1. A set of *organisms* (O), or, better, of sets of organisms $Pot(O)$ belonging to the same species which make up *populations*, where **pop** symbolizes a population (**pop** $\subseteq Pot(O)$) and POP the set of populations such that **pop** $\in POP$.
2. The *time*, represented by a dense linear order $\langle T, < \rangle$, on the set of instants T, where $<$ represents the temporal relationship "is posterior to"; $\langle T, < \rangle$ is isomorphic with the pair $\langle \mathrm{R}, < \rangle$, consisting in the set of real numbers R and in the relation-less-than on the real numbers $<$. It is possible to define a distance function for real numbers, establishing that $d(\alpha, \beta) = |\alpha - \beta|$, where $\alpha, \beta \in \mathrm{R}$ and $|\ |$ is the function of absolute value. In addition, one can add real numbers and define the derivative for functions of R in any numerical spaces. If we interpret R by means of T, the distance between instants is what is known as "lapse," "duration" or "interval." Each interval goes from t to t_{+1} where t coincides with the beginning of the interval and t_{+1} coincides with the end of the interval, being then $\Delta T = t_{+1} - t$.
3. A set of *types of population factors* ($(F_i)_{i \leq k}$). Every set F_i has to be considered as a type of population factor and its members $f_i \in F_i$ as variables or expressions of population factors of this type. Each of the "types of population factors" is a set of variables that can modify the intensity of population processes. A very common way to classify them is in the following subsets: F_{amb} or "environmental factors," which would be variables that represent some components of the environment of organisms, such as resources and physical and chemical conditions of the environment; F_{gen} or "genetic factors," which would be variables related to genetic structure, social structures and physiological characteristics, and, finally,

F_{bio} or "biotic (or biological) factors," which would be variables that measure biotic interactions such as predation, parasitism, and intra- or interspecific competition.

The functions that occur in the predicate *are interpreted as follows*:

4. N_t is a function that assigns to a population (set of organisms) in a given time t the *population size* (or cardinality of the set), expressed in natural numbers: $N(pop, t) = n_t$,; N_t is usually written for the function that assigns a value to the population (set of organisms) at a given time t, and that represents the number of organisms that make up that set (population) at that instant of time, and n_t for the value assumed by that function.
5. B is a function that assigns to a population (set of organisms) at a given time t, its *natality* (or cardinality of the set) expressed in natural numbers: $B(pop, t) = b_t$; B is usually written for the function that assigns a value to the population (set of organisms) at a given time t, and that represents the number of *born organisms* (O_b) that make up that set at that instant of time, and b_t for the value assumed by that function.
6. D is a function that assigns to a population (set of organisms) at a given time t, its *mortality* (or cardinality of the set) expressed in natural numbers: $D(pop, t) = d_t$; D is usually written for the function that assigns a value to the population (set of organisms) at a given time t, and that represents the number of *death organisms* (O_d) that make up that set at that instant of time, and d_t for the value assumed by that function.
7. E is a function that assigns to a population (set of organisms) at a given time t, its *emigration* (or cardinality of the set) expressed in natural numbers: $E(pop, t) = e_t$; E is usually written for the function that assigns a value to the population (set of organisms) at a given time t, and that represents the number of *emigrated organisms* (O_e) that make up that set at that instant of time, and e_t for the value assumed by that function.
8. I is a function that assigns to a population (set of organisms) at a given time t, its *immigration* (or cardinality of the set) expressed in natural numbers: $I(pop, t) = i_t$; I is usually written for the function that assigns a value to the population (set of organisms) at a given time t, and that represents the number of *immigrated organisms* (O_i) that make up that set at that instant of time, and i_t for the value assumed by that function.

   Auxiliar definition:

   $DP = \{B \cup D \cup E \cup I\}$, *demographic processes*, is the union of all demographic processes (death, birth, emigration and immigration).

   Auxiliar definition:

   $DF := DP/(N_t \cdot \Delta T)$. *Demographic functions* (Lotka 1925) are the functions that express through rates the values of demographic processes (death, birth, emigration and immigration). It assigns to a demographic function its expression per capita and per time lapse by means of the equation $DF = DP/N(pop, t) \cdot (\Delta T)$.
9. The rate of population change RPC is a function that calculates a real number that represents the variation in the number of individuals per individual from the

set of demographic processes (DP), the size of the population (N_t), and the set of population factors ($(F_i)_{i \leq k}$) in an instant of time (T).

We can now define the class of (actual) *models of population dynamics* (**M**(**PD**)), which is the total class of structures that satisfy the "frame conditions" and, in addition, the "substantial laws" of **PD** through the set-theoretical predicate "being a model of population dynamics" as follows:

Definition 2
M(**PD**): If $x = \langle O, T, <, (F_i)_{i \leq k}, N, B, D, E, I, RPC \rangle$, then x is a *model of population dynamics* ($x \in$ **M**(**DP**)) if and only if

1. For every $t, t_{+1} \in T$: $\mathbf{pop}_t, \mathbf{pop}_{t+1} \in POP$, and being $N(pop, t) = n_t$ and $N(pop, t_{+1}) = n_{t+1}$ such that $\Delta N = n_{t+1} - n_t$, for every DP, and being $DF = f(DP, N_t, T)$ and for every $f_i \in (F_i)_{i \leq k}$, there exist a $RCP(\langle fd_1, \ldots, fd_4 \rangle, n_t, \langle f_i, \ldots, f_x \rangle, t)$ (in R) such that:

$$\Delta N = RCP\left(\left\langle fd_1, \ldots, fd_4 \right\rangle, n_t, \left\langle f_i, \ldots, f_x \right\rangle, t\right) \cdot N_t.$$

The condition of definition, or axiom, 1 formulates in a more formal way the fundamental law/guiding principle of population dynamics (**PDGP**) of Sect. 10.2.1, which establishes that a "match" or "fit" takes place between the observed (or estimated) change in population size over time and the rate of population change, multiplied by the population size at the initial time. Every structure of type x that satisfies it is an (actual) model of **PD**.

