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The machinery of the world is far too complex for the simplicity of men.

—Jorge Luis Borges

Go as far as you can see; when you get there, you'll be able to see further.

—Thomas Carlyle

To Blumina, again.

Foreword

So far as I know, this is the only book titled *Scientific Philosophy* published since Reichenbach's dated and forgotten work of 1961. Moreover, although Romero's work belongs in the movement initiated in the 1920s by the Vienna Circle, it departs radically from the empiricist tradition, if only because it takes metaphysics seriously to the point of seeking to update it in the light of current science.

This book is controversial, because it criticizes a number of sacred cows, such as the beliefs that science has no philosophical presuppositions, that space and time are immaterial, that matter does not matter, and that values are not of this world. But no one can doubt that the author has strived to offer good reasons for his heterodoxies and that his prose is crystal clear to anyone who bothers to understand his technical terms. Surely, the readers of Romero's sober and calm didactic prose may miss the ironies of Bertrand Russell's. But then, the mentor of a group of twenty or so explorers of white dwarfs, black holes, and cosmic rays and the like finds no time to waste on a cloud of gnats intent on snuffing out the few candles that illumine the dark recesses of the long postmodernist cave where we have been abandoned.

The most obvious criticism of this work is that it identifies science with contemporary physics, whence it neglects some of the classical philosophical conundrums, such as the nature of mind and the individualist-holism dilemma that has plagued social science. The said collapse of "science" onto "physics" also leads to underrating or even ignoring the views that to philosophize is to search for the good life, that justice is both definable and attainable, that objectivity does not entail impartiality, and that good philosophy is our only defense against bad science and evil technology. A different title, such as "The philosophical roots of science," might be more faithful, but it might also deter those who fear the intrusion of superstition.

Romero's search for objectivity and testability endangers the vast edifice of bayesianism, or the interpretation of probability as degree of belief rather than as the measure of real possibility. But the enemy of arbitrariness and the reader in search of intellectual stimulation is likely to welcome such attacks on the philosophical industries of the day.

In sum, let us read, discuss, and try to outdo this recent vindication and update of Aristotle's conception of scientific philosophy, or philosophical science, as both a tool and an ideal of those who search for the truth inside or outside the nine-to-five cage.

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Preface

This book is the result of my long engagement with philosophy as a research scientist. During the three decades I have pondered about many of the major philosophical problems posed by physics, I have sought for reasonable articulations of the wide worldview implied by our best current scientific theories, I have reflected upon the nature of the scientific enterprise, and I have despaired of the work of many professional philosophers. Philosophy has became, at least in most of the English-speaking world, a sophisticated and highly technical activity. This technicality, unfortunately, many times serves no major purpose since the topics dealt with are completely at odds with science. It seems to me that the image of the world many philosophers adopt is that of the common sense and everyday intuitions. The physical depiction of the world on which much of the current philosophical debate is based is more like that of the Greek atomists or that presented in Lucretius's *Rerum Natura* than that of contemporary physics. This is very regrettable since current science is in desperate need of philosophical work to clarify the ultimate meaning of its theories and to yield a coherent view of the world. It is not surprising that many scientists, when they learn that academic philosophers devote long articles, intricate arguments, and even lengthy treatises to conclude things such as that they do not exist or that there are no physical objects other than people and atoms, give up philosophy altogether. And this is regrettable because then some of those very same scientists feel the need to express some philosophical implications of their work... and end articulating absurdities such as that the universe is a mathematical structure or that the computer viruses are a form of life. In the meanwhile, the main loser is our civilization, which depends critically on a science whose deep meaning is mostly ignored.

This book is a reaction to such a state of affairs. As a working scientist, I know well the advantages of some philosophical instruction as well as the perils of an open anti-philosophical stance. Some philosophical insight helps the scientist to grasp better the full meaning of concepts such as those of "law," "theory," "model," "truth," "relevancy," "property," "existence," "space," "state," "time," "chance," "probability," and many others that are used in everyday research. A scientist who understands what he or she is doing can allegedly do a better work. A scientist, on the other hand, who despises philosophy is at risk of falling inadvertently into some bad or obsolete philosophy that might hinder further research.

This work presents a clear and straight view of the main philosophical issues that in my opinion are relevant to scientists. Of course, some philosophers will disagree with my views. I have tried to stay as close as possible to the standard scientific image in order to present elucidations of the main concepts of philosophical importance that appear in the special sciences. The overall approach is epistemologically realistic and ontologically materialistic (many would prefer the word "naturalistic"). The text emerged from lectures on scientific philosophy addressed to scientists at the Universities of La Plata, San Martín, Mexico, Karlsruhe, and Barcelona. The book can be used as a textbook for a short (one semester) graduate course for either scientists and philosophers with some background in science. Those general readers who are concerned with philosophy but are tired of reading incomprehensible jargon and wild speculations will find here, I hope, some stimulating and direct material.

The first part of the book provides an exposition of the main topics of scientific philosophy: semantics, ontology, epistemology, ethics, and aesthetics. The second part of the book presents some applications of the scientific method in philosophy. I focus on three major problems: the nature of mathematics, the interpretation of quantum mechanics, and the ontology of space-time. Along with several problems in the neurosciences, I think that these are the more urgent philosophical issues in current scientific research. Unavoidably, these chapters are more demanding for the reader. For this reason, I include in them more references and more introductory material. I hope they will stimulate some readers to pursue further research on such subjects.

Sitges, Catalonia, Spain Gustavo E. Romero
11 January 2018

Acknowledgments

I am most grateful to Mario Bunge for inspiration, guidance, and critical reviews of my work along many years. His friendship has been one of the joys of my life. I have no doubt that he would disapprove many of my claims in this book. Nevertheless, at the same time, I am sure that he would be satisfied of the overall scientific-oriented spirit of the book.

I want to thank the many students who have taken my courses on philosophical topics over the years at the universities of La Plata, San Martín, UNAM-Morelia, Karlsruhe (KIT), and Barcelona. Their questions and interest have shaped the material of this book. I am also grateful to my enthusiastic PhD students Luciano Combi and Federico López Armengol for many discussions on foundational issues. I have learned many things from conversations on the topics of this book with friends and colleagues. I want to mention Santiago Perez-Bergliaffa, Valenti Bosch-Ramon, Pablo Jacovkis, Janou Glaeser, Gerardo Primero, Nicolás Pérez, Matías Castro, Federico Aisenberg, Federico Langer, Carlos Romero, Silvio Sánchez Mújica, Héctor Vucetich, Sergio Riva de Neyra, Nelson Pinto-Neto, Felipe Tovar Falciano, Rafael González del Solar, and Javier López de Casenave. I also benefited from many correspondents through the Internet. Gerardo Primero, Nicolás Pérez, Pablo Jacovkis, and Sergio Riva de Neyra made valuable remarks on early drafts of this book. I sincerely thank their comments.

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Some material presented in this book has been adapted from the articles listed below. I am very thankful to the editors of the journals for permission to use this stuff.

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Contents

List of Special Symbols

The next list describes several special symbols that will be later used in the book.

$\stackrel{\text{def}}{=}$	Stipulative definition
$\emptyset$	Empty set
$\vdash$	"Is a theorem" or "is entailed"
$\mathcal{D}$	Designation
R	Reference
$\hat{=}$	Representation
I	Intension
M	Meaning
V	Truth value
T	Theory
$\dot{+}$	Juxtaposition
$\dot{\times}$	Superposition
$\circ$	Composition
$\diamond$	Null thing
$x \rceil y$	x is separated from y
$\text{Comp}(x)$	Composition of x
U	Universe
Ξ	Set of basic things
Θ	Set of all things
P	Property
$S_L(X)$	Lawful space state of X
$X \rhd Y$	X acts upon Y
$X \bowtie Y$	X interacts with Y
$h(X)$	History of X
$h(X/Y)$	History of X in presence of Y

$E_L(X)$	Event space of X
$E_{\text{mode } i}$	Existence predicate
e^0	Null event
W	The World (composition of all events)

List of Figures

Part I
Basic Scientific Philosophy

Chapter 1
Introduction

Science needs philosophy. Without semantics it is not possible to interpret formal systems and theories. Without ontology such basic concepts as those of law, cause, chance, space, and time remain vague. Without epistemology there is no good methodology of adequate control of observation and experiment, no understanding of knowledge nor of the difference between science and charlatanism. Without ethics there is no regulation of the scientific enterprise or values to guide the use of technology. These are just a few examples that support the general statement that without philosophy there is no science. Science is based on general philosophical assumptions, and in turn science informs philosophy, in a virtuous cycle. From this mutual support results the advancement of knowledge. If philosophy fails, science is hindered. And without science, philosophy quickly degrades to domesticated speculation based on common sense. . . at best.

Some examples of the usefulness of philosophy for science are in order. The lack of an adequate interpretation of quantum mechanics, for instance, has obstructed the formulation of a consistent theory of quantum gravity. Failure at evaluating the testability of scientific programs has resulted in a waste of valuable resources in many occasions. Dogmatic acceptance of dualistic ontologies has fostered the development of pseudosciences of the mind producing unnecessary suffering to psychiatric patients. Abandonment of realism led to the collapse of social sciences under postmodern constructivism and its unbearable verbiage.

A philosophically illustrated scientist will be in better conditions to address specific scientific problems with clarity and lucidity. But philosophy has not always been well informed by science. Rather the contrary. Anti-scientific philosophies such as existentialism, postmodernism, and modern skepticism have seriously damaged the image of the philosophical enterprise among research scientists. Although extreme forms of relativism are still popular in some sectors of the humanities, a significant part of the academic philosophy nowadays is again mainly scientifically oriented, especially in connection with problems of physics, neuroscience, and technology. Unfortunately, another part seems to be lost in the search of witticisms and poor attempts to dazzle with logical tricks (see, for example, the diagnosis

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presented by Ladyman and Ross 2007 in their Chapter 1). For the latter group a good prescription is to reinforce their contact with current science.

This book provides an introduction to the main branches of what can be called scientific philosophy, i.e. philosophy informed by science and concerned with the philosophical aspects of scientific problems. Scientific philosophy proceeds like science, proposing theories that can be put to the test, and uses as many exact tools as possible. The main way to test a philosophical theory is by its interactions with more specific theories of science. A philosophical theory that remains alien to science, that is of no use for improving our understanding of the general topics underlying diverse scientific theories, that does not stimulate further research, or that does not change with the advancement of science, such a theory, I maintain, must fall.

According to Russell (1917):

> [. . .] there are two different ways in which a philosophy may seek to base itself upon science. It may emphasise the most general results of science, and seek to give even greater generality and unity to these results. Or it may study the methods of science, and seek to apply these methods, with the necessary adaptations, to its own peculiar province.

In this book I try to follow both paths.

The main branches of scientific philosophy are philosophical logic, semantics, ontology, epistemology, ethics, and aesthetics. The approach I come up with is based on the analysis and discussion of specific topics and problems and not on the exposition of alternative doctrines. Neither I provide an historic overview. My basic goal is to offer the reader the tools to explore by him or herself a wide variety of philosophical problems and to present my specific views on some of them. In issues of ethics and aesthetics I do not present specific normative proposals. I restrict myself to the elucidation of the basic concepts, offering the tools for the construction of normative systems. Every specific system is strongly dependent on the particular cultural, economic, and social context of its formulation. I cannot develop such proposals here without loss of generality and focus on my primary goal that is to present the basics of a scientific way of doing philosophy. Such an important task is left for a future work.

The scientific way of doing philosophy can be traced to pre-Socratic thinkers such as Anaximander, Parmenides, and the atomists. From them, it follows a thread that goes through such illustrious names as Grosseteste, Bacon, Galileo Galilei, D'Holbach, Helvétius, Frege, Peirce, Boltzmann, Russell, the logical empiricists, and current thinkers as Nicholas Rescher, Adolf Grünbaum, Mario Bunge, and many others.

Perhaps the most comprehensive work of scientific philosophy is the monumental *Treatise on Basic Philosophy*, in 8 volumes, by Bunge (1974–1989). In what follows I shall adopt Bunge's classification of philosophy, and often, but not always, his views. The resulting philosophy can be characterized as naturalistic.

In Chap. 2 I present the basics of philosophical semantics, the investigation of the structure and contents of our languages and their relation to the world. I introduce a two-dimensional theory of meaning based on set theory and inspired by the work of Frege and developed by Bunge. Then I discuss the concept of truth, which is of paramount importance in science.

Chapter 3 is devoted to ontology, i.e. the broadest theory about the world that emerges from our particular sciences. I characterize in this chapter concepts that permeate our entire scientific views, including those of thing, property, law, system, structure, causality, chance, matter, emergence, energy, and more. The approach is based on the idea that there are some kind of permanent individuals or things, but I admit that this ontology might result not fully appropriate at some specific level of analysis of reality. I offer in an appendix an alternative approach based on 'events'.

Chapter 4 is devoted to epistemology. Such important concepts for science as those of knowledge, understanding, explanation, model, and theory are elucidated there. The definitions I propose should be tested by the working scientist against the daily experience of actual scientific research. Surely they can be refined and expanded to accommodate features that I have missed. Altogether, however, I hope they can provide a good starting point.

Ethics is the topic of Chap. 5. I am both naturalistic and fictionalist about good and bad: I think that these concepts are fictions we have created to guide our actions in our social interactions. My debt with the thought of Vaihinger (1923) is great here, as in Chap. 6, devoted to aesthetics. My methods, instead, come from Bunge (1974–1989), Beth (1964), and Martin (1958).

Fictionalist is also my interpretation of mathematics (Chap. 7). This chapter starts the more specific and controversial part of the book. The next two Chaps. 8 and 9, deal with the interpretation of quantum mechanics and some of its problems. These chapters are more technical and demand some knowledge of the subject by the reader. My interpretation of quantum mechanics is realist and literal. It might be dubbed the "minimalist interpretation". I do not find in quantum mechanics reasons to support the existence of many worlds, many minds, or many observers. I acknowledge that Bohm's theory is an interesting alternative to the standard theory, but I think that so far we do not need an ontology populated by particles and pilot waves. The world, in my view, is just a world of quantum fields and spacetime. At least as far as our current scientific knowledge informs us.

Spacetime is the subject of Chap. 10. I critically discuss presentism, the doctrine that only the present exists, and defend a kind of emergent substantivalism that I think is imposed by a correct reading of general relativity. Such discussions close the book.