The class of *partial potential models* of **PD** characterizes the point of departure for population dynamics. It is constituted by that which is intended to systematize, explain, and predict. In order to characterize this class, it is necessary to distinguish between theoretical and non-theoretical concepts within **PD**, i.e., between specific concepts of population dynamics (or **PD**-theoretical) and non-specific concepts of population dynamics (or **PD**-non-theoretical).

A detailed discussion of the application of the **T**-theoreticity criterion to every **PD**'s term (or concept) is beyond the aim of this paper. We conjecture that the concepts of "biotic (or biological) factors" (F_{bio}) among the population factors ($(F_i)_{i \leq k}$) and of rate of population change (RPC), which inherits its theoreticity from the biotic (or biological) factors of the population factors, are **PD**-theoretical while the rest of the concepts are **PD**-non-theoretical.

We are now able to characterize the class of partial potential models of **PD** through the set-theoretical predicate "being a partial potential model of population dynamics" as follows:

Definition 3
$\mathbf{M_{pp}}$(**DP**): $y = \langle O, T, <, N_t, B, D, E, I \rangle$ is *a partial potential model of population dynamics* ($y \in \mathbf{M_{pp}}$(**PD**)) if and only if exists an x such that

1. $x = \langle O, T, <, (F_i)_{i \leq k}, N_t, B, D, E, I, RPC \rangle$ is a $\mathbf{M_p}$(**DP**)
2. $y = \langle O, T, <, N_t, B, D, E, I \rangle$.

10.4 The Concept of Theory from the Point of View of Metatheoretical Structuralism

In the same way that in the case of law discussed above there has long been the problem of establishing the nature and structure of a scientific theory. After decades of discussion, different conceptions coexist, often at odds, of what a theory is and whether there is a theory structure that is shared by all scientific disciplines.

As it was already said three main philosophical conceptions about scientific theories have been developed during the twentieth and the twenty-first century so far: the "classical (or received)" view, the "historical (or historicist)" view and the "semantic (or model-theoretic)" view.

The main representative of the classical view in biology during the first half of the twentieth century was J. H. Woodger, who aimed to apply and develop the philosophy of the science of logical positivism for the specific field of biology (Woodger 1937, 1939, 1952, 1959, 1965).

In relation now to the general adequacy of the classical view for the analysis of biological theories, we could say that, though scientists like C.H. Waddington (1968–1972) promoted and employed such a view, among philosophers, and despite the efforts outlined, opinion about the applicability of the classical view to biology was divided. Thus, Morton Beckner (1959) did not accept the classical view, but assumed that its application to biology was, at best, limited and, with its treatment of biological theories as families of models, anticipated to some extent the analysis of such theories later carried out within the framework of the semantic conceptions. Thomas Goudge (1961, 1967), for his part, was quite explicit in pointing out that, regardless of the applicability that this conception might have in physics, it would not capture important features of biological theories and explanations. On the other hand, Michael Ruse (1973) and Alexander Rosenberg (1985) were two philosophers who during the seventies and eighties sustained the applicability of the classical view of theories to biology. Other philosophers, on the other hand, argued in favor of the relevance of this conception for biological theorization, although with varying degrees of caveats and subtleties (e.g., Hull 1974).

Even though it is admitted that "[t]here are many ideas about the nature of theory in sci¬ence and in philosophy" and that "[i]n ecology, there is currently no consensus regarding the definition, role, and generality of theories" and "ecologists use the label theory to refer to many things" (Marquet et al. 2014, p. 701), there are authors who have assumed the classical view of theories (Marquet et al. 2014; Murray 2001; Peters 1991; Roughgarden 1998). On the other hand, there are authors who consider that taking this option in some disciplines like ecology is not adequate (Castle 2001; Sagoff 2003; Pickett et al. 2007).

With regard to the historicist view, although Kuhn (1970) and Laudan (1977) themselves consider Darwinism to be a paradigm and a research tradition, respectively, they do not carry out a systematic analysis of it using such notions. And even though there are many authors who follow them and consider Darwinism or other developments within biology, such as Mendelism, a paradigm or disciplinary matrix, a research tradition or, in the terminology of Lakatos (1970), a research programme, there are not many detailed analyses, in terms of these concepts, of these fields in particular or of biology in general. On the other hand, as Jean Gayon points out, while there are authors who are rather skeptical about the usefulness of the category of 'paradigm' for the history of Darwinism (e.g. Greene 1971; Mayr 1972), Burian (1989) suggests "that the 'Darwinism' at the end of the 19th century was a genuine 'paradigm' in the initial sense given to the word by Thomas Kuhn (an exemplary model of scientific research), but certainly not in the sense of a 'disciplinary matrix'" (Gayon 1998, f.n. 19, p. 409). Other authors follow Burian's path, but in other areas of biology, and accept the character of 'shared examples' or 'exemplars' of many achievements in biology, but not necessarily their character of 'disciplinary matrices' (Darden 1991; Schaffner 1986, 1993). In fact, taking the historical character of entities such as disciplinary matrices, research traditions and research programmes, it is more usual to affirm and discuss the revolutionary or evolutionary character of certain proposals in the field of biology and their development over time (see, among others, Ruse 1979, 2005; Oldroyd 1980; Maienschein et al. 1981; Cohen 1985; Bowler 1988) than to clearly identify their components as disciplinary matrices, research traditions, or research programmes.

However, we also find some attempts to apply, even systematically, such notions to biology—so, e.g., the Lakatosian concept of scientific research programme is used by Michod (1981) for the analysis of the history of population genetics, by Meijer (1983), Van Balen (1986, 1987) and Lorenzano (2013) for the analysis of the history of so-called "classical", "formal" or "Mendelian" genetics, by Torres (1996) for the analysis of the origin of life and by Denegri (2008) for the analysis of parasitology; we can also mention that Pickett et al. (2007) use some Kuhnian ideas to analyze the paradigm changes in ecology.

The *semantic view* has had an impact in diverse areas of biology, and some of its versions have been applied to them. For example, Suppe (1974) tries to shed light on some philosophical problems related to speciation and taxonomy through the use of his own version of the semantic view. And Giere (1979) exemplifies his own version of the semantic view with the most basic part of classical (or Mendelian) genetics. In addition, attempts have also been made to apply in a systematic way van Fraassen's state-space approach to the analysis of the structure of the theory of evolution, and thus eventually of population genetics (Beatty 1980, 1981; Lloyd 1984, 1986; Thompson 1983, 1986). This, in turn, has motivated the position taken by authors such as Sloep & van der Steen (1987a, b) and Ereshefsky (1991) and the response and/or further developments of Beatty (1987), Lloyd (1987, 1988) and Thompson (1987, 1989, 2007). This variant of semantic view has also been applied to the analysis of theories of sex and gender (Crasnow 2001) and of ecology (Castle 2001). We also find the use of the axiomatization à la Suppes for attempting to identify the class of models of the theory of evolution by natural selection and of population genetics (Magalhães & Krause 2000).

However, it is metatheoretical structuralism that has produced the greatest number of analyses of particular theories belonging to the biological sciences. Just to mention a few, in the field of evolutionary biology, we can see the analyses of the structure of the theory of evolution by natural selection made by Ginnobili (2016), Ginnobili & Blanco (2017), Díez & Lorenzano (2013, 2015), as well as of the theory of common descent made by Blanco (2012); in the field of inheritance and genetic theories (classical, molecular and population genetics), the works of Balzer & Dawe (1986, 1990), Balzer & Lorenzano (2000), Casanueva (1997), Casanueva & Méndez (2005) and Lorenzano (1995, 2000, 2014); cellular and tissue theories have been the object of structuralist analysis by Asúa & Klimovsky (1987, 1990), as has the theory of excitable membranes by Müller & Pilatus (1982), and of neuroendocrinology by Bernabé (2019).

Finally, we can say that in ecology in particular, the analyses have made their historical journey parallel to the philosophy of science. In the first place, as we have already mentioned authors who, starting from the analysis of the theories of the discipline from the received view, have made severe criticisms (see Ibarra & Larrañaga 2011; Lawton 1999; Marquet et al. 2014; Roughgarden 2009). But on the other hand we can point to authors who have analyzed the discipline from other views and have led to the reconstruction of theories of ecology in recent decades (Castle 2001; Scheiner & Willig 2011; Díaz & Lorenzano 2017).

The point of departure of the structuralist explication of the concept of a theory is the recognition that the term "scientific theory" is ambiguous, or better, polysemic, in its pre-systematic use. Sometimes it means just one law (like when one speaks indistinctly of the *law* of gravitation or of the *theory* of gravitation). This sense is not explicated by the structuralist concept of a theory, but by the structuralist concept of a law. Sometimes, the use of the term "scientific theory" corresponds to what is explicated by the structuralist notion of *theory-element*. In this sense, a theory-element is the smallest portion of science that seems to possess all the characteristics usually associated to theories. However, even this smallest sense of theory *cannot be identified with a clas*s (or set or population or collection or family) *of models*, although it *can be identified mainly through them*. Despite the fact that such a class is the most basic component for the identity of a theory, it is not the only one. A *theory-element*—i.e., the simplest kind of set-theoretical structure that can be identified with, or can be used as a rational reconstruction of, or can be regarded as a formal explication of, a theory (in an informal, intuitive sense)—can be identified, as a first approximation, with an ordered pair consisting of the "(formal) *core*," symbolized by **K**, and the theory's "domain of intended applications," symbolized by **I**: $\mathbf{T} = \langle \mathbf{K}, \mathbf{I} \rangle$.

The *core* **K** constitutes the formal identity of any empirical theory with a certain degree of complexity, which is composed by the ordered classes of *potential models*, *actual models*, *partial potential models*, *constraints*, and *links*, i.e., $\mathbf{K} = \langle \mathbf{M_p}, \mathbf{M}, \mathbf{M_{pp}}, \mathbf{C}, \mathbf{L} \rangle$.

In the previous section we already introduced the classes of *potential models*, (*actual*) *models*, and *partial potential models*.

While the inner theoretical relationships between the different models of a theory are represented by the so-called *constraints* **C**, the intertheoretical relationships are represented by the so-called (*intertheoretical*) *links* **L**. They characterize the theory's "essential" relationships to other theories by connecting the **T**-non-theoretical terms with the theories they come from.

Any empirical theory is related to "reality" or "outside world," i.e., to some specific phenomena or empirical systems submitted to some specific conditions, to which it is intended to be applied and for which it has been devised. These empirical systems also belong to a theory's identity because otherwise we would not know what the theory is about, for the class of models contains "all" models, intended as well as non-intended. They constitute what is called the theory's *domain of intended applications* **I**. The domain of *intended applications* of a theory, even when it is a kind of entity strongly depending on pragmatic and historical factors that, by their very nature, are not formalizable, is conceptually determined through concepts already available, i.e., through **T**-non-theoretical concepts; thus, each intended application may be conceived as an empirical (i.e., **T**-non-theoretical) system represented by means of a structure of the type of the partial potential models $\mathbf{M_{pp}}$. All we can formally say about **I** is, thus, that it is a subset of the class of partial potential models $\mathbf{M_{pp}}$.