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Chapter 2
Philosophical Semantics

2.1 Introduction: Formal Languages

The most basic assumption of science is that there is a reality to be known. Without the postulate of the independent existence of a real world the scientific effort would be in vain. I do not discuss this basic assumption here. I shall come back to this issue in the next chapter, devoted to ontology. Now I want to focus on how we represent the world in our attempts to understand it.[1]

In order to represent some features of the world we use conceptual systems called *languages*. In our daily life natural languages such as English, German, or Spanish are, or seem to be, enough for most purposes. Unfortunately, natural languages are plagued by *vagueness*, lack of precision, and ambiguity. If we want to penetrate deeper into the structure of reality we should adopt formal languages as those provided by logic and mathematics (Fig. 2.1).

A formal language is a conceptual system equipped with a set of specific rules to generate valid combinations of symbols. A *symbol* is an artificial *sign*. A sign is any object that "stands for" another object. Natural signs are usually called *indicators*, as when we say that dark clouds indicate a forthcoming storm.

More precisely, we define a formal language L as the triplet

$$L = \langle \Sigma, R, O \rangle , \tag{2.1}$$

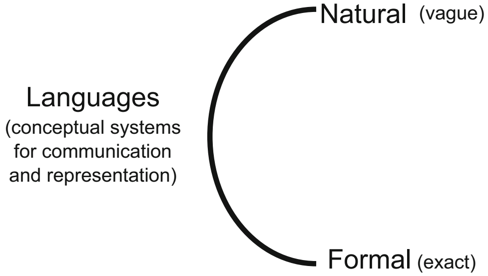
where:

- Σ is the set of primitive terms of the language.
- R is the set of rules that provide explicit instructions about how to form valid combinations of the elements of Σ.

[1]By "the world" I mean the totally of existents, whatever they are.

G. E. Romero, *Scientific Philosophy*, https://doi.org/10.1007/978-3-319-97631-0_2

Fig. 2.1 Language: ordinary and formal



- O is a set of extra-linguistic objects that are denoted and represented by the elements of the language L.

  The set R can contain three disjoint subsets:

$$R = S_y \cup S_e \cup P_r, \tag{2.2}$$

where

- $S_y \overset{\text{def}}{=}$ set of syntactic rules,
- $S_e \overset{\text{def}}{=}$ set of semantic rules,
- $P_r \overset{\text{def}}{=}$ set of pragmatic rules.

  If $S_e = P_r = O = \emptyset \Rightarrow L$ is called a *logistic system* or *calculus*.

The rules S_y determine how to construct valid combinations of symbols called *formulas*.

The simplest form of a powerful logistic system is called first order logic. I shall call this system L_1. The rules of a language L_1 are expressed in a second language L_2, called *metalanguage*. This avoids the emergence of certain paradoxes such as the Russell paradox[2] and the many paradoxes of self-reference[3] (see Sainsbury 2009). The metalanguage can be formed with elements of L_1 and natural languages. The primitive symbols of Σ_{L_1} are:

1. A series (finite or infinite) of predicate signs: 'p_1', 'p_2', etc.
2. The equal symbol '$=$'.
3. The negative symbol '$\neg$'.
4. A series (finite or infinite) of constants: 'a', 'b', etc.

[2]The Russell paradox: consider the class of all classes that are not members of themselves. Let us call this class A. Then if $A \in A \rightarrow A \notin A$ and if $A \notin A \rightarrow A \in A$.

[3]Paradoxes of self-reference are like the Liar's paradox: consider the statement "I lie". If I lie, then what I say is false. Then "I lie" is false, and I say the truth. Then I do not lie, contrary to the hypothesis.

5. A series (finite or infinite) of variables: 'x_1', 'x_2', etc.[4]
6. The basic connective '$\wedge$'.
7. The existential symbol '$\exists$'.
8. The parentheses '(' and ')'.
9. The comma ','.

In this list all symbols between quotation marks '...' belong to the language vocabulary Σ_{L_1}, whereas the sentences are formulated in the metalanguage. We call *term* of L_1 to any constant, variable, or valued predicate such as '$p(a, b, c, \ldots)$'. Valid combinations of symbols are called *formulas*.

The syntactic rules (elements of $R = S_y$) are:

- S_{y1}: If 'p' is a predicate and 'a', 'b', 'c', etc., are terms, then '$p(a, b, c, \ldots)$' is a formula.
- S_{y2}: If 'φ' and 'ξ' are formulas, then '$\varphi \wedge \xi$' is a formula.
- S_{y3}: If 'φ' is a formula, then '$\neg\varphi$' is a formula.
- S_{y4}: If 'a' and 'b' are terms, then '$a = b$' is a formula.
- S_{y5}: If 'φ' is a formula and 'x' a variable, then '$(\exists x \ \varphi x)$' is a formula.
- S_{y6}: There is not any further sequence of primitive symbols that is a formula.

We can introduce now a number of useful definitions.[5]

- D_1: $(A \vee B) = (\neg (\neg A \wedge \neg B))$.
- D_2: $(A \rightarrow B) = (\neg A \vee B)$.
- D_3: $(A \equiv B) = (A \rightarrow B) \wedge (B \rightarrow A)$.
- D_4: $(\forall x \ \varphi x) = (\neg \exists x \ (\neg \varphi x))$.

In the formula '$\exists x \ \varphi x$', 'x' is called a bound variable. The symbol '$\exists$' is called a quantifier. The symbols '$\wedge$', '$\vee$', '$\rightarrow$', and '$\equiv$' are called conjunction, disjunction, implication, and identity, respectively.

This formulation of L_1 is not unique. For instance, we might have adopted '$\forall$' as primitive quantifier. From definition D_4 is clear that the quantifiers are not independent and it is matter of convention which one is adopted as a primitive operator.

The operation of *deduction* allows to obtain valid formulas from axioms (i.e. primitive rules) or other valid formulas. Deduction is simply the successive application of the syntactic rules. A formula is valid if it is constructed in conformity with the syntactic rules. Formulas obtained through deduction are called *theorems*, and preceded by the symbol '$\vdash$' in any formal presentation of the system.

Deducibility ($\vdash$) should not be confused with implication ($\rightarrow$). In general $A \vdash B$ is stronger than $A \rightarrow B$. Actually if $A \vdash B$ then $A \rightarrow B$ but the converse is not valid.

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[4] If the variables are few, it is usual to adopt 'x', 'y', etc.

[5] These are stipulative definitions. For a discussion of the different kinds of definitions see Gupta (2015).

- D_5: $\vdash$ = "is a theorem" or "is entailed".

  Another important definition is that of *consistency*.

- D_6: A set of formulas Δ is said *consistent* if $\neg(\Delta \rightarrow \varphi \wedge \neg\varphi)$ for any $\varphi \in \Delta$.
- D_7: A set Δ of formulas is inconsistent or incoherent if $\Delta \rightarrow \neg\varphi \wedge \varphi$ for some $\varphi \in \Delta$.
- D_8: $\varphi \wedge \neg\varphi$ is called a *contradiction*.

If we want to apply a formal language to the world, we need to add another set of rules in order to relate symbols and formulas with extra-linguistic objects. Let O be a set of extra-linguistic objects. An interpreted formal language $L^I{}_1$ is given by:

$$L^I{}_1 = \langle \Sigma, R, O \rangle , \tag{2.3}$$

where $R = S_y \cup S_e$ and $O \neq \emptyset$.

The rules in S_e relate the elements of Σ and valid formulas obtained from them through the syntactic rules with objects in O. There are three basic semantic relations: denotation, reference, and representation. Once these relations have been introduced we can define the derivative concepts of sense, meaning, and truth. When all these relations and concepts are made explicit for a given language, we say that there is an interpretation or a model for the language.

The semantic rules are formulated, as the syntactic ones, in the metalanguage L_2.

In what follows I shall define and discuss the semantic relations of denotation, reference, and representation, as well as the concepts of sense, meaning, and truth. Pragmatic rules will not be considered here since they concern to the relations between language and users, and are more relevant for the semiotics of natural languages than for philosophy.

2.2 Denotation and Designation

Denotation is a relation that assigns symbols to objects of the universe of discourse of a language:

$$D : \Sigma \rightarrow O. \tag{2.4}$$

For instance, a proper name denotes a specific person: "Gustavo Esteban Romero" denotes the author of this book. In general, the constants a, b, ... etc. of Σ denote some specific objects belonging to O.

The relation of denotation should not be confused with that of *designation*. Designation ($\mathcal{D}$) relates symbols to concepts:

$$\mathcal{D} : \Sigma \rightarrow C, \tag{2.5}$$

where C is a set of *constructs*, i.e. conceptual entities constructed by abstraction. Abstraction usually proceeds by imposing an equivalence relation to a set, an operation that results in the partition of the set into disjoint subsets. Each subset is identified with a construct or concept.

2.3 Reference

Reference is a relation between constructs and objects of any kind, either factual items of the world or formal constructs:

$$R : C \to \Omega; \qquad \Omega = O \cup C. \tag{2.6}$$

If $\Omega = O$ we say that the reference is *factual*. If $\Omega = C$ we say that the reference is *formal*.

Given a construct $c \in C$, the class of reference of c is the set of all objects x referred by c:

$$[c]_{\mathrm{R}} = \{x \in \Omega : \ R(cx)\}. \tag{2.7}$$

The relations among symbols (Σ), constructs (C), and objects ($\Omega = O \cup C$) are schematically represented in Fig. 2.2.

The relation of reference can be specified to become a function in the case of predicates and statements.

A predicate is a function from some multiple domain of objects $A_1 \times A_2 \times \ldots \times A_n$ to statements (S):

$$P : A_1 \times A_2 \times \ldots \times A_n \to S. \tag{2.8}$$

The value of P at $\langle a_1, a_2 \ldots, a_n \rangle \in A_1 \times A_2 \times \ldots \times A_n$ is the atomic statement $P_{a_1 a_2 .. a_n}$.

The reference class of a predicate is the collection of its arguments:

$$R(P) = \bigcup_{i=1}^{n} A_i, \tag{2.9}$$

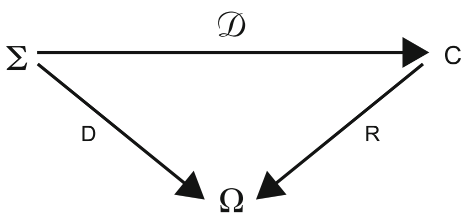


Fig. 2.2 Semantic relations of designation, denotation, and reference

and the reference class of a statement $s \in S$ is:

$$R(P_{a_1 a_2, \ldots, a_n}) = \{a_1, \; a_2, \ldots, \; a_n\}, \tag{2.10}$$

i.e. the set of its arguments.

In the case of a complex statement $W = W(s_1, s_2, \ldots, s_n)$, with $s_1, s_2, \ldots, s_n \in S$, the reference class is the union of all sets of arguments:

$$R\left(W\left(s_1, s_2, \ldots, s_n\right)\right) = \bigcup_{i=1}^{n} R(s_i). \tag{2.11}$$

If the predicate is quantified, then the reference class is the reference class of the predicate. The quantification does not have referential import.

Notice that individuals do not refer, even if they are constructs; they are referred by statements and predicates.

Let us define, at this point, a *theory* as a set T of statements S, that is closed under the operation of entailment ($\vdash$): any $s \in T$ is either an axiom (a basic statement) or a consequence of the set of axioms ($A = \{A_i; \, i = 1, \ldots, n\}$).[6] Symbolically:

$$T = \{s : A \vdash s\}. \tag{2.12}$$

Then, the reference class of the theory is:

$$R(T) = \bigcup_{i=1}^{n} R(A_i), \tag{2.13}$$

where n is the number of axioms $A_i \in A$. This means that the reference class of any theory can be determined from the references of its axioms. In other words: reference is conserved under the operation of deduction. This is an important property: if we can correctly axiomatize a given theory, then the semantic analysis of the axioms will completely determine the reference class of the whole theory. When theories are presented only in a heuristic fashion, it is not uncommon that some supposed referents result illegitimately introduced at the level of theorems or even through ad-hoc statements.

Finally, let us notice that reference is different from extension. The latter concept involves in turn the concept of *truth* (see below). The extension of a predicate is formed by those objects that make the predicate a true statement. The extension of $(\forall x)\,(Px \vee \neg Px)$ is everything. The extension of $(\forall x)\,(Px \wedge \neg Px)$, instead, is nothing. These abstract formulas have no reference. Contrarily, the statement 'Prague is the most beautiful city in the world and Prague is not the most beautiful city in the world' has no extension but its reference class is {Prague}, and the statement refers to the city of Prague.

[6]Notice that the axioms are also trivially entailed by the axiomatic basis: $A_i \vdash A_i$.

Pure logistic systems do not refer since they are not interpreted. Logic does not have any reference class. Mathematics, instead, has purely formal reference classes: it refers only to constructs. Factual science refers to the objects that populate the world.

2.4 Representation

Some constructs not only refer, but also *represent* things, their properties, and changes. In particular, any statement represents a *fact* of its referents. The same construct can refer to a thing and represent some of its properties. We designate the *relation of representation* by:

$$\hat{=} : C \to F, \tag{2.14}$$

where C is a set of constructs and F a set of facts, understood as states or changes of states of a thing (a factual object).

The basic rules that govern this relation are:

- $Repr_1$: Properties of real things are represented by predicates (in particular, functions).
- $Repr_2$: Real things are represented by sets equipped with relations, functions, or operators.
- $Repr_3$: Events (changes) in things are represented by sets of statements (either singular or existential).
- $Repr_4$: Laws (regular patterns of events) are represented by sets of universal statements.

The representation relation is not symmetric (facts do not represent constructs), reflexive (constructs do not represent themselves), nor transitive (facts do not represent anything at all).

If a construct is a theory T about entities of some kind K, we say that $T \hat{=} K$ if there is a function $\hat{=} : S \to 2^T$ from the set of states of the elements of K to the set of all subsets of statements of T. If a subset of statements t represents a specific fact s we write '$t \hat{=} s$'.

I remark that representations are not necessarily unique. The same feature of reality can be represented in different ways. We can introduce the following criterion of equivalence for different representations of the same facts:

Criterion If c and c' are two constructs and T a factual theory, then c and c' are *equivalent representations* of the same factual item if and only if (hereafter, iff) they are interchangeable in all law statements of T.

This means that the law statements of a theory must be invariant under the replacement of c and c' if c and c' are equivalent representations.

We can extend the concept of equivalent representations to the whole theories:

Let T and T' be two theories with the same factual referents. Let us designate $\mathbb{P}$ and $\mathbb{P}'$ their respective predictive basis (i.e. the set of predictive statements of the theories). Then, T and T' are semantically equivalent iff there exists a set of transformations for $\mathbb{P}$ and $\mathbb{P}'$ that allows to convert T into T' preserving the truth value of all statements. It is enough to demonstrate that there is at least one statement of T that cannot be transformed into a statement of T' to prove that both theories are not semantically equivalent.