Theories are not statements but are *used* to make statements or claims, which then have to be tested. The (empirical) statements (or claims) made by means of scientific theories are, intuitively speaking, of the following kind: that a given domain of intended applications may actually be (exactly or approximately) *subsumed* (or *embedded*) under the theory's principles (laws, constraints, and links). Normally, in any "really existing" theory, the "exact version" of the so-called *central empirical claim* of the theory—that the whole domain of intended applications may actually be (exactly) subsumed (or embedded) under the theory's principles—will be strictly false. What usually happens is that either there is a subclass of intended applications for which the empirical claim is true or that the central empirical claim is, strictly speaking, false but *approximately true*.[21]

Some "real-life" examples of scientific theories can actually be reconstructed as *one* theory-element, but usually single theories in the intuitive sense have to be conceived as aggregates of several (sometimes a great number of) theory-elements. These aggregates are called *theory-nets*. This reflects the fact that most scientific theories have laws of very different degrees of generality within the same conceptual setting. Usually there is a single fundamental law or guiding principle "on the top" of the hierarchy and a vast array of more special laws—which apply to specific situations—with different degrees of specialization.

Each special law determines a new theory-element. What holds together the whole array of laws in the hierarchy is, first, the common conceptual framework (represented in a model-theoretic way by the class of potential models), second, the common **T**-theoretical and **T**-non-theoretical distinction, and third, the fact that they are all specializations of the same fundamental law.

[21] For a structuralist approach to features of approximation and a precise formal explication of the notion of the approximative empirical claim, see Balzer et al. (1987), chapter VII.

The theory-element containing the fundamental law(s)/guiding principle(s) is called the "*basic* theory-element" of the theory, i.e., of the theory-net. The other theory-elements of the theory-net are specializations or "*specialized* theory-elements."

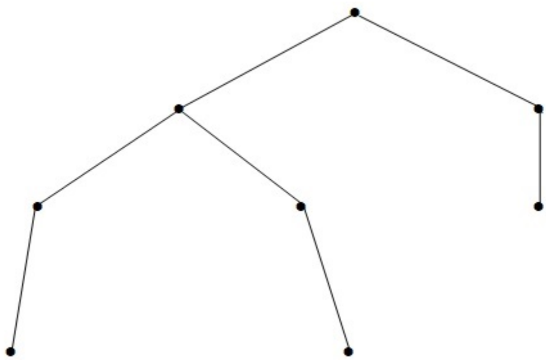
When the highest degree of concretization or specificity has been reached, i.e., when all functional dependencies (concepts) are completely concretized or specified, "*terminal* special laws," which determine the most specific class of (theoretical) models, are obtained. The empirical claims associated to the corresponding "*terminal* specialized theory-elements" can be seen as particular, testable and, eventually, refutable hypotheses, which enables the application of the theory to particular empirical systems.[22] In the simplest model-theoretic way of representing these particular empirical claims, they state following: "*data model*" *d* of **T** can actually be (exactly or approximately) extended to, or subsumed or embedded in, the "*theoretical model*" *m* of **T**.

The resulting structure of a theory may be represented as a net where the nodes are given by the different theory-elements, and the links represent different relations of specialization (see Fig. 10.3).

A theory-net **N** is the standard structuralist conception of a theory from a static or *synchronic* point of view. In this sense, a theory is *a complex*, *strongly hierarchical*, and *multi-level* entity.

But a theory can also be conceived as a kind of entity that develops over time. A theory in the *diachronic* sense is not just a theory-net, which exists in the same form through history, but a *changing* theory-net, which grows and/or shrinks over time. Such an entity is called a *theory-evolution* **E**. It is basically a sequence of theory-

Fig. 10.3 Theory-net



[22] This is the model-theoretic, semantic, in particular, structuralist version of what has been said in Sect. 10.2 about the testability and eventually refutability of particular hypotheses/terminal special laws. While in the classical approach of testing the particular hypotheses/terminal special laws are the entities to be tested, in the structuralist approach the "empirical claims" associated to *terminal* special laws are the entities that carry the weight of testing and to which it is able to direct "the arrow of *modus tollens*" (Lakatos 1970, p. 102).

nets satisfying two conditions: at the level of cores, it is required for every new theory-net in the sequence that all its theory-elements are specializations of some theory-elements of the previous theory-net; at the level of intended applications, it is required that the domains of the new theory-net have at least some partial overlapping with the domains of the previous theory-net.

Finally, it can be said that the structuralist view has been proposed to represent not just *intratheoretical changes* that occur in science (by means of the concept of a *theory-evolution*) but also different types of *intertheoretical changes*, such as *crystallization*, *embedding*, and *replacement with* (*partial*) *incommensurability*. It is worth noting that the process of crystallization of a theory would allow the treatment of the role of models (in the sense of laws or theory-elements) in the genesis of new empirical theories (in the sense of theory-nets and, later, of theory-evolutions) within the structuralist framework.

10.4.1 The Theory-Net of Population Dynamics

According to our proposal, and as any other robust unified theory such as classical mechanics or thermodynamics, **PD** can also be better analyzed as a theory-net.

The Basic Theory-Element of Population Dynamics

The "*basic* theory-element" of **PD** consists of its "(formal) *core*," symbolized by **K**(**PD**), and its "domain of intended applications," symbolized by **I**(**PD**).

The Basic Core of Population Dynamics

The basic *core* of population dynamics **K**(**PD**), which constitutes its formal identity, is composed by the ordered classes of *potential models*, *actual models*, *partial potential models*, *constraints*, and *links*.