2.5 Intension and Sense

Intension, informally, is what a predicate "says". It is the complement of the extension of the predicate: the greater the intension, the smaller the extension.

Formally, we can characterize the intension as follows:

Definition Let C be a set of predicates or statements. The intension I is a function of C over the set of all subsets of C, $\mathcal{P}(C) \subset C$, such that for all P and Q of C:

1. $I(P \wedge Q) = I(P) \cup I(Q)$.
2. $I(\neg P) = \overline{I(P)}$.
3. If $P = Q \rightarrow I(P) = I(Q)$.

We also introduce the following conventions:

- D_1: $I(c)$, with $c \in C$, is *intentionally empty* iff $I(c) = \emptyset$.
- D_2: $I(c)$, with $c \in C$, is *intentionally universal* iff $I(c) = C$.
- D_3: If $(P \subset C) \wedge (Q \subset C) \rightarrow P$ is *intentionally included* in Q iff $I(P) \subseteq I(Q)$.
- D_4: c and c' are *co-intensive* if $I(c) = I(c')$.
- D_5: c and c' are *intentionally independent* iff $I(c) \cap I(c') = \emptyset$.
- D_6: c and c' are *intentionally dependent* iff $I(c) \cap I(c') \neq \emptyset$.

Several theorems can be straight forwardly derived. Among them, that tautologies are intentionally empty.

If a construct is part of a theory, then the concept of intension can be exactified, and we called it the *sense* of c.

Definition the sense of a construct is the union of the items of the same type that entail or are entailed by it:

$$S(c) = \{x : x \vdash c\} \cup \{y : c \vdash y\} = A(c) \cup J(c). \tag{2.15}$$

$A(c)$ is the *purport* or logical ancestry and $J(c)$ is the *import* or logical progeny of c.

If c is any proposition of a theory T, then $A(c)$ and $J(c)$ are sets of propositions. The sense $S(c)$ is the 'content' of the proposition c.

I shall now proceed to formulate the *meaning* of a *construct* c using its sense and reference.

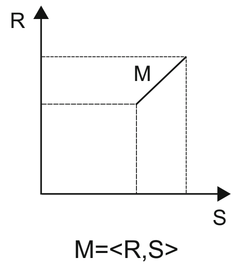


Fig. 2.3 Meaning as a two-dimensional concept

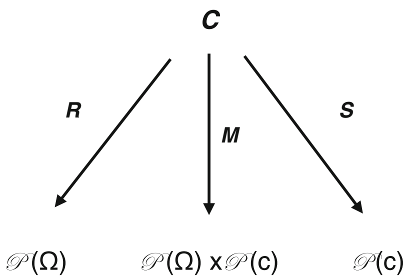


Fig. 2.4 Different semantic relations (reference R, sense S, and meaning M) between constructs and objects

2.6 Meaning

Meaning is an *attribute*[7] of constructs and the signs that designate them. A full characterization of meaning requires the specification of both the reference and the sense of a given construct. More precisely, if c is a construct with reference $R(c)$ and sense $S(c)$ we define the meaning of c, $M(c)$, as the ordered pair:

$$M(c) = \langle R(c), S(c) \rangle \,. \tag{2.16}$$

Note that $R : C \to \mathcal{P}(\Omega)$, and $S(C) : C \to \mathcal{P}(C)$, then $M : C \to \mathcal{P}(\Omega) \times \mathcal{P}(C)$.

Meaning is a two-dimensional concept that can be represented in a real plane (see Fig. 2.3).

The relations between constructs C and all kind of objects Ω (notice that $C \subset \Omega$) are illustrated in the diagram shown in Fig. 2.4.

Let p and q be two propositions. We can define a calculus of meanings through the following definitions:

- $M(p) = M(q) \Leftrightarrow (R(p) = R(q)) \wedge (S(p) = S(q))$ (identity).
- $M(p) + M(q) = \langle R(p) \cup R(q), S(p) \cup S(q) \rangle$ (addition).

[7] I call 'attribute' to properties of constructs and other conceptual objects. The word 'property' itself is reserved for factual objects. 'Attribute' suggests that we are who ascribe the feature to the construct, i.e. that constructs are *fictions*.

- $M(p) \times M(q) = \langle R(p) \cap R(q), S(p) \cap S(q) \rangle$ (multiplication).
- $\neg M(p) = \left\langle \overline{R(p)}, \overline{S(p)} \right\rangle$ (complement).

Several theorems can be easily obtained. For instance, meaning is idempotent: $M(p) + M(p) = M(p)$, and the multiplication of meaning is distributive:

$$M(p) \times [M(q) + M(r)] = [M(p) \times M(q)] + [M(p) \times M(r)] . \tag{2.17}$$

We can also define a null and a universal meaning.

Null meaning:

$$\square \equiv M(p) \times [\neg M(p)] =$$
$$\left\langle R(p) \cap \overline{R(p)}, S(p) \cap \overline{S(p)} \right\rangle = \langle \emptyset, \emptyset \rangle .$$

Universal meaning:

$$U_{\mathrm{M}} \equiv M(p) \times [\neg M(p)] = \left\langle R(p) \cup \overline{R(p)}, S(p) \cup \overline{S(p)} \right\rangle = \langle \mathcal{P}(\Omega), \mathcal{P}(\mathbb{P}) \rangle ,$$

where $\mathbb{P}$ is the set of all propositions in the theory.

I remark that the sense and reference are well-defined only in the case of formalized theories that are closed under the operation of deduction ($\vdash$). This implies that ordinary languages with open contexts are unavoidably defective. This semantic indeterminacy is called *vagueness*, and is the main reason for adopting formalized languages when precision is important.

Before discussing vagueness, I want to emphasize that the conception of meaning presented above is *not* related to the concept of truth, that we have not introduced yet.

Two propositions are said to be synonymous iff:

$$M(p) = M(q). \tag{2.18}$$

In such a case we adopt the notation 'p Syn q' and 'q Syn p'.

Two propositions p and q are semantically disjunct iff:

$$M(p) \times M(q) = \square. \tag{2.19}$$

We then say that both propositions are unrelated: $p \wr q$.

Finally, we define the *significance* of a symbol as the composition of meaning and designation. A symbol designates a construct that has some meaning.

In our previous diagram, if Σ are the symbols of a language, we can represent the various relations introduced so far through the sketch shown in Fig. 2.4.

A symbol acquires an indirect sense and reference through the construct it designates. If a sign has no designation, we call it *syncategorematic*.

The difference of meaning between two constructs c and c', can be exactified with the operation of *symmetric difference* between sets.

The symmetric difference between two sets A and B is $A \triangle B$. It is defined such that:

$$\begin{aligned} A \triangle B &= (A \cup B) - (A \cap B) \\ &= \{x : (x \in A) \vee (x \in B) \wedge x \notin (A \cap B)\}\,. \end{aligned} \tag{2.20}$$

Then, the *difference in sense* between c and c' is:

$$\delta_S(c, c') = S(c) \triangle S(c'), \tag{2.21}$$

and the difference in reference between c and c' is:

$$\delta_R(c, c') = R(c) \triangle R(c'). \tag{2.22}$$

The *difference in meaning* between c and c' results:

$$\delta_M(c, c') = \left\langle \delta_R(c, c'), \delta_S(c, c') \right\rangle. \tag{2.23}$$

The concept of difference in meaning can be used to quantify the shift of meaning between constructs in different, historically successive theories.

Summing Up Languages are conceptual systems with a vocabulary, formation rules, and a universe of discourse. If the latter is lacking the language is abstract. Otherwise it is interpreted. Symbols denote objects and designate concepts. Concepts refer to individuals of any kind. Some concepts can be used to represent things, properties, and facts. All concepts have a meaning, formed by sense and reference, when they belong to formalized theories. Meaning is precise only in the case of exact interpreted languages. Otherwise, it is affected by vagueness.

2.7 Vagueness

Vagueness is an attribute of some concepts and, hence, of some propositions containing them (Russell 1923). A concept is *vague* if its sense is imprecise, and hence its extension is imprecise too.

To characterize the concept of vagueness, let us introduce first the concept of *nuclear meaning*:

If p is a proposition shared by all members T of a family τ of theories, then the nuclear meaning of p is such that:

1. $S_{\text{NUCL}}(p) = \bigcap_{T \in \tau} S_T(p)$,
2. $R_{\text{NUCL}}(p) = \bigcap_{T \in \tau} R_T(p)$.

Then, we define the vagueness of p with respect to T as:

$$\mathrm{Vag}_T\ M(p) = \langle \Delta_T R(p), \Delta_T S(p) \rangle\,, \tag{2.24}$$

with

$$\Delta_T R(p) = R_T(p) \vartriangle R_{\mathrm{NUCL}}(p), \tag{2.25}$$

$$\Delta_T S(p) = S_T(p) \vartriangle S_{\mathrm{NUCL}}(p), \tag{2.26}$$

where $\vartriangle$ is, as before, the symmetric difference between sets.

Notice that vagueness is not a vague concept only for propositions belonging to a well-formed theory T.

In order to minimize vagueness, we have to maximize the formal structure of a number of similar, alternative formulations of any theory. Only when

$M(p) \to M_{\mathrm{NUCL}}(p), \quad \mathrm{Vag}\ \ M(p) \to \langle \emptyset, \emptyset \rangle\,,$

for every $p \in T$, the theories T of a family τ get their final, exact form.

The ideal of science is to produce only exact propositions about the world.

The vagueness of a predicate p is propagated to its extension. The extension is defined by:

$$E(p) = \{x : (x \in D) \wedge (V(Px) = 1)\}\,, \tag{2.27}$$

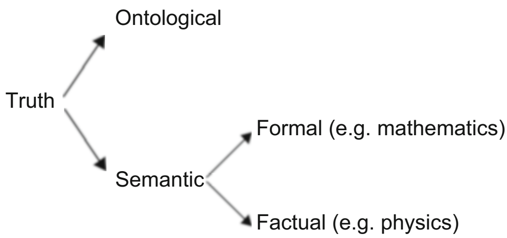
where D is some domain of individuals and V designates the truth value of the predicate evaluated for x. If p is vague, then $E(P)$ will not be a well-defined set. This vagueness results in the "sorites" paradox.[8] It can be removed through the exactification of p.

2.8 Theory of Truth

"Truth" is a polysemic word. We can differentiate al least two kinds of truths: ontological and semantic. *Ontological truth* is the adequacy of thought to reality. More specifically is a matching of the processes in the brain of a knowing subject to processes in the world. The latter are series of changes that can occur either in the physical environment or in the body, including the brain itself. Ontological truth is then a fact-to-fact correspondence, and should be studied by science, in particular by

[8]The sorites paradox (sometimes translated as the paradox of the heap because in Ancient Greek the word "sorities" means "heap") is a paradox that arises from vague predicates. The classical example is a heap of sand. If you take away a grain of sand from the heap you still have a heap. So, the operation 'heap minus 1 grain = heap' holds for any heap. The application of the operation does not alter the heap. Repeat the operation a large number of times and, nevertheless, the heap will disappear. The paradox resides in the impossibility to determine how or when the heap disappears.

Fig. 2.5 Kinds of truth



the neurosciences. *Semantic truth*, on the contrary, is the adequacy of a conceptual object such as a proposition to reality. A proposition asserting the occurrence of an event *e* is said to be true if *e* happens.

Semantic truth is attributed to propositions according to some *theory of truth*. Truth is not a property of the proposition: there is no analysis of the proposition alone that might reveal whether it is true or not. Since we can separate propositions into formal (i.e. those of logic and mathematics) and factual ones (i.e. those that refer to facts), semantic truths can also be divided into formal and factual ones (see Fig. 2.5).

The elucidation of the concept and criterion of semantic truth corresponds to philosophical semantics. A *truth criterion* should specify a truth *valuation function* that maps propositions into truth values. This function is a partial function since not all propositions have truth value. It should be reminded that we are those who attribute values to propositions so, if we do not do it, the propositions remain neither true nor false. Examples of propositions that lack of truth value are non-tested hypotheses, undecidable propositions in some formal systems, and untestable propositions such as propositions about singular events inside black holes (e.g. "Dr. Spock smiled after crossing the event horizon"). Note that the same proposition might have truth value for some individuals while not having a definite value for others (as in the case with the above proposition about Spock: for people falling along with Spock into the black hole, if any, the proposition has a well-defined truth value; for those remaining outside the event horizon, conversely, it is impossible to assign a truth value to the proposition).

In short: truth and falsity are not intrinsic properties of factual propositions, but attributes assigned to them on the basis of some evidence.

2.8.1 A Short Overview of Some Theories of Truth

Before discussing in some detail a concrete proposal for a theory of truth, I shall briefly review some popular theories. Details can be found in any of the standard books on the subject (e.g. Kirkham 1995).

A theory of truth has been defined as a theory that can answer the following problem:

If X belongs to some language L_1 and P_{TL2} is an open statement in some metalanguage L_2 such that

P_{TL2}: 'X' is true iff Y,

then to provide a theory of truth is to specify the nature of the truth bearer X in L_1, and to determine the necessary and sufficient conditions in L_2 to call 'X' true.

This is more or less Tarski's approach to the problem.

The more common answers to the problem of truth can be classified as 'traditional' or 'recent' theories. The word 'theory' here should not be taken in a strict sense, since several of these approaches are not real theories but rather vague suggestions, hypotheses, and conjectures.

The traditional theories of truth are:

- Correspondence theory of truth.
- Coherence theory of truth.
- Pragmatic theory of truth.

The more 'recent' theories are:

- Consensus theory of truth.
- Deflationary theory of truth.

I shall make a few comments on each of them.

Correspondence Theory

- This is the dominant theory, especially popular with empiricists.
- In its most basic formulation the Correspondence Theory proposes that a proposition is true if it corresponds to the facts. Example: "The apple is on the table" is true only if the apple is in fact sitting on the table.
- This theory is often traced back to Thomas Aquinas's version: "A judgment is said to be true when it conforms to the external reality" (*Summa Theologica*, Q. 16). Actually, the basic idea is already found in Aristotle and some pre-Socratic thinkers (e.g. Parmenides).
- The proposal of truth as correspondence also leaves room for the idea that the word "true" may be applied to people (a "true friend") as well as to thoughts (a "true idea") and non-linguistic representations (a "true picture").

The main strengths of the idea of truth as correspondence are (1) simplicity, and (2) appeal to common sense. Among the weaknesses we can mention (1) difficulties pertaining to linguistics and exactification of the theory, (2) circular reasoning ('p' is true in L_1 iff p, but how we know that p is true in L_2?), (3) awkwardness in application to mathematics, (4) it might lead to skepticism about the external world if the connection with factual evidence is not made clear.

Coherence Theory

- The simplest formulation of truth as coherence is "Truth is that which is maximally coherent".

- This theory is preferred by many idealists. For idealists, reality is like a collection of beliefs, which makes the Coherence Theory particularly attractive.
- The Coherence Theory of truth states that if a proposition coheres with all the other propositions taken to be true, then it is true. The truth of a belief or of a proposition can only consist in their coherence with other beliefs or propositions; truth, then, comes in degrees (the more propositions form the system, the more sound the system is).
- Notice that coherence theorists hold that truth consists in coherence with a set of beliefs or with a set of propositions held to be true, not just an arbitrary collection of propositions.

The main strength of the Coherence Theory is that it makes sense out of the idea of mathematical truths. A simple example: $(5 + 5 = 10)$ is true because: $10 = 10$, $1 \times 10 = 10$, $10 = (2 \times 3) + 4$, etc., are all true.

Some weaknesses of the Coherence Theory: (1) It falls prey to circular reasoning. For instance, proposition A is true because propositions B and C are true. But how do we know that B is true? Because proposition A and C are true. But what external evidence is there to support the truth of any of these propositions? (2) A set of propositions can be perfectly coherent but altogether false. For instance, a novel can have a self-consistent argument and be completely fictitious at the same time.

Pragmatism

Pragmatism is usually associated with the names of Charles S. Peirce and William James.

- "Ideas (which themselves are but parts of our experience) become true just insofar as they help us to get into satisfactory relations with other parts of our experience ... truth in our ideas means their power to 'work' "—William James.
- The key thing for James and pragmatism is the idea of "working". If believing that there is a gaping hole in the middle of the cafeteria prevents you from falling and breaking a leg, or making a fool of yourself in front of an examining committee, then that belief works. It is 'true'.

There are some obvious weaknesses of these pragmatic views: (1) What is true for one person can be false to another (subjectivism). (2) Relativism (truth is relative to success). (3) Pragmatism is *prima facie* at odds with science: not all truths help to maximize "our power". Lies can do it very well; unfortunately, in many situations lies 'work' perfectly for many purposes.

Let us now quickly mention some more 'modern' views.

Consensus Theory

The basic assumption here is that something is true if everyone agrees that it is true. This is, in my opinion, a very sad position. Just consider the following points.

- In the past, we have been all wrong.
- We rarely agree: different religions, ideologies, etc., all of them coexist purporting to have knowledge of 'true' and often produce contradictory statements.

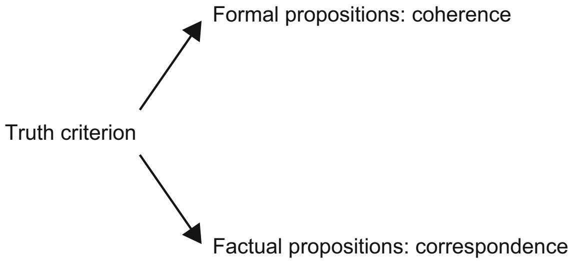


Fig. 2.6 Traditional criteria for truth

- Subjectivism: truth depends on what human beings believe.
- Consensus is at odds with science: old, wrong theories had consensus once.

Deflationist Theory
The latest proposal concerning truth is that truth is irrelevant, if it is something at all. For the Deflationist Theory 'truth' is a superfluous concept. It adds nothing. To state that X is true is the same as to simply state X. More than 'deflationist' I would say that this position is 'defeatist': it gives up about truth. Some objections:

- Deflationism avoids the answer, but not the problem.
- Relativism: contradictory things can be stated.
- Deflationism is at odds with science: we search for a true representation, not just a representation of nature.

Actually, there is no reason to maintain that there is only one theory of truth that can succeed. If formal and factual truth are of different nature, then we can expect that different theories might apply to formal and factual propositions (see Fig. 2.6). In what follows, I shall present in more detail theories for formal and factual truth. Most of what I have to say is based on Bunge (1974a,b, 2010, 2012).

2.8.2 Formal Truth

Let L be some formal system and p a proposition of L. We say that the truth value $V_L(p)$ in L is 1 iff p is a theorem in L (theoremhood):

$$L \vdash P.$$

An abstract formula $\varphi(x)$ in L has truth value 1 in L iff there is a model[9] of $\varphi(x)$ (statisfiablity).

[9]A model of an abstract formula is a structure (e.g. an interpretation) that satisfies the formula within a formal theory.

If a formal proposition or formula has truth value 1, we say that they are *true* in L. If a formal proposition or abstract formula are not true we say that they are *false* and we assign them the truth value 0.

Examples: The proposition '$3 + 5 = 8$' is true in arithmetic of integer numbers.

The formula '$AB - BC = 0$' is true in the arithmetic of integer numbers, but not in the arithmetic of matrices.

The function $V_L(p) : \mathfrak{B} \to \{0, 1\}$ assign values of 0 or 1 to the set $\mathfrak{B} \subset L$ of decidable propositions of L. Notice that undecidable propositions do not have truth value in L, although they might be true or false in a different system L'.

In short, formal truth equals either satisfiability (i.e. existence of a model) or theoremhood. This is essentially Tarski's theory of truth, which is considered sometimes as a theory of correspondence (Tarksi 1983). Actually, it is a coherence theory of truth for propositions and formulae in formal languages with a metalanguage (see Kirkham 1995 for discussions).

2.8.3 Factual Truth

Factual truth is an attribute of propositions concerning facts. We assign a truth value to a proposition p on the strength of empirical tests such as a run of observations. The assignment is done through a new proposition in the metalanguage: p has a truth value $V_E(p)$ with respect to evidence E. The truth values can change if the evidence changes. The evidence E is formed by a set of propositions that express empirical determinations of some property M whose value according to p is μ. Then

$$EM = e \pm \beta, \tag{2.28}$$

where e is the measured value of M and β is the corresponding error. Then, p is true with evidence E if

$$|\mu - e| < \beta. \tag{2.29}$$

If we have two different pieces of evidence E and E' we should assign a truth value with the strength corresponding to the evidence of smaller error.

Complete truth is rarely known in science. Hence it is desirable to introduce a truth valuation function admitting truth values others than 0 and 1. We adopt a valuation function of partial truth $V : P \to [0, 1]$ that applies a set of propositions to the unit real interval.

The function V is determined by the following postulates (Bunge 2010, 2012):

- A_1: If p is a quantitative proposition that has been found to be true with the relative error β, then $V(p) = 1 - \beta$.

  Example: p ="Blumina is 9 years old". The actual age is, say, 10 years old. Then $\beta = 1/10$ and $V(p) = 9/10$.

- A_2: If $p \neq \neg q$ for some q, $V(\neg p) = 0$ iff $V(p) = 1$
  and $V(\neg p) = 1$ iff $V(p) < 1$.
  If $p = \neg q$ for some $q \rightarrow V(\neg p) = V(q)$.
- A_3: For any two propositions p and q, if $p \leftrightarrow q$, then $V(p) = V(q)$.
- A_4: If $p \neq \neg q$, then

$$V(p \wedge q) = \frac{V(p) + V(q)}{2}, \tag{2.30}$$

  and if $p = \neg q$, then $V(p \wedge q) = 0$.

  This can be generalised to any number of propositions p_i, $i = 1, 2, \ldots, n$:

$$V\left(\bigwedge_{i=1}^{n} p_i\right) = \frac{1}{n}\sum_{i=1}^{n} V(p_i). \tag{2.31}$$

  As I shall discuss later, this is correct only if all propositions have the same relevancy.
- A_5: For any two propositions p and q, such as $p \neq \neg q$:

$$V(p \vee q) = \max\{V(\neg p), V(q)\}. \tag{2.32}$$

  Otherwise, $V(p \vee q) = V(q \wedge \neg q) = 1$

Notice that in the proposed system meaning precedes truth since only when we understand a proposition we can test it. In turn, the result of a test leads to an assignation of truth value. Hence, truth depends on meaning and not the other way around.

2.8.4 Relevancy

The theory of factual truth outlined above is not free of problems. Let us come back to the example we used to illustrate axiom A_1: p = "Blumina is 9 years old". If Blumina is actually 10, this statement about the age of Blumina has truth value 0.9, i.e. it is approximately true. Lets us now consider the following statement, which is almost false: "Blumina is 1 year old". Its truth value is 0.1. On the contrary, the statement "Blumina is younger than the age of the solar system" is completely true, with a value $V = 1$. The statement is also completely irrelevant to solve the issue of the age of Blumina, despite it refers to Blumina and her age. We can now draw upon A_4 to arrive at some awkward results.

If q = " Blumina is 1 year old", p_1 = "Blumina is younger than the solar system +1 second", p_2 = "Blumina is younger than the solar system +1/2 seconds", ..., p_n = "Blumina is younger than the solar system $+1/n$ seconds", then we have

$V(q) = 0.1$, and $V(p_i) = 1, i = 1, \ldots, n$. Thus:

$$V\left(q \bigwedge_{i=1}^{n} p_i\right) = \frac{V(q)}{n+1} + \sum_{i=1}^{n} \frac{V(p_i)}{n+1}, \tag{2.33}$$

and,

$$V\left(q \bigwedge_{i=1}^{\infty} p_i\right) = \lim_{n\to\infty} \frac{V(q)}{n+1} + \lim_{n\to\infty} \sum_{i=1}^{n} \frac{V(p_i)}{n+1} = 0 + \lim_{n\to\infty} \frac{n}{n+1} = 1. \tag{2.34}$$

Therefore, the value of the molecular statement is 1, i.e. it is true despite q was false.

With a relevant false statement and a large number of irrelevant true statements we have constructed a true statement. All statements have the same reference.

This result suggests that we should take into account the *relevancy* of the different statements when we are evaluating their contribution to a specific problem.

To this goal we define a relevancy bi-valued function Rel: $P \to \{0, 1\}$. Given a problem F, and a statement p with the same reference as the problem, the relevancy function assigns a value 1 (relevant) or 0 (irrelevant) to p according to:

1. If p expresses a sharp value μ, then Rel $p = 1$.
2. If Rel $p \neq 1$ then Rel $p = 0$.

Then, we can reformulate the postulate A_4 as:

$$V_F\left(\bigwedge_{i=1}^{n} p_i\right) = \frac{1}{n} \sum_{i=1}^{n} \text{Rel } p_i . V(p_i). \tag{2.35}$$

So now V_F is 0 in our example.

In principle we can propose a generalized relevancy function:

$$\text{Rel}_F : P \to [0, 1]. \tag{2.36}$$

This is a function that assigns to each statement a relevancy between 0 and 1 with respect to a problem F. Its explicit form is not general but depends on the specific problematic and the sense of the various statements.

2.8.5 Truth Bearers

When discussing "the problem of truth", analytical philosophers use to distinguish two different problems: the nature of truth bearers and the truth conditions. I have elaborated above about the truth conditions for both formal and factual truth. I shall now make some remarks on the objects to which we attribute truth values.

Ontological truth is attributed to thoughts and other processes in the brain. Brains are complex physical objects that can undergo changes that correlate with changes in the external world or other parts of the brain.

Semantic truth, conversely, is attributed to statements and propositions. I have used these words so far interchangeably, but now we can differentiate them.

A *statement* is an illocutionary act that expresses an assertive sentence. The statement is a physical object, either a written sentence that expresses some state of affairs or an utterance. Now, different statements can express the same fact. For instance, the following true statements share the same meaning:

'The snow is white'.

'La nieve es blanca'.

'The color of the snow is white'.

All these statements refer to snow and all say the same: that it is white. Since we have a semantic theory of meaning, we can form a concept, a class, with all statements of identical meaning. We shall call such a class a *proposition*:

$$p = \{x : x \ \text{Syn} \ s\}\,, \tag{2.37}$$

where s is some concrete statement and Syn is the operation that assigns to s all its synonymous statements s':

$$s \ \text{Syn} \ s' \leftrightarrow \langle R(s), S(s)\rangle = \left\langle R(s'), S(s')\right\rangle \tag{2.38}$$

where R and S are, as before, the reference and sense of s.

A proposition is then an equivalence class of statements. Synonymity is the corresponding equivalence relation.

Notice that (1) p is a concept, not a physical object, (2) strictly, p can be defined only when sense and reference can be consistently calculated, i.e. when s belongs to a formalized interpreted language or theory, and (3) this definition is not the one proposed by Bunge (1974a,b), who considers propositions as equivalence classes of thoughts. I do not follow Bunge on this because it is far from clear to me what is a class of thoughts or which is the equivalence relation between thoughts (Romero 2017).

Now, with our definition of proposition we can attribute truth to any statement, and the truth value will be inherited by the corresponding propositions, since statements with the same meaning have the same truth value:

$$\forall x (x \ \text{Syn} \ s) \rightarrow V(x) = V(s). \tag{2.39}$$

Beliefs are psychological attitudes of attachment to some propositions or systems of propositions. There is not direct link between the truth value of propositions and that we might attribute to beliefs: anybody can believe false statements and consider as false actually true propositions. The believing processes should be studied by sociology, psychology, and the neurosciences but not by philosophical semantics. Belief should not have any place in neither science nor philosophy.[10]

Another important question is whether theories can be true. Theories are hypothetical-deductive systems that are constructed to represent some aspect of reality. Any theory involves an infinite number of statements, in the form of theorems entailed by the axioms plus some complementary assumptions and conditions. Hence, it is *not* possible to establish the truth value of a theory from the truth values of the entailed statements. Simply, there is no way to test all statements of a theory since actual infinities do not exist, or, if they exist, supertasks[11] are physically impossible (Romero 2014). However, it is perfectly possible to determine whether some theory T is *truer* than other theory T' that refers to the same facts. We say that T is truer than T' over a domain D if the finite number of statements S of T with reference in D has a higher average truth value and a lower mean error than the corresponding set S' of T'. For example, Special Relativity is truer than Newtonian mechanics and General Relativity is truer than Special Relativity plus Newton's gravitation theory.

2.8.6 Analytic/Synthetic Distinction of Propositions

A lot has been written about the analytic/synthetic distinction since the controversy initiated by W. v. O. Quine famous article "Two Dogmas of Empiricism" (Quine 1951). It is not my intention to review this controversy here. I shall limit myself to offer some definitions that are free, I think, of the usual problems mentioned in connection to this subject. The reader is referred to Bunge (1961, 1974a,b) for further details.