In the previous section we already defined the classes of *potential models* $\mathbf{M_p}$(**PD**), (*actual*) *models* **M**(**PD**), and *partial potential models* $\mathbf{M_{pp}}$(**PD**).

In a truly complete reconstruction of **PD** we should include the constraints and the links this theory has to other (underlying) theories. However, due to space limitations, we will not discuss them or make them explicit. So the *basic core of population dynamics* (**K**(**DP**)) will be characterized as follows:

Definition 4

$$\mathbf{K}(\mathbf{DP}) := \langle \mathbf{M_p}(\mathbf{DP}), \mathbf{M}(\mathbf{DP}), \mathbf{M_{pp}}(\mathbf{DP}) \rangle.$$

The Intended Applications and the Basic Theory-Element of Population Dynamics

The *domain of intended applications* constitutes the class of those empirical systems to which one wishes to apply the fundamental law/guiding principle of the theory. They cannot be characterized by purely formal means. All we *can* say from a formal point of view is that an intended application is a partial potential model, which means that $\mathbf{I}(\mathbf{DP}) \subseteq \mathbf{M}_{\mathbf{pp}}(\mathbf{DP})$. Members of **I**(**DP**)—to which one wishes to apply the fundamental law/guiding principle of **DP**—are empirical systems, characterized in **DP**-non-theoretical terms—i.e., systems represented by structures/data models of type *y* ($\langle O, T, <, N_t, B, D, E, I\rangle$) where certain organisms that make up a population in which a set of demographic processes (birth rate, mortality, emigration, and immigration) that determine the population size is modified in a certain interval of time, or, for short, where changes in population size over time take place.

Now the *basic theory-element of population dynamics* (**T**(**PD**)) can be characterized as follows:

Definition 5

$$\mathbf{T}(\mathbf{PD}) := \langle \mathbf{K}(\mathbf{PD}), \mathbf{I}(\mathbf{PD}) \rangle$$

The Empirical Claim of Population Dynamics

Population dynamics (**PD**) pretends that certain empirical systems such as those characterized above, characterized in **DP**-non-theoretical terms, satisfy the conditions imposed by **PD** in the following sense: those are the data of the experience that should be obtained if reality behaves as **PD** says. This pretension is asserted by the empirical claim of population dynamics, which may be formulated in the following way:
(I) Any given intended system can be, adding a set of **PD**-theoretical components $(F_i)_{i \leq k}$ and *RPC* to the **PD**-non-theoretical part of the corresponding theory-core ($\langle O, T, <, N_t, B, D, E, I\rangle$), (exactly or approximately) extended to, or subsumed or embedded in, a **PD** (actual) model.

This claim may be trivial if the conditions imposed by the core on the **PD**-theoretical components are weak. But this should not be a reason for rejecting the core as trivial. This core serves as a basic core for *all* the intended applications of population dynamics. Interesting, non-trivial claims may be obtained by incorporating additional restrictions through the so-called “specializations.”

Specializations of Population Dynamics

There are different possible ways of specializing population dynamics. As already advanced in Sect. 10.2.1, specializations consist of specifications of

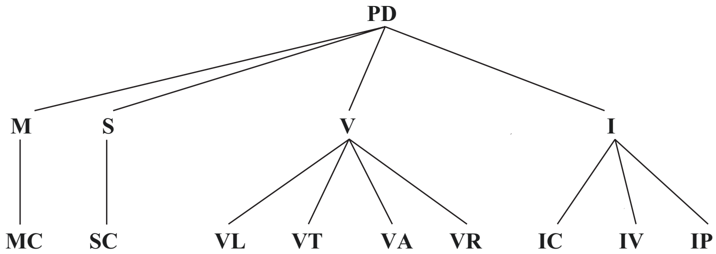


Fig. 10.4 Theory-net of population dynamics

(i) Types and numbers of components of the *rate of population change* (*RPC*) acting together (i.e., types and numbers of demographic processes (*DP*) and of population factors $((F_i)_{i \leq k})$), and of
(ii) (a) the specific mathematical form assumed by *RPC* and (b) the specific mathematical form assumed by the fundamental law/guiding-principle (being it continuous, discrete, exponential, linear, logistic, etc.)

The diverse possibilities of specialization can be partially or totally realized in an isolated or joint way. One specialization of **PD** in which the two types of specification have been fully realized is denominated *terminal specialization*.

The theory-net of population dynamics (**N**(**PD**)) looks as follows—with the "*basic* theory-element" of **PD** at the top and in which are only depicted "*specialized* theory-elements" of **PD** corresponding to the examples given in Sect. 10.2.1 (Fig. 10.4):

On a first level of specialization of **PD** theory-net we have either that *RPC* only depends on the demographic processes of birth and mortality and is not affected by population factors ("Malthusian populations") (**M**) or that *RPC* depends on the demographic processes of birth and mortality and is affected by genetic factors ("structured populations") (**S**) or that *RPC* depends on the demographic processes of birth and mortality and is affected by environmental and biotic factors ("Verhulst populations") (**V**) or that *RPC* depends on the demographic processes of birth and mortality and is affected by biotic factors that also involve a population of another species ("interspecific populations") (**I**). On a second level of specialization of **PD** theory-net we reach the level of terminal specializations by specifying *RPC* mathematical form, i.e., the specific equations. If **M** is further specialized, we have a case of no population limitations of continuous and exponential variation (**MC**) (see case 1 from Sect. 10.2.1). If **S** is further specialized, we have a case of continuous and exponential variation (**SC**) (see case 2 from Sect. 10.2.1). If **V** is further specialized, we can have either a case of carrying capacity and continuous logistic variation with linear dependence between *b*, *d* and N_t (**VL**) (see case 3 from Sect. 10.2.1), or a case of carrying capacity and continuous logistic variation with linear dependence between *b*, *d* and the population size in an instant of time previous to *t* (**VR**) (see case 4 from Sect. 10.2.1), or a case of carrying capacity and continuous logistic variation with non-linear dependence between *b*, *d*, N_t and *C* (**VA**) (see case 5 from Sect. 10.2.1), or a case of carrying capacity and continuous logistic variation with linear dependence between *b*, *d* and N_t (**VT**) (see case 6 from Sect. 10.2.1). Finally, if **I** is further specialized, we can have either a case of carrying capacity and continuous logistic variation with dependence on b and d with N_{t1}, K_1, N_{t2} and α (**IC**) (see case 7 from Sect. 10.2.1), or a case of exponential continuous variation and demographic processes without dependence on population size, for prey (**IV**), and for predator (**IP**) (see case 8 from Sect. 10.2.1).[23]