- Df1: An expression is *analytic* in S if and only if it is justifiable by means of an examination of its component signs, with the sole help of other expressions of S and/or the logic L presupposed by S.
- Df2: An expression is *synthetic* in S if and only if it is not analytic in S.

Here, S is some formal language.
There are several kinds of analyticity, namely:

1. *Tautologies*: propositions true in S by virtue of their form and independently of their meaning.
2. *Contradictions*: propositions false in S by virtue of their form and independently of their meaning.

[10] The reader can already foresee that I shall reject the usual definition of knowledge as true belief. See Chap. 2.

[11] A supertask is the implementation of an infinite number of physical operations ('tasks') in a finite time.

3. *Tautonymies*: propositions true in S by virtue of the meanings of the terms occurring in them.
4. *Heteronymies*: propositions false in S by virtue of the meanings of the terms entering in them.
5. *Axioms true by convention*: propositions both basic and true in S by virtue of stipulations.

If analyticity is *contextual* (dependent on S and its logic), then the analytic/synthetic dichotomy is contextual as well.

The analytic/synthetic dichotomy becomes relative but not superfluous: *it is perfectly valid in each context* and must be kept if we do not wish to confuse empirical with linguistic problems and procedures.

Summing Up Only some brain processes and statements can be true, false, or something in between. Propositions are constructs that inherit the truth value of the statements from which they are abstracted. A truth value cannot be assigned to a theory or to a worldview. A theory, however, can be truer than another. The same holds for worldviews. Science thrives for finding ever truer theories about the world.

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Chapter 3
Ontology

Ontology is the part of philosophy that is concerned with the most general features of reality. It aims at providing the basic framework for science, clarifying key concepts as those of physical existence, thing, property, change, chance, causality, probability, state, time, space, law, structure, system, life, mind, society, and many more. Ontology is not concerned with individuals and their specific properties, but with the broadest categories of existence. In what follows I shall present an ontological theory that is realist (assumes the existence of objects outside the human mind), materialist (admits only material entities), systemic (the existents associate to form systems), deterministic (whatever occurs is subjected to laws), and emergentist (different levels of composition provide qualitative novelty). The basic source for this chapter is Bunge (1977, 1979, 2010). See also Heil (2003) for similar views on properties and things. Short, general introductions to ontology are given by Aune (1985) and Conee and Sider (2005).

3.1 Things and Composition

We can characterize the basic elements of our ontological theory by the following postulates. The validation of these postulates is provided by their usefulness as founding blocks of science. Hence, they are not uncontroversial or immune to criticism. Actually, it is expectable that some of them be replaced or refined with the deepening of scientific knowledge. In an appendix I offer an alternative ontology based on basic events, instead of basic things. Other ontological systems are reviewed, for instance, by Lowe (2002) and Loux and Zimmerman (2010).

- O_1: There exist concrete objects named *things*. The set of all things is denoted by Θ.

G. E. Romero, *Scientific Philosophy*, https://doi.org/10.1007/978-3-319-97631-0_3

- O_2: Things can *juxtapose* ($\dot{+}$) and *superimpose* ($\dot{\times}$) to form new things according to the following rules:
  - O_2D_1: A thing x is a physical sum or juxtaposition of all individuals of a given set $\{x_i\}$, $i = 1, \ldots, n$ iff every part of x is a part of at least one of the members of the set $\{x_i\}$.

Example The juxtaposition of an electron and a proton yields a hydrogen atom. The juxtaposition of a large number of atoms yields a gas. The juxtaposition of many human beings produces a society.

- O_2D_2: A thing x is a physical product or superposition of all the members of a set $\{x_i\}$, $i = 1, \ldots, n$ iff every part of x is a part of every member of the set.

Example The superposition of two electromagnetic fields yields another electromagnetic field. Juxtaposition and superposition are two modes of *composition*, i.e. the way things associate to yield other, more complex things. We say the thing x is composed by the things y, w, z,... and designate the relation of composition by the symbol '$\circ$':

$$x = y \circ w \circ z \circ \ldots \tag{3.1}$$

We differentiate only two modes of composition just because our experience of the world suggests things behave this way, but new evidence can lead us to modify these assumptions in order to better account for the way the world is. Composition is not the only element required for the emergence of new systems by association (either juxtaposition or superposition). As we shall see, structure and environment play also a fundamental role.

- O_3: The null thing $\diamond$ is a fiction introduced in order to give the structure of Boolean algebra[1] to the laws of composition of things:

$$x \dot{+} \diamond = x, \tag{3.2}$$

$$x \dot{\times} \diamond = \diamond. \tag{3.3}$$

- O_4: Two things are *separated* if their superposition is the null individual:

$$x \rceil y \Leftrightarrow x \dot{\times} y = \diamond. \tag{3.4}$$

Remark Since modern science admits fields that fill the whole Universe, there are not *isolated* things, i.e. things that are separated from all other things.

$$\neg \exists x \, (\forall y \quad x \rceil y)\,. \tag{3.5}$$

[1]For the concept of Boolean algebra see Appendix B.

- O_5: Let T be a set of things. The *aggregation* of T (denoted by $[T]$) is the supremum of T with respect to the operations of composition.[2]
- O_6: The *Universe* (U) is the aggregation of all things:

$$U = [\Theta] \Leftrightarrow (x \sqsubset U \Leftrightarrow x \in \Theta)\,, \tag{3.6}$$

where the symbol '$\sqsubset$' means 'is part of'. It stands for a relation between concrete things and should not be mistaken with '$\in$', which is a relation between elements and sets (i.e. abstract entities or constructs).

I emphasize that the Universe is a thing, the supreme thing, and not a set of things (a concept).

We can define the composition of a thing as:

$$\mathrm{Comp}(x) = \{y/y \sqsubset x\}\,. \tag{3.7}$$

- O_7: All things are composed of *basic things* $x \in \Xi \subset \Theta$ by means of juxtaposition or superimposition. The basic things are elementary or primitive:

$$x, y \in \Xi \wedge (x \sqsubset y) \Rightarrow x = y, \quad or \quad y \in \Xi \rightarrow \neg\exists x\,(x \sqsubset y)\,. \tag{3.8}$$

Comment: This is a much debated assumption. Ladyman and Ross (2007), for instance, deny that there might be basic things. They may be right, but as far as we can see from our current physical theories there is always some fundamental level of composition. It is true that such level has changed significantly along the history of physics, but today quantum fields seem to be basic entities. Of course this might change in the light of new evidence (more on this in Chap. 9).

- O_8: All things have *properties* $P_i \in P$. These properties can be *intrinsic* (if they depend only on the thing) or *relational* (if they depend on the thing and other things).

Examples Electric charge is an intrinsic property of the electron. Velocity is a relational property of any massive particle and an intrinsic property of a massless boson like the photon.

We can represent a thing as an ordered pair formed by an individual and the set of its properties P.

$$X = \langle x, P(x)\rangle\,. \tag{3.9}$$

There is only one universal property shared by all material objects: energy.

[2]The supremum of a subset S of a partially ordered set T is the least element in T that is greater than or equal to all elements of S, if such an element exists. Consequently, the supremum is also referred to as the least upper bound.

Energy is the potential to change. Only material things can change. Concepts do not change. Then, *to be material is to have energy, to be able to change*. Materiality is not related to mass. Massless things, such as photons, have energy, are material, and can change.

Material existence is identified with changeability. Conceptual existence, instead, is identified with being part of a conceptual system. We feign that conceptual objects have autonomous existence. But they do not have it. They are convenient fictions we invent to represent the world and to simplify our language.

Given a thing X, a conceptual *model* of it, X_m, can be constructed by a nonempty set M and a finite sequence $\mathcal{F}$ of mathematical functions over M, each of them representing a property of X:

- – $O_8 D_1$ - $X_m \equiv \langle M, \mathcal{F}\rangle$, where $\mathcal{F} = \langle \mathcal{F}_1, \ldots, \mathcal{F}_n\rangle$: $M \to V_i$, $1 \leq i \leq n$, V_i is a vector space, and $\mathcal{F}_i \hat{=} P_i \in P(x)$.
  We say that X_m represents X: $X_m \hat{=} X$.
- O_9- The *state* of a thing is the set of functions $\{\mathcal{F}_i : M \to \Re, i = 1, \ldots, n\}$ such that $\mathcal{F}_i \hat{=} P_i$.

The set of accessible states of a thing X is the *lawful state space of* X: $S_L(X)$. The state of a thing is represented by a point in the n-dimensional space $S_L(X)$.

We can introduce now the concept of *law*.

- O_{10}: A *law statement* is a restriction upon the state functions of a given class of things.

Notice that since law statements are restrictions upon functions, they take the form of *differential equations* if the restrictions are purely local or *integro-differential* equations otherwise. In the case that properties are represented by operators, law statements can also appear as algebraic equations or inequations (as it is the case, for instance, with the non-commutativity of some operators in quantum mechanics).

- O_{11}: A *natural law* is a property shared by a class of things and represented by an empirically corroborated law statement. Laws are patterns of repetition of events occurring to some classes of things.
- O_{12}: There are not lawless things, i.e. all things have properties restricted in regular ways.

This axiom simply states that there are not 'magical' things.

- O_{13}: The *history* $h(X)$ of a thing X is the part of $S_L(X)$ defined by:

$$h(X) = \{\langle t, F(t)\rangle : t \in M\}, \tag{3.10}$$

where t is an element of some auxiliary set M (usually $\Re$), and F are the functions that represent the properties of X. A history of a concrete thing is a $(n+1)$-dimensional curve in the lawful state space.

Example In classical mechanics the properties of a particle are position, momentum, and mass. Since mass is constant, it is usually ignored and the history is represented by the curves $\vec{v}(t)$ and $\vec{x}(t)$ in the 7-dimensional space of coordinates $x_1, x_2, x_3, v_1, v_2, v_3, t$.

- O_{14}: Two things interact if each of them modifies the history of the other:

$$X \bowtie Y \Leftrightarrow h(X \circ Y) \neq h(X) \cup h(Y). \tag{3.11}$$

We can define that thing X *acts* upon a thing Y if we previously introduce the *conditional history* of a thing:

$h(X/Y)$: "history of the thing Y in presence of the thing X".

Then $X \triangleright Y$: "X acts on Y"

$$X \triangleright \stackrel{def}{=} h(Y/X) \neq h(Y). \tag{3.12}$$

- O_{15}: An *event* is a change of a thing X, i.e. an ordered pair of states:

$$e = \{s_1, s_2\} \in E_L(X) = S_L(X) \times S_L(X). \tag{3.13}$$

The space $E_L(X)$ is called *event space* of X.

- O_{16}: A *process* p is an ordered series of events:
  $p = \left\langle \left\{e_i, e_{i+1}, \ldots, e_f\right\}, \prec \right\rangle$,
  where $\prec$ is an ordering relation. If the events are continuous $p = e(t)$, with $t \in \Re$ a real parameter.

The basic ontology sketched so far is realistic because it assumes the existence of things endowed with properties, and objective, because it is free of any reference to knowing subjects.

The basis of primitive concepts of this ontology is

$$B = \{\Theta,\ P,\ \dot{+},\ \dot{\times},\ \diamond\}. \tag{3.14}$$

As in any axiomatic system, the meaning of the concepts designated by these symbols is determined through the role they play in the axioms.

3.2 Properties and Substance

In the ontology outlined above properties are primitive features of things. The theory is realist about properties in the sense that there is a trivial answer to the question "do properties exist?". This answer is yes. But properties do not exist in themselves, they exist *in re*. There are not isolated, self-existent properties. Every property is a property of something. Of course, we can abstract a concept of a given property from a class of things and feign that it exists independently. We can then talk of properties such as electric charge, spin, and rest mass as if they were individuals. They actually are conceptualizations of recurrent features of different individuals. The abstraction is usually done imposing a resemblance or, more stringently, an equivalence relation upon a set of entities (see Küng 1967, and Rodriguez-Pereyra 2002).

Properties can be represented by functions or by predicates, but these should not be confused with them. Properties have an ontological status that functions and predicates, which are constructs, lack. In particular, not all predicates correspond to material properties. For instance, if we consider the predicate "it is not predicable of itself" and we assume that it represents a property we obtain a contradiction. Because if there is such a property, then the predicate applies, but also because of the meaning of the predicate, it should not apply. The contradiction, a version of Russell paradox (see Lowe 2006), is in the application of our language to reality and not the in the world, since there is not such a property.

Even assuming that properties are primitive features of things in our ontology, we are entitled to enquire: given two properties, under what conditions we can say that they are the same? A possible identity criterion is this (based on Heil 2003):

(PI_1): If $P_1(x)$ and $P_2(y)$ are properties of things x and y, then $P_1 = P_2$ iff P_1 and P_2 contribute equally to the total power of x and y.

By *total power* of a thing x I refer to the number of legal changes and interactions that might involve that thing. We can rephrase this criterion using our previous notation as:

(PI_2): Two properties, P_1 and P_2, of a thing x are identical iff the history $h(x)$ of x is invariant under the replacement of P_1 by P_2.[3]

Intrinsic properties exist in things independently of our ability to represent them. Science tries to provide ever better characterizations of properties. For instance, the charge e of a particle (say an electron) can be characterized in electromagnetic theory as the property such that when the particle is exposed to a magnetic field B it moves in a circular motion with cyclotron frequency given by

$$\omega_e = \frac{|e|B}{m}\omega_e = \frac{|e|B}{m},$$

where m is another property of the particle known as its rest mass. In quantum mechanics, however, a more sophisticated characterization of e is possible in terms of Gauge invariance (see Chap. 7). The deeper our knowledge of nature is, the more complete our characterization of properties results.

Relational properties may or may not be subject-dependent. The so-called qualities depend on the subject. Qualities such as "being hot", "red", or "smooth" exist only in relation to a sentient being. Other relational properties, such as

[3]Bochenski (1962) offers the following, purely logical, criterion: $\phi \equiv \psi \leftrightarrow \forall(x)(\phi x \equiv \psi x)$.

velocities and locations, are mind independent and exist for systems of things, i.e. inter-related individuals.

Scientific research aims at producing knowledge of those things we find in the world; this knowledge is obtained through the faithful representation of things's properties. In order to represent properties, they are abstracted, conceptualized, and formalized as much as possible. Then, predictions are achieved through particularization of these abstract representations through specific models of concrete material things (see Chap. 4).