10.5 Making Them Explicit: Laws and the Connection of Models to Theories: Discussion on the Basis of Previous Analysis

We would like to discuss now the issues of (a) the existence of laws in biological sciences, (b) the place of models in theories of biology, and (c) the unifying power of biological theories, in the light of the analyses carried out.

10.5.1 On Claim (a) That There Are "Laws" in Biological Sciences

It is worth mentioning that in the literature it has been recognized that there exist certain areas of science where fundamental laws/guiding principles—though maybe with another terminology, such as "basic principles" or "fundamental equations"—occur explicitly formulated in linguistic terms and sometimes even in an axiomatic or quasi-axiomatic way. Newton's Second Law is an example of that, i.e., of a fundamental law/guiding principle explicitly formulated in linguistic terms, even in an axiomatic way since its first public occurrence, in the first edition of *Principia Mathematica Philosophia Naturalis* (Newton 1687) although it was mistakenly ranked at the same level of the other two "Axioms, or Laws of Motion": the Law of Inertia and the Law of Action and Reaction.

On the other hand, in the literature of philosophy of science it has also been pointed out that there are other areas of science where fundamental laws/guiding principles do not occur explicitly and clearly formulated in linguistic terms. An example of one of these areas is evolutionary biology and the so-called "principle of natural selection." In biology textbooks (beginning with Darwin's *Origin of Species*) we cannot find nor "observe" that principle formulated in all their generality, abstraction and schematization, although there is an agreement about the fact that a fundamental law/guiding principle "is there" and a lot of discussion about the right and convenient way of identifying and formulating it.[24]

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[23] The theory-net of PD is a clear example of Levins' following claim: "This is a modeling sequence from the general to the particular, adapting general knowledge to particular cases by successive specifications that might reach the end point of assigning numerical values. At each stage of specification the model is more precise and realistic but less general (Levins1993, p. 551):

[24] For a discussion and a proposal on this issue from a structuralist point of view, see Ginnobili (2016) and Díez and Lorenzano (2015).

However, philosophers of science have also pointed out to other areas of science where nothing can be found or "observed" at all that possesses the criteria mentioned in Sect. 10.2 and that would, therefore, be considered a fundamental law/guiding principle in a plausible way. And precisely the field of population dynamics is an example of that. If we consider what is sometimes called a "law" in the area of population dynamics, namely, the so-called "Malthus law" (or "equation") or "Lotka-Volterra equations,"[25] it is easy to recognize that neither Malthus' law nor the equations of Lotka and Volterra are schematic and general enough to connect all or almost all of the terms of their theories nor to be accepted by their respective scientific communities as valid for all applications, with modal import, and as providing a conceptual framework adequate to formulate all the special laws of population dynamics. These laws, therefore, cannot be considered fundamental laws of population dynamics. That is to say no such law can be "observed" in the literature of ecology (Lockwood 2008; Ibarra and Larrañaga 2011).

We grant that, sometimes, we cannot "observe" (explicit linguistic formulations of) general laws (or guiding principles) in the standard presentations of the respective theories, i.e., in the different texts (either journal articles, manuals, or textbooks) written by scientists or science teachers.

Nevertheless, this article has argued for the existence of a fundamental law/guiding principle of population dynamics that even though not stated explicitly in biological literature underlies implicitly the usual formulations of the theories, systematizing them, making sense of ecologists' practice, and unifying the different and heterogeneous models under just one theory.

In Sect. 10.3 a fundamental law/guiding principle in this area has been made *explicit* against what can be called "narrow inductivism" or "restricted empiricism" in metascience.[26] And it is easy to realize that in the formulated fundamental law/

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[25] The equations are named within ecology as "laws,", "rules," "models," or "theories" in an indistinct and confused way.

[26] Nowadays, it can be considered a truism in philosophy of science that empirical science goes beyond "appearances," "phenomena," or "facts" in order to understand them better. Empirical science postulates, in addition, a realm of entities that are not directly empirically accessible, but they are accepted, *at least* inasmuch as the linguistic frameworks or theories in which they essentially occur are accepted as well (Carnap 1950). Thus, for instance, electric fields and wave functions are accepted, at least inasmuch as the theories of electromagnetism and quantum mechanics, respectively, are accepted. And scientists had good reasons to do so. Let us call that view on science "non-narrow inductivism" (inspired by Hempel 1966) or "non-restricted empiricism" (inspired by Carnap 1956). The analyses (explications) of (metascientific) concepts, such as *law*, *model*, or *theory*, can be considered as forming *interpretative schemes* or *explanatory models*—in the sense of Hintikka (1968) within epistemic logic, and of Stegmüller (1979) and Moulines (1991, 2002) within philosophy of science—of a philosophical nature, which propose or exhort us to "see the world" of science in a certain way. And a philosopher of science who uses one of these explanatory models overcomes narrow inductivism and restricted empiricism on a metascientific level in a similar way to what has been said and recommended for the case of the scientist. She/he interprets in a non-narrow inductive or non-restricted empiricist way what scientists do: not because we do not (directly) "see" their "fundamental laws/guiding principles," they are not "(in some sense) there" to be seen. As Goodman says, "We see what we did not see before, and see in a new way. We have *learned*" (Goodman 1978, p. 173).