Another issue related to properties is whether there are properties of properties, i.e. second order properties. Properties are ways material things are: they are not parts of things. In similar way as a property is a feature of a thing, a property of a property would be a feature of a property or a way a property is. But to say this adds nothing to the original property, except, perhaps, some complexity. Properties are the way they are, complex or not. Everything we can say about properties can be said in the same predicate, without need to have predicates of predicates. I conclude, along with Bunge and Heil, that there are not second order properties. Or at least we do not need them to represent the world.[4]

At this point the reader might wonder: if properties express all powers of things, and we can only interact with things through their powers, why we think there are things at all? Why not to apply Occam's razor and assert that only properties, arranged in certain ways, exist? Do we have any chance, even in principle, to interact with a thing if it is devoid of properties? Is it meaningful the idea of a thing without properties? Why not to introduce an ontological theory of properties dispensing with things? Do we need things at all in our description of the world? Borges, famously quoted Swift stating that "if certain ermines and furs be placed in a certain position, we style them a judge, and so an apt conjunction of lawn and black satin we entitle a Bishop" (*A Tale of a Tub*). Similarly, why not to conclude that what we call things are nothing else than bundles of properties? Why not abandon the assumption of an underlying substance, since it seems to add nothing at all?

This is of course the route taken by *bundle theorists* since Hume. For them, material objects or things are nothing else than 'bundles' of compresent properties or relations. Things are collections of powers that affect and are affected by other collections of powers. Among some illustrious proponents of this view we can mention Hume, Boscovich, Russell in his books *Our Knowledge of the External World* and *Analysis of Matter* (Russell 1914, 1927), and Holton (1999). Although I think that this view is defensible and I myself will offer a sketch of an ontological

[4]A closely related problem is whether there are properties of events. In an ontology where events are considered as individuals, energy (the capability to generate new events) is a property of basic events. Clusters of events and processes can have properties such as length, duration, and, at some limit, all the properties we associate with things. Event ontology is a research project, particularly attractive for the foundations of quantum spacetime but much of the project must still be implemented in order to assess its viability as a sound alternative to the thing-based ontology that is usually assumed in the sciences at the macroscopic level. See Appendix A.

theory without substance in Appendix A, I think that there are reasons to resist the apparent charm of the theory, at least at macroscopic level. Let us see.

The main objection seems to be related to this question: why would a world formed by things whose nature is exhausted by their properties would be more reasonable than a world formed just by bundles of properties? If we accept some form of the Principle of Sufficient Reason (see Chap. 4) and have some sympathy towards ontological economy, then, in the absence of a compelling reason, it seems we should prefer a bundle ontology. I think, however, that there is an important reason to hold that there are substantival individuals, despite they do not exist independently of their properties. The existence of things, or material particulars, is assumed in an ontology out of our epistemic deficiencies. This assumption expresses the idea that more powers can be found for any particular. If we define an electron by a set of properties (or a bundle, say), then it should be something like this:

$$\text{electron} = \{m_e,\ s = 1/2,\ e,\ \text{lepton number} = 1,\ \ldots\},$$

where I list some properties such as rest mass, spin, electric charge, and lepton number. There was a time when these were all the properties of the electron. In bundle theory parlance, the electron *was* these properties. However, further research has revealed additional properties such as weak isospin and weak hyper-charge. Did the electron changed? Of course not. What changed was our knowledge of the electron. The hypothesis of an underlying but unobservable substance encourages us to foster new research in order to improve our knowledge of the thing we call “an electron”, and whose properties or ways of being we know only fragmentarily.

The hypothesis of a substance is also supported by the following considerations: If a thing is nothing more than a collection of concrete properties, what exactly holds these properties together? Why do we not perceive random properties “floating about”? Why do they collect into the type of object we call “things”? Assuming there is a substance with different intrinsic properties and many ways of relating to other particulars is a classic solution that is already present in the Greek atomism of Leucippus and Democritus.

The idea of a substance as an underlying substratum for properties is explicitly developed by Aristotle, for whom substance was what always survives to change. In modern times the concept is clearly formulated by Locke:

> The idea then we have, to which we give the general name substance, being nothing, but the supposed, but unknown support of those qualities, we find existing, which we imagine cannot subsist, *sine re substante*, without something to support them, we call that support *substantia*, which, according to the true import of the word, is in plain English, standing under or upholding. (Locke 1997, II xxiii 2)

Properties—or, in Locke’s terms qualities—must belong to something. Of course, they belong to objects, but what are these objects over and above their properties? All that seems to be left is a bare ‘something’, which has no properties in its own right, except the property of being the support of other properties.

According to Lowe (1998) substances do not depend for their identity upon anything other than themselves. Specifically, Lowe proposes:

> x is a substance if and only if x is a particular and there is no particular y such that y is not identical to x and the identity of x depends on the identity of y.

Beyond the possible objections to this and other definitions of substance, it seems that we cannot dispense with the very concept of substance in order to make sense of the world as we see it. The major controversy seems to be not in the existence of substances, but in whether substances are basic or not. Bundle theorists seek to reduce the concept of substance to an underlying collection of non-substantial entities. They do not necessarily deny the existence of substances but rather define substances as such:

> x is a substance if and only if x is a collection of a proper kind of non-substantial entities.

It might be the case that substance and some non-substance theories are fully equivalent descriptions of reality. A substance-based approach looks like more appropriate for a description at some macro-level of the world, whereas non-substantial objects such as properties and events may be more adequate to the micro scales (Romero 2013, 2016, see also Appendix A).

As for the ontological theory we have adopted here (Sect. 3.1), a material object is not composed of properties and some further ingredient; rather an object is something which simply has properties. Any feature of it can be regarded as a property, but that does not render the object a simple collection of properties. In our ontology, we have assumed the existence of things as basic ontological entities: properties and property-bearers are inseparable because the first are just the way things are. The very separation of things into properties and property-bearers is just a mental operation of abstraction. There are no bare-particulars (Bunge 1977; Heil 2003).

3.3 Existence

The concept of existence is essential to ontology. Since the pre-Socratics philosophers, questions about existence have being the core of the Western metaphysics. However, there is little agreement as to the very meaning of "existence". Discussions within the framework of scientific philosophy are mostly based on the concept of existence introduced by Whitehead and Russell (1910, 1912, 1913) in *Principia Mathematica*. Current formal languages adopt an existence operator '$\exists$' that acts as a particularizator for variables. If we have some predicate function '$f(x)$', then $\exists x \ f(x)$ can be interpreted as 'for at least one x, $f(x)$'. First order formal languages also contain a generalizator '$\forall$' such that '$\forall x \ f(x)$' means 'for all x, $f(x)$'. Clearly, both operators are related: $\exists x f(x) \equiv \neg\forall x \neg f(x)$. Since Quine (1948, see also Quine 1939, 1943, and 1930) it has been popular to think that the existential quantifier '$\exists$' of first order logic exhausts the concept of existence in such a way that the only objects whose existence should be admitted in our ontology are those accepted in the domain of '∃'. In Quine jargon, "to be is to be the value of a variable"—i.e. of a quantified variable. For Quine and followers, there are not such a thing as properties, since they are represented by predicates, and predicates are not values of variables—in first order logic at least. At the same time, it seems impossible not to quantify over mathematical objects, or at least over classes and sets, if we want to use modern mathematics to describe the world.

Not strangely, many authors have protested against Quine's restricted interpretation of existence; it has been claimed that the combination of a quantifier with a predicate and the respective propositional function does not fully express the meaning of 'existence' (see, among many others, Church 1958; Bunge 1977; Menne 1982). Menne (1962), in particular, points out that there is a correspondence between logical quantification and formal coherence:

$$\exists x f(x) \leftrightarrow \{x/\ f(x)\} \neq \emptyset,$$

where $\emptyset = \{x/\ x \neq x\}$ is the empty class.[5] Formal existence, hence, signifies nothing more than freedom from contradiction. In the logical calculus of the *Principia* and further formulations existence appears only in this sense. Empirical science and natural language, however, adopt other senses of 'existence'. We can quantify over variables in whose domain there might be numbers, unicorns, electrons, planets, wave-functions, Don Quixote, and many other objects that require additional intensional specification. We can attain this introducing a predicate indicating a *mode of existence*.

The predicate, without which the existence operator cannot be meaningfully applied, reveals itself through the mode of existence, expressed by an intensional predicate. Formal existence indicates coherence; ontological existence, instead, is constructed from the former and from an intensional determination; this means that ontological problems of existence can be decided only intensionally and not in a purely formal-logical way. The expression of ontological existence requires both formal existence and a predicate expressing the mode of existence.

How many modes of existence there are is a matter of fact. I propose only three modes: material, formal, and fictional existence. Something exists materially iff it has energy (i.e. if it is capable of change). Something exists formally iff it is a part of a well-defined formal system. Last, something exists fictionally, if it

[5]Menne (1962) writes: "The existence of a class is of a purely logical form; it is certainly to be distinguished from the existence of its elements. There results correspondingly: an object exists logically if the extension belonging to the predicates is not empty; in other words, if it possesses no contradictory properties. Entirely analogously, then, a class exists precisely if its properties (that are not to be confused with the properties of its elements!) are not contradictory. To be sure, there exists no object which could be the element of a null class, for such an object would indeed be contradictory in itself. But the null class does exist if the property 'possesses no element' is not contradictory in itself. Without detriment to type theory, therefore, existence as formal, logical existence belongs to classes."

is characterized in some context that is not formal, e.g. by isolated definition or description. In this way, we can say that a given electron exists materially, Hilbert spaces exist conceptually, and Don Quixote exists fictionally in Cervantes' novel. We can formalize these ideas as follows.

Let $E_{\text{mode } i}$ be a predicate that specifies the mode of existence. Then, if we want to assert the existence of number 3, we can write:

$$\exists x (E_{\text{formally}}\, x \ \wedge \ x = 3),$$

or

$$\exists x (E_{\text{formally}}\, x \ \wedge \ x \in N \ \wedge \ 2 < x < 4),$$

where N is the set of natural numbers.

Similarly,

$$\exists x (E_{\text{fictionally}}\, x \ \wedge \ x = \text{Zeus}),$$

and

$$\exists x (E_{\text{materially}}\, x \ \wedge \ x = \text{Mars}).$$

In these latter two formulas, the proper names 'Zeus' and 'Mars' can be replaced by adequate descriptions. Since our partition of the set of existents into material things, formal concepts, and fictions depends on our knowledge of the world and our languages (either natural or formal), objects to which we attribute material existence might be considered on closer analysis merely conceptual (e.g. the mechanical aether) or even fictional (e.g. Zeus). Both formal concept are fictional entities do not interact with material entities and do not change. They can replaced by other concepts or we can feign that the exist materially for pragmatic reasons but they are all *conceptual artifacts*: inventions of the human mind. In a broad sense, they are all *fictions*.

Summing up: Formal existence is a superordinate concept and in this sense a presupposition of ontological existence; the latter is composed out of the former and a determination of mode. Ontological questions of existence, then, can only be settled empirically and not on the mere grounds of formal logic.

What about properties? In the previous section I claimed that properties exist in some sense. What sense is this? As pointed out by Church (1958), when we claim that '$\exists x \;\; f(x)$', we are not only claiming the existence of x, but of x such that $f(x)$. Properties are always associated with individuals in the ontology presented in Sect. 3.1. Then, the existence criterion for a property is simply to be the property of an object. The mode of existence for the property is the same as the mode of existence of the object. The length of a triangle is as conceptual as the triangle itself, and the length of a table as material as the table itself. The set of existents do not contain things *and* properties, but things *with* properties.

3.4 Levels, Systems, Structure

Since things compose with things to form new, more complex things, a hierarchy of things seems to exist. Reality appears to have *levels* of organization. A level is a collection of things that share certain properties and undergo changes according to some common laws that apply to all of them. For instance, all chemical objects share some properties and obey to chemical laws, but they do not have biological properties or are constrained by social laws.

Reality (the set of all real objects) seems to be composed by five major levels: physical, chemical, biological, social, and technical. The objects in any level above the physical level are composed of entities belonging to lower levels. The higher levels (the individuals that form them) have emerged in the course of time through the association of individuals of lower levels.

There is no mental level. This is so because the ontology adopted here is materialist: the mind is conceived as a system of functions of an organism or a complex system. If the system is biological the mind is the result of a specific activity of the brain in connection with the rest of the different subsystems of the organism in interaction with the environment. The mind is not as an emerging entity but a complex activity of highly evolved organism. Hence, mind belongs entirely to the biological level.

The structure of the level system is $\mathcal{L} = \langle L, < \rangle$ where L is the set of levels and $<$ is an ordering (precedence) relation upon the elements of L. For any level L_n, $L_n < L_{n+1}$ iff $\forall\sigma \left[\sigma \in L_{n+1} \Rightarrow \mathrm{Comp}(\sigma) \in L_n\right]$, where as before $\mathrm{Comp}(\sigma)$ is the composition of σ. According to this we have the following hierarchy of levels: physical < chemical < biological < social < technical.

Within each level things compose to form more complex things. A composed thing is a *system*. Everything, except basic entities, is a system. A system is characterized by its *composition*, *environment*, *structure*, and *mechanism*.

The composition of a system is the collection of its parts.

The environment of the system is the collection of things that interact with the system.

The structure is the collection of relations (bounds or links) among the components of the system, as well as with the environmental objects. The former is the *endostructure*, the latter the *exostructure*. The total structure is the union of the two.

Finally, the mechanism is the collection of all internal processes that occur in the system.

A *subsystem* is a system such that its composition and structure are part of another system. Example: the digestive system is a subsystem of the human body.

The maximal system is the Universe, i.e. the system of all subsystems; it is studied by cosmology, the most extreme form of mega-physics.

Any given system can be modeled by an ordered quadruple:

$$\mu(\sigma) = \langle C(\sigma), E(\sigma), S(\sigma), M(\sigma) \rangle , \tag{3.15}$$

where the components are sets that represent each one of the four collections that characterize the system. All elements of the system can change with time.

The composition at level L is $\mathrm{Comp}|_L(\sigma) = \mathrm{Comp}(\sigma) \cap L$. In general, we only model a system at some fixed level of composition.

3.5 Causality

Causality is a relation between events, i.e. a relation between changes of states of material things. It is *not* a relation between things. We define (Romero and Pérez 2012):

$\mathfrak{C}(x)$: "an event in a thing x is caused by some event $e^x_{x_i}$".

$$\mathfrak{C}(x) \stackrel{def}{=} (\exists e^x_{x_i}) \left[e^x_{x_i} \in E_{\mathrm{L}}(x) \right] \Leftrightarrow (\exists x_i)(x_i \rhd x).$$

$C(x, y)$: "an event in a thing x is caused by an event in a thing y".

$$C(x, y) \stackrel{def}{=} (\exists e^x_y) \left[e^x_y \in E_{\mathrm{L}}(x) \right] \Leftrightarrow y \rhd x.$$

In these definitions, the notation 'e^x_y' indicates with the superscript the thing to whose event space belongs the event e, whereas the subscript denotes the thing that acted triggering the event. The implicit arguments of both $\mathfrak{C}$ and C are events, not things. For simplicity in the notation we refer to the things that undergo the events with lower case.