guiding principle we can identify all criteria of fundamental laws/guiding principles indicated in Sect. 10.2. First, **PD** fundamental law/guiding principle can be seen as a *synoptic* law because it establishes a substantial connection between the most important terms of **PD** in a "big" formula. It contains all the important terms that occur in **PD**, both the **PD**-theoretical ones (the set of biotic factors and the rate of population change) and the **PD**-non-theoretical ones, which are empirically more accessible (populations and their sizes, time, the demographic processes, and the sets of environmental and genetic factors). Second, **PD** fundamental law/guiding principle has been *implicitly accepted as valid in every intended application of the theory* by the respective community of scientists, i.e., by the community of ecologists who accept or use **PD**. In fact, accepting **PD** implies accepting **PD** fundamental law/guiding principle while rejecting **PD** fundamental law/guiding principle implies rejecting **PD**. And of course ecologists may not succeed in applying **PD** to particular empirical systems and may decide to use another theory with another fundamental law/guiding principle. But to the extent that they work with **PD**, they accept as valid, even though just implicitly, **PD** fundamental law/guiding principle. Third, **PD** fundamental law/guiding principle is *highly schematic* and *general* and it possesses *very little empirical content* that it is, when considered in isolation, irrefutable or "empirically non-restrict" (Moulines 1984) (i.e., it has a "*quasi-vacuous*" character). Because to examine the empirically determined (or estimated) change of population size and the theoretically postulated population factors and the rate of population change, and to set out to test what the law claims—namely, that the observed (or estimated) change in the size of the population in a certain period of time corresponds to the product of the rate of population change multiplied by the size of the population at the beginning of the time interval—without introducing any kind of further restrictions, amounts to a "pencil and paper" exercise that does not involve any empirical work. Nevertheless, fourth, as we would expect in the case of any fundamental law/guiding principle, despite being irrefutable, it *provides a conceptual framework* in which all special laws can be formulated; that is, special laws with an increasingly high degree of specificity and with an ever more limited domain of application, until we reach "terminal" specializations whose associated empirical claims can be seen as particular, testable and, eventually, refutable hypotheses, which enables the application of **PD** to particular empirical systems (its *systematizing* or *unifying* role). And fifth, **PD** fundamental law/guiding principle expresses a non-accidental regularity that is able to give support to counter-factual statements (if it is taken "together-with-their-specializations" within the corresponding theory-net), even when it is context-sensitive and with a domain of local application, and that, in its minimal sense, what is attributed is the *necessity of the models*, and, in that sense, it should be considered as *necessary in its area of application* (i.e., it possesses *modal import*). This means that when the theory-net of **PD** contains an application with *s* as the relevant specialization of **PD** fundamental law/guiding principle and *i* as the empirical system/application, then, given the constrictions that the specialization *s* determines at the **PD**-non-theoretical level, a certain data model *should* be obtained for the empirical system *i* to which the theory-net of **PD** is intended to apply, i.e., the empirical system *i* to which the theory-net of **PD** is intended to apply *should* behave in a certain way—represented by the corresponding data model. Recalling that any specialization presupposes all that is "above" it in the corresponding branch of the theory-net of **PD**, notably the fundamental law/guiding principle, the counterfactual "if *s* were the case, then *i* (i.e., its corresponding data model) would be the case" is true according to the theory-net of **PD**.

On the other hand, it is easy to realize that Malthus' law and the equations of Lotka and Volterra should be considered *special laws* of **PD**.

10.5.2 On Claim (b) That Many of the Heterogeneous and Different "Models" of Biology Can Be Accommodated Under Some "Theory"

Let us suppose that a theory (a theory-net in the structuralist sense) is not clearly visualized and, nevertheless, certain "laws" or "equations" or "models" are clearly identified, but they cannot be taken as fundamental laws/guiding principles or "models" *of a theory*; they are rather considered "autonomous" with respect to "theories" and do not cover the entire supposed domain of application of the corresponding realm.

This situation could arise under the following two circumstances:

The first occurs when these laws, equations, or models are *indeed isolated laws* or *equations* or *models*. This circumstance can occur *in a synchronic* or *in a diachronic way*. Both situations are "entirely compatible" with metatheoretical structuralism.

In fact, the law of ideal gases and Ohm's law are mentioned in the structuralist literature (Balzer 1996) as examples of isolated laws. Even though they are not part of theory-nets, they are perfectly conceptualizable in structuralist terms, namely, as theories that can actually be reconstructed as *only one theory-element* (see Fig. 10.5).

On the other hand, this "isolation" of the theory-elements, in the structuralist terminology (or "autonomy" of the "models" in the model views terminology), cannot only be systematically and synchronously established but can also remain diachronically invariable or not.

If it were the last thing, it could be a case where "a law is in search of a fundamental law/guiding principle, of which it becomes a special law" or, in other words, where "a model is in search of its theory (i.e., its theory-net) to which it can be incorporated" (see Fig. 10.6).

Or it could be a case where "a law, or a model, from which—together with many other things—a theory (i.e., a theory-net) is developed (and, finally, ends up consolidating or crystallizing)" (see Fig. 10.7).