Causation is a form of event generation: a given event in the lawful event space $E_{\mathrm{L}}(x)$ is caused by an action of a thing y iff the event happens *only* conditionally to the action, i.e. it would not be the case of e^x_y without an action of y upon x. Notice that time does not appear in this definition, allowing backward causation and non-local effects.

An alternative and equivalent definition is this:

Two events e_1 and e_2 are causally related iff there is at least a process[6] p such that e_1 and e_2 are components of p and e_1, and it is never the case that e_1 is not a component of p. Then, we say that e_1 is a cause of e_2. The event e_2 is an effect of e_1. In symbols:

$$e_1 \rhd e_2. \tag{3.16}$$

The process p involving e_2 can never occur without the existence of e_1.

[6] A series of events.

The world is legal and determinate, but not strictly causal. There are events that are not causally related and processes that are not causally originated. Some examples are atomic spontaneous transitions and muon decays.

3.6 Chance and Probability

In epistemology the word *chance* is used to designate the unpredictable character of some events in some theoretical framework. For instance, a car accident or the result of a roll of dice. The epistemological concept of chance is but a name for ignorance. Instead, the *ontological sense of chance* is that some events belong to a random sequence. A random event has an objective stochastic *propensity* that can be quantified by a probability. *Propensity*, in turn, is the property of a system to change from one state to another.

Causal propensity: if a system is in a state A then will evolve to a state B.

Stochastic propensity: if a system is in a state A then there is a probability P that will change to a state B.

Stochastic propensity is represented by the probability function $P : E \rightarrow [0, 1]$, which is defined by the following axioms:

- A_1: If F is a set and $E_i \subset F \Rightarrow$ all unions and intersections of E_i are in F. $E = \{E_i\}$ is the set of all subsets of F.
- A_2: $P : E \rightarrow [0, 1]$.
- A_3: For any $A \subset E$, $0 \leq P(A) \leq 1$.
- A_4: If $(A \in E) \wedge (B \in E) \wedge (A \cap B \neq 0) \Rightarrow P(A \cup B) = P(A) + P(B)$.
- A_5: $P(F) = 1$.

These are Kolmogorov axioms for probability (see Appendix C for a full characterization of the concept of probability). I emphasize that probability is the quantitative measure of stochastic propensity, and hence a measure of a physical property. It is incorrect to assign probabilities to hypotheses or propositions because hypotheses and propositions are conceptual, not physical, objects.

A parent ontological concept is that of *disposition*. Traditionally, the features of concrete things, and the predicates that represent them, have been divided into manifest (such as mass, charge, and age) and dispositional (such as solubility, sociability, and instability). A property of a thing is *actual* or *manifest* if the thing possesses it, and *potential* or *dispositional* if emerges under suitable conditions.

In general, we say that a disposition or a dispositional property is a property actually possessed by a thing that, under appropriate environmental conditions, generates another property. The latter property is then manifest, whereas the former is not.

Specifically, a thing x has the disposition D_x if x has the actual property A *and* x interacts with another thing y in such a way that x acquires the relational property R:

$$D_x \Leftrightarrow A_x \wedge \exists y \;\; \exists R \, (y \neq x \quad \wedge \quad x \bowtie y \quad \wedge \quad R\, xy)\,. \tag{3.17}$$

As an example let us consider longevity. This is a dispositional property of some individuals. Instead, life expectancy at birth is a statistical or collective property of a population. In general, real probability quantifies dispositional properties of individuals, whereas statistical parameters such as average, variance, etc., are manifest properties of collections of individuals.

3.7 Space, Time, and Spacetime

Space and time are usually considered as basic ontological categories, i.e. very broad and general concepts necessary for any meaningful discussion of the world. Much has been said about whether these categories represent some kind of entities. The idea that space and time are things with independent existence is called *substantivalism*. This position was famously espoused by Newton who wrote that:

> Absolute space, in its own nature, without relation to anything external, remains similar and immovable

> Absolute time, and mathematical time, of itself, and from its own nature, flows equally without relation to anything external.

In this view, space and time do not interact with other things. Space is a kind of stage where the events occur and time a kind of flow that fills all space. This kind of substantivalism has been criticized by Leibniz and others. For Leibniz "space is nothing else, but an order or a relation" and instants, considered without the things, are nothing at all. . . They consist "only in the successive order of things". This view, that maintains that space and time are *not* things, but relations among changing things, is known as *relationism*. According to relationism the existence of space and time is not autonomous but subsidiary to the existence of things.

The introduction of the concept of spacetime by Hermann Minkowski in 1908 and the development of the theory of General Relativity provided new elements to the ontological controversy. It is now clear that space and time are not independent from each other but different aspects of spacetime. The specific metric properties of spacetime are determined by the material bodies, so it seems to be dependent on them. On the other hand, the curvature of spacetime seems to affect the motion and other properties of physical objects. The controversy between substantivalists and relationists has continued: Is spacetime a physical entity that can exist without other objects? Is it an emergent relational property of all existents? Or is an emergent physical thing? Arguments for an against these positions have been proposed and the problem is still open (see Pooley (2013) for a review and Romero (2017) for details). I will come back to this issue in the second part of the book.

3.8 Matter

I offer now an elucidation of the important concept of *matter*. We say that an object is material iff its lawful space state has more than one point, i.e. if the object can change. Materiality, then, is co-extensive with changeability. In turn, the capability to change is called *energy* (see Bunge 1981, 2000). As I already mentioned, this is the only universal property of all existents: essentially is the capability to interact. Concepts and fictions do not change or interact, only material things do it. Having a mass is not a necessary condition for materiality: photons and other massless particles have energy and interact, hence they are material.

Matter itself is not material since it is a concept, not a thing with energy. Matter is just the class of all material things:

$$M = \{x : x \quad \text{is} \quad \text{material}\}\,. \tag{3.18}$$

Similarly, *reality* is the set of all real (i.e. existing independently of the mind) things. Being a concept, reality is not real.

3.9 Mind

The mind is a collection of activities of an organism with a major involvement of brain processes that enables consciousness, perception, thinking, judgment, and memory. In words of Bunge (1980): the set of mental events is a subset of the set of the events in the plastic neural systems of the brain of a complex organism. Hence, all processes called mental are either neural processes or processes in the organism in close connection with neural events. More precisely, for every mental process M, there is a series of processes $N = \{N_1, N_2, \ldots, N_n\}$ in an organism endowed with a nervous system, such that $M = N$. For instance, seeing is the specific function of the visual system; feeling fear, a specific function of the system centered in the amygdala[7]; deliberating and making decisions are mainly (but not only) functions of the prefrontal cortex, and so on. In the present context, a function is understood as a process in a concrete thing, such as the circulation of blood in the cardiovascular system, the flow of air in the lungs, and the formation of a decision in the prefrontal cortex. And a specific function of a system S is one that only S can perform. For

[7] Recent research indicates that feeling fear involves many areas of the brain besides the amygdala, as well as internal and external sensors and effectors outside the brain. There are studies that found that people without amygdala can still feel fear, with which the amygdala can not be considered necessary or sufficient condition to feel fear. All these suggests that some mental processes are far more complex than what is usually supposed by simple forms of the brain-mind identity theory. See for example Barrett (2017).

instance, of all different organs of the human body, only the brain can think, albeit not in isolation but as a part of an organism in some environment.

Some consequences are immediate. If the mind is a collection of functions of an organism with a neural system, then it is not a thing but an activity of a thing. Hence, as breathing cannot exist without lungs, there is no mind without organism and brain. As the brain and the organism age or deteriorate, their functions also decline, and finally disappear. The brain can sicken, and our mental functions will in consequence wane. No mind survives the destruction of the brain, because there is no function without organ. No digestion without digestive organs, no breathing without respiratory system, no smiles without lips, no mind without brain.

There are machines that reproduce functions of the living organism: artificial hearts, lungs, kidneys. Is it possible for a machine to have mind? In order to have a mind, a computer or a complex machine should be able to perform the full set of cognitive functions of the brain: to perceive, to think, to judge, to memorize, to recall, and to have self-consciousness. There are machines that can perceive, memorize, and recall. Some can even take decisions. But so far they are dependent of human programming. Whether in the future technology will enable the creation of machines capable of all higher cognitive mental functions and self-programming, I do not know.[8]

3.10 Materialism

Materialism is the ontological hypothesis that all real things are material. Since the criterion of materiality is changeability, according to materialism whatever exists can change, and hence has energy. Concepts, being abstractions, are not real but fictitious. Of course, they can nevertheless be very useful to represent real objects.

Materialism can be developed into a full ontological theory. The most popular forms of materialism are physicalism (whatever exists is a physical object), mechanicalism (whatever exists is a mechanical system), naturalism (existents are natural objects), and emergentism o emergentist materialism (existents are material but do not belong to a single ontological level). Physicalism cannot explain the existence of supra-physical properties such as those of biological or social systems. These systems have emergent properties not found in the objects studied by physics. Mechanicalism also fails, since there are many ways in which objects can relate that are not mechanical. This is valid even within physics (think, for instance, about atomic transitions, field superpositions, and many other examples in modern physics). Naturalism cannot explain the existence of artificial systems, in particular those studied by sociology, such as societies, or technology, such as instruments, methods, or regulations. Naturalism neither can account for formal sciences, since

[8]For an optimistic view on this topic see Minky (1982); for criticisms, Bunge (1956). An updated defense of artificial intelligence in given by Shanahan (2015).

they are not natural, but the product of human activity. Emergent materialism (Sellars 1922, 1932; Bunge 1981, 2000) holds the existence of different levels of organization of material systems. The members of any level above the physical level have some properties that emerged from the interactions of the components of the systems or between the relation of the system with the ambient medium. A property is called *emergent* if it is not possessed by any of the components of the system (Bunge 2003). The main goal of the scientific investigation of material systems consists in the search for adequate explanations of their emergent properties in terms of the basic ones.

3.11 Information

Another widely misused concept is that of information. *Information* is a concept associated with the transmission of signals that codify some statements in some language.

Information is defined on the set of pairs signal-receiver, where a receiver is a system (biological or not) competent to decode the signal. Specifically,

Definition If a signal (mark, sign, inscription, sound, etc.) is a sentence or represents a sentence of some language L, then the information conveyed by the signal is the proposition designated by the sentence.

If S and S' are sets of signals representing the sets of propositions P and P' respectively, then

1. the information conveyed by S is larger than, or equal to, the one conveyed by S' iff P' is a proper subset of P;
2. the information gain accompanying the substitution of S for S' equals $P - P' = P \cap P'$.

These propositions define what can be called the semantic concept of information.

Not being a thing, semantic information has no energy and has not independent existence. Its ontological status is that of a fiction. In particular, there is not a "law of conservation of information" as stated by some authors.

In short, the semantic information or message conveyed by a signal consists of the proposition or propositions the signal stands for. It follows

(a) that non-propositional signals convey no information,
(b) that the greater is the content of a proposition, the richer is the information carried by the signal representing that proposition, and
(c) that the truer a proposition is, the more accurate is the information carried by the signal representing that proposition.

I will close this chapter with the characterization of the entities that form the higher levels of ontological composition: biological and social systems. A full treatment is beyond the scope of this book. The reader is referred to Bunge (1979, 2003) and references therein.

3.12 Biological Systems

An biological organism is a system such that

1. its composition includes proteins (both structural and functional, in particular enzymatic) as well as nucleic acids (which make for its reproducibility and the likeness of its offspring);
2. its environment includes the precursors of all its components (and thus enables the system to self-assemble most, if not all of, its biomolecules);
3. its structure includes the abilities to metabolize, to self-repair, and to reproduce.

Are there non-biological organisms? One can imagine very complex artificial systems that can perform the processes described in the third item above. But the exact composition of such non-biological organisms is open to discussion. So far, no synthetic machine can evolve without human assistance.

3.13 Social Systems

A *society* is a system of interrelated individuals that display some level of coordinated activity and share an environment. This idea is formalized as follows:

A society σ is representable as an ordered quadruple $S =<$ Composition of σ, Environment of σ, Structure of σ, Mechanism of $\sigma >$, where the structure of σ is the collection of relations (in particular connections) among components of σ. Included in the structure of σ there might be the relations of work and of managing which are regarded as typical of human society in contrast to animal societies. The mechanism that operate in a society are mostly unknown to our current social sciences.

A human society has four sub-systems: *biological*, *political*, *economical*, and *cultural* (see Bunge 1979, and 2003, for further details).

Summing Up I propose an ontology based on *things*, changeable entities endowed with properties. Things combine with other things and form *systems*. Systems are grouped into *levels* according to their shared properties: physical, chemical, biological, social, and artificial. The systems that populate each level emerge from the previous level when new functions appear with increasing complexity. The changes of things are restricted by *natural laws*. There are no lawless changes. Some changes are *causal* (triggered by previous events) and others are *probabilistic* (stochastic but lawful). The common property of all things is *energy*, the capability to change. Objects endowed with energy are called *material*. Otherwise, they are concepts and fictions. Information is not a physical property or a thing. Information is the propositional content of encoded signals, and hence it is a concept.

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Chapter 4
Epistemology

Episteme, as distinguished from *techne*, is etymologically derived from the Ancient Greek word ἐπιστήμη for knowledge or science, which comes from the verb ἐπίσταμαι, "to know". In Plato's terminology episteme means knowledge, as in "justified true belief", in contrast to *doxa*, common belief or opinion. The word epistemology, meaning the study of knowledge, is derived from *episteme*.

Epistemology is the general study of cognitive processes and their outcome, i.e. knowledge. Specific mechanisms of knowledge acquisition are investigated by neurosciences and psychology. Philosophical epistemology, instead, has a general problematics that includes the nature of knowledge and understanding, the characterization of science, theories and models, the ways of explanation, interpretation problems of specific sciences and theories, and so forth.

In what follows I shall present some views on the these topics. General references are Bunge (1983a,b, 1998a,b). See also Niiniluoto (1999), Rescher (2000), and Williams (2001).

4.1 Knowledge

Knowledge is the product of cognitive operations made by an inquiring subject. It is not a thing or a substance, but a series of changes in the brain of the knower. The outcome of learning is a collection of brain processes that cannot exist outside the brain. Knowledge is not independent of the knowing subject, although we often feign it is so for practical reasons. Knowledge is different from belief: I can know a story, for instance, but do not believe it. Belief implies a psychological adherence to some propositions. It is possible to believe something without understanding it, so belief is not necessarily associated with neither truth nor justification despite a widespread opinion.

G. E. Romero, *Scientific Philosophy*, https://doi.org/10.1007/978-3-319-97631-0_4

Knowledge acquisition requires a modification of the brain of the knower. This can be done in different ways, hence there are different kinds of knowledge. Namely:

1. *Sensory-motor knowledge*: the result of learning from actions.
2. *Perceptual knowledge*: the result of perceiving events, either internal or external to the subject.
3. *Conceptual or propositional knowledge*: the result of ideation, conjecturing, testing, and correcting.

I emphasize that there is not knowledge without a plastic brain, since fixed neural arrays cannot be modified and hence learning is not possible. A machine can learn as far as it changes in response to some stimulus and then can behave differently from before. Not all learning is beneficial: we can learn trivialities, falsehoods, or highly harmful habits.

The three kinds of knowledge are *interrelated*: conceptual knowledge can improve motor skills and perception; perception is used to evaluate conjectures; motor skills can help to improve perception and build instruments such as books, that enhance the ability to learn.

Since knowledge depends on changes in the brain of a knower, knowledge evolves with the subject: $K = K(t, s)$, where t is time and s the knowing subject. The collection of neural processes of s changes with time. Knowledge, being a collection of physical processes and not a set, is physical, not conceptual. Hence, knowledge can be destroyed: it is enough to destroy the brain of s to terminate with the associated cognitive processes.

From a methodological point of view it is convenient to feign that cognitive processes have a transferable content, so that we can think of this content independently of any knowing subject. This is a convenient fiction that allows us to discuss ideas without any reference to the ideation mechanism in concrete individuals. However, ideas do not exist by themselves: we just act as if they do. Hence, there is no knowledge in a library or in the internet; knowledge is only in the brains of the readers. When they interact with the books or the screen of a computer, they experience cognitive processes, that resemble those of the authors of the texts.

I insist: books and articles do not have knowledge. They are instruments designed to create knowledge.

Neuroplasticity There is no knowledge without changes in the brain. If a brain can change in response to some stimulus or spontaneously it is said to have *neuroplasticity*. The brain acts as a dense network of fiber pathways consisting of approximately 100 billion ($\sim 10^{10}$) neurons. It consists of three main parts: stem, cerebellum, and cerebrum. Of the three, the cerebrum is most important in learning, since it is where high-level functions such as memory and reasoning occur. Each area of the cerebrum specializes in one or more functions—sight, hearing, speech, touch, short-term memory, long-term memory, language, and reasoning.

Some recent brain research findings indicate:

- Frequency and recency of neuron synapses increase memory.
- Emotions strengthen memory.
- Learning causes changes to the physical structure of the brain.
- Memories are stored in multiple parts of the brain.
- Our brains are programmed to focus on new and unusual inputs.

Perhaps the most important property of the brain regarding learning is its neuroplasticity. Neuroplasticity, also called brain plasticity, is the process in which the neural synapses in the brain and different pathways are altered as an effect of environmental, behavioral, and neural changes. The brain makeups changes when it is exposed to new external inputs, so that it may retain the associated information.

The processes related to neuroplasticity are not quick or simple; rather, they take place throughout the lifetime of the individual and can involve many different aspects. Along with altering the neural synapses and pathways, they involve changes to the neurons, vascular cells, and glial cells. Neuroplasticity also occurs hand-in-hand with synaptic pruning, which is the brain's way of deleting the neural connections that are no longer necessary or useful and strengthening the necessary ones. How the brain decides which connections to prune out depends on the life experiences and how recently connections have been used. In much the same way, neurons that grow weak from underuse die off through the process of apoptosis. In general, neuroplasticity is a way for the brain to fine-tune itself for efficiency.

Neuroplasticity happens continually as the individual learns and memorizes new data, and as the brain develops; however, it can also be spurred by a physical trauma. In such cases, neuroplasticity serves as an adaptive mechanism that allows someone to compensate for function loss after suffering a bodily injury. For example, if someone suffers a brain injury, neuroplasticity allows the brain to 'rewire' itself in order to restore or maximize brain functioning by rebuilding neural circuits and allowing an uninjured part of the brain to take over the damaged part.

Research has shown that the brain never stops changing through learning. Changes associated with learning occur mostly at the level of the connections between neurons. New connections can form and the internal structure of the existing synapses can change.

As an example of neuroplasticity let us consider London taxi drivers. London taxi drivers have a larger hippocampus (in the posterior region) than London bus drivers (Maguire et al. 2006). This is because this region of the hippocampus is specialized in acquiring and using complex spatial information in order to navigate efficiently. Taxi drivers have to navigate around London whereas bus drivers follow a limited set of routes.

Plasticity can also be observed in the brains of bilinguals (Mechelli et al. 2004). It looks like learning a second language is possible through functional changes in the brain: the left inferior parietal cortex is larger in bilingual brains than in monolingual brains.

Plastic changes also occur in musicians brains compared to non-musicians. Gaser and Schlaug (2003) compared professional musicians (who practice at least 1 h per day) to amateur musicians and non-musicians. They found that grey matter (cortex) volume was highest in professional musicians, intermediate in amateur musicians, and lowest in non-musicians in several brain areas involved in playing music: motor regions, anterior superior parietal areas and inferior temporal areas.

Finally, Draganski et al. (2006) showed that extensive learning of abstract information can also trigger some plastic changes in the brain. They imaged the brains of German medical students 3 months before their medical exam and right after the exam and compared them to brains of students who were not studying for exam at this time. The brains of medical students showed learning-induced changes in regions of the parietal cortex as well as in the posterior hippocampus. These regions of the brains are known to be involved in memory retrieval and learning. Altogether, we can conclude that there is a massive empirical basis for the philosophical hypothesis that knowledge is a reaction of the brain to learning (for more references see LeDoux 2003).

4.2 Understanding

Understanding is a cognitive operation that applies to facts, symbols, and constructs. It consists in fitting an item into the pre-existing cognitive or epistemic network of knowledge, or in transforming this network to accommodate the new item in a consistent way. It is a complex operation that proceeds in different ways and degrees. The main operations that lead to understanding are *description*, *subsumption*, and *explanation*. I shall deal with the first two now and with the latter in the next section.

A *description* is a characterization of a fact or a concept. From a logical point of view a description is an ordered set of statements. Mathematical descriptions can be complete, but never factual ones. A description can reveal some features of a fact, but since none description is exhaustive, we never fully understand from description.

Subsumption is also an ordered set of statements, but one in which the last statement follows from the preceding ones. A singular fact can be subsumed under a general pattern:

$$\forall x Px \vdash Pa, \tag{4.1}$$

or

$$\forall x (Px \Rightarrow Gx) \wedge Pa \vdash Ga. \tag{4.2}$$

Sometimes, the pattern occurring in a subsumption is merely a classificatory statement and not a law statement. In such a case:

1. $S = \{x : P(x)\}$.
2. $a \in S$.

Then, $P(a)$.

Subsumption provides a higher understanding than mere description since it allows to deal with an arbitrary number of statements. Nevertheless, subsumption is still inadequate if our goal is to understand why events occur.

4.3 Explanation

The difference between subsumption and explanation is not logical: both are cases of deduction from regularities and circumstances, in particular law statements and data. Whereas subsumption answers only "how-questions", explanation deals with "how-or-why-questions". The logical form of explanation is (Bunge 1983a, 2006):

$$\forall x\,[(Fx \Rightarrow Mx) \wedge (Mx \Rightarrow Gx) \wedge Fa] \vdash Ga\,, \tag{4.3}$$

where M stands for some *mechanism*. A mechanism is a collection of processes in a material system that allows the system to perform some *functions*. The functions are the specific activities of the system. Accordingly, to explain is to exhibit or conjecture a lawful mechanism that makes the system work the way it does.

Mechanisms, and hence explanations, can be classified in accordance with the underlying class of process: *causal*, *random*, or *mixed*. A mechanism is not necessarily *mechanical*, of course. It can be physical but not involving mechanics, or it might be chemical, biological, social, or even a combination of processes of different ontological levels. All real mechanisms are lawful, but the law-mechanism relation is one-to-many, not one-to-one: the same laws can yield different mechanisms in varying circumstances. There are not universal mechanisms since all mechanisms are stuff-dependent and system-specific.

Explanation *subsumes* subsumption, logically, epistemologically, and ontologically. *Logically* because given an explanation we can detach the corresponding subsumption:

$$\forall x\,[(Fx \rightarrow Mx) \wedge (Mx \rightarrow Gx)] \vdash (Fx \rightarrow Gx)\,. \tag{4.4}$$

Epistemologically because explanation requires more knowledge than subsumption. And *ontologically* because explanation goes deeper into the structure of reality than subsumption.

An explanation is an epistemic process involving three components: (1) an explainer (e.g. a human being), (2) the object of the explanation (e.g. luminosity of a star), (3) the explanatory premises (e.g. nuclear fusion reactions occur at such and such pressures, radiation is transported in the stellar interior according to such and such processes, etc.).

The objects of explanation can be things, properties or states of things, and events. Not everything can be explained (since our knowledge is limited) and not everything explainable is worth of being explained. The value of a particular explanation will depend on our axiology (see next chapter).

The basic methodological rules of explaining are the following:

- E_1. Check the existence of the item to be explained (fact, thing, event).
- E_2. Try to explain existents by existents, and only exceptionally by conjectural existents (never by fictions).
- E_3. Explain the observable by the non-observable or the unobservable by the observed.
- E_4. Avoid ad-hoc explanations, i.e. those which require hypotheses that cover only the item to be explained.
- E_5. Mistrust hypotheses and theories that purport to explain everything.

4.4 Sufficient Reason

The Principle of Sufficient Reason (PSR) has an illustrious history that pervades the whole Western thought (see Schopenhauer 2012). Spinoza stated the principle in his famous major work, the *Ethics* (Spinoza 1985). In E1p11d2, we read:

> For each thing there must be assigned a cause, or reason, both for its existence and for its nonexistence.

For Spinoza not only there must be a reason for what there is, but also for what there is not. This seems to be a particularly strong version of the principle.

Leibniz introduced the expression 'Principle of Sufficient Reason' and he is its best known exponent and defender. In the *Monadology*, sec. 32, he wrote:

> There can be no fact real or existing, no statement true, unless there be a sufficient reason, why it should be so and not otherwise, although these reasons usually cannot be known by us.

And in his second letter to Samuel Clarke, he simplifies:

> The principle of sufficient reason, namely, that nothing happens without a reason.

This is not far from the only extant fragment of Leucippus:

> Nothing happens in vain, but everything from reason and necessity.

The PSR was under attack in the eighteenth century by the empiricists, especially David Hume. Hume's critique of causality can be easily extended to sufficient reason. Logical positivists and modern analytic philosophers have also distrusted of the PSR, in part because of its alleged theological implications and in part because its dubious nomological status.

I want now to clarify the epistemological status of the PSR. I maintain that this principle, properly understood, plays an important role in scientific research. Far from being an obscure tinge from an outdated rationalism in search of theological justifications, I submit that the PSR is a fundamental working hypothesis in the toolkit of any research scientist.

I distinguish four different main forms of the principle (Pruss 2010)[1]:

- PSR 1. Everything that is the case must have a reason why it is the case.
- PSR 2. Necessarily every true proposition has an explanation.
- PRS 3. Every event has a cause.
- PSR 4. *Ex nihilo nihil fit* (nothing comes from nothing).

These statements are certainly not equivalent. They have presumably different strength and meaning. But in order to compare them and their import, vagueness should be removed from some terms that appear in the statements.

The word 'reason' is polysemous. I differentiate two main meanings: (1) a mental faculty consisting in thinking in a cogent way, and (2) an ontological justification of the occurrence of an event or a state of affairs. PSR 1 does not refer to properties of the brain, so we better try to refine (2) so as to make of PSR 1 a meaningful statement. An ontological justification for events and states of affairs might be the specification of a sufficient system of causes. In such a case PSR 1 $\rightarrow$ PSR 3. But there is another possible meaning of 'ontological justification': the specification of a system of laws and facts such that given a number of conditions A, then the event or state of affairs B follows. For instance, the specification of the law of gravitation and the masses of all objects in the solar system, plus some adequate initial conditions, justify the state of motion of the earth with respect to the sun. In this sense, we can say that there is a 'reason' for the earth motion around the sun. I call this type of justification 'nomological justification'. Under this interpretation, PSR 1 is not a law, but a metanomological statement (Bunge 1961, 1967). Since laws can be understood as constant relations among properties of things, PSR 1 would be tantamount to

- PSR 1a. All events are lawful.

Let us now turn to PSR 2. This version refers to propositions, i.e. classes of statements, and not to the world. As it has been enunciated, it is a statement about our uses of language. Since explanation is an epistemic operation and not a semantic one, in its current form PSR 2 is meaningless. It can be minimally modified, nevertheless, to become a meaningful statement, namely:

- PSR 2a. Necessarily every true proposition satisfies truth conditions.

This is trivially true, but says nothing about the world. Since the proponents of the PSR think that they are saying something about the way the world actually is, we can attempt a different approach replacing propositions by what they represent: facts. We obtain:

- PSR 2b. Necessarily every fact has an explanation.

[1]These forms do not exhaust of course all statements that have been proposed as possible enunciations of the PSR, but are, in my opinion, those more commonly adopted in the philosophical literature.

Given our account of ‘explanation’, PSR 2b can be rendered into:

- PSR 2c. Every fact results from lawful processes.

There is no need for the word ‘necessary’ given the unrestricted universal quantification, so I dropped it in this reformulation. PSR 2c is very similar to PSR 1a. If we define facts as either events (changes in the state of things) or states, and admit that events are related to either previous states or other events, then both statements have the same import.

I turn now to PSR 4. In the formulation given above, PSR 4 is defective since ‘nothing’ is not a thing but a concept: an empty domain of quantification. I propose the following reformulations of PSR 4:

- PSR 4a. There are not bare facts.

PSR 4a means that all facts are part of a system of facts, the world, where no event occurs isolated. Although this implies a nomic determinism, it is certainly *not* a causal determinism, as the one required by PSR 3. Using unrestricted quantification[2] we can rewrite PSR 4a as:

- PSR 4b. Every fact results lawfully from previous facts.

This form is quite