And although this can only be determined retrospectively, all these circumstances, whether it be an isolated law or model, which so remains, or an isolated (or incipient) law or model, which is later incorporated into a theory or from which a theory is developed and ends up crystallizing a theory (theory-net), would be susceptible of being represented by the structuralist metatheory, through their con-

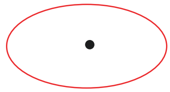

Fig. 10.5 Theory-net with only one theory-element

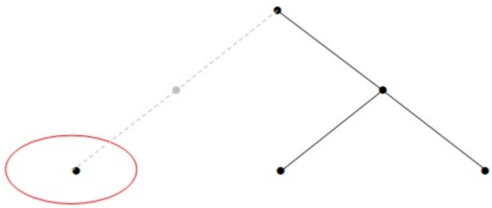

Fig. 10.6 Model in search of a fundamental law/guiding principle

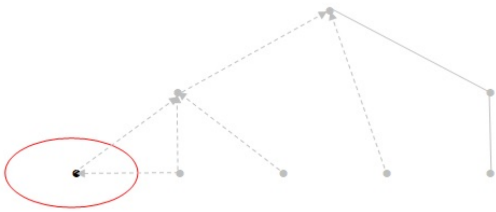

Fig. 10.7 A law from which a theory-net is developed

ceptualization as an isolated theory-element (the simplest and smallest notion of theory) or as its incorporation (or reduction, exact or approximate) to a theory-net (as specialization) or as part of a crystallization process, respectively.[27]

Another circumstance occurs when the *laws*, *equations*, or *models*, despite their appearance of "autonomy" from "theories" and from any fundamental law/guiding principle, *are not*, in fact, *autonomous* in a sense that can be made precise as follows. Here we would be faced with cases of laws, equations, or models, which would be special cases of fundamental laws/guiding principles that are not "observed" in their greater generality and schematism, but which, whether or not their existence is accepted in the usual way, "are there," being susceptible of becoming explicit. As it has been argued above, the really different and heterogeneous models (laws, equations) of population dynamics can be accommodated under one theory, i.e., one theory-net. Despite the differences and heterogeneity of the models presented in Sect. 10.3, they can be placed in the theory-net of population dynamics.

[27] For a systematic treatment of this less known metascientific concept, see Moulines (2014).

10.5.3 On Claim (c) about the Unifying Power of Biological Theories

As stated before, what all models of population dynamics share is that they appeal to the *same* theory, i.e., theory-net. Such models may differ substantially in their form. In fact, the laws obtained by specialization from the fundamental law/guiding principle do not preserve the logical or mathematical form.

The theory-net of population dynamics arises from the specification received of the concepts of population factors and of rate of population change. In each specific case, specific population factors and the specific way in which they are combined with specific demographic processes by the rate of population change should be searched for in order to account for the specific changes in the size of the population. The different ways in which population dynamics can be applied are established by the different special laws of the theory.

The interrelations between different theory-elements allow them to be seen as parts of "something unitary." In other words, the relation of specialization in a theory-net seems to be a guarantee of cohesion and allows a better understanding of what the valuable unification of bona fide scientific theories consists of.

The unifying power of a theory depends not only on the number of successful applications/models but also (and more prominently) on how heterogeneous such applications/models are. Therefore, the evaluation of the unifying capacity of a theory must take into account the heterogeneity of cases in which it is applied, through the heterogeneity of the different specializations, of the different specifications that the concepts of the theory receive. Population dynamics applies to a heterogeneity of cases—from the **PD** "empirical"/non-theoretical level—thanks to the heterogeneous way in which the concepts of biotic factors and rate of population change—from the **PD**-theoretical level—are specified. The reason why population dynamics is unifying is because it constitutes a collection of theory-elements that deal with different types of cases by subsuming or embedding them in some line of specialization of its theory-net, which is the "multidirectional development" of a common fundamental law/guiding principle.

10.6 Conclusion

In this chapter a unifying analysis of the concepts of law, model, and theory has been first presented and then applied to population dynamics. In this area a fundamental law/guiding principle and special laws as well as its theory-net have been identified and made explicit. Finally, the consequences of the analysis were drawn in favor of the ideas that there are "laws" in biology (special and fundamental laws/guiding principles where a theory-net has been identified) that many of the heterogeneous and different models of biology can be accommodated under some "theory" (in case a theory-net has been identified), and that theory-nets in biology possess unifying power.

What an approach to the theme of the unifying power of science must achieve is not only to show how more cases of those already known are incorporated but rather the association in the same framework of different parcels of the world. This is, we insist, where the true unifying power of theories resides. With its notion of theory-net metatheoretical structuralism is the perspective that most clearly captures both the different successful applications/models of a theory and what they all have in common.

Just as the unifying capacity counts as an epistemic virtue when choosing between conflicting theories, the ability to explicate that merit may well count as a virtuous criterion for the choice of metascientific approaches to such theories at the same time. Something similar can be said about the very unifying power of the metatheoretical view. And metatheoretical structuralism has shown its unifying power with the unifying analysis (explication) of the (metascientific) concepts of law, model, and theory presented here.

In any case, such an analysis proposes or exhorts us to "see the world" of science in a certain way. We hope to have contributed with the present chapter to the plausibility of such a way of seeing the world of science and to encourage other philosophers of biology to do the same.[28]

Acknowledgments This research was supported by the research projects PICT-2014-1741 (ANPCyT, Argentina), FFI2012-37354/CONSOLIDER INGENIO CSD2009-0056 (Spain), and FFI2016-76799-P (Spain).

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[28] For an application of metatheoretical structuralism to the reconstruction of systemic analysis as an empirical scientific theory and to the discussion of the relationships between systemic analyses and functional explanations, see Olmos et al. (2019, Chap. 11, this volume).

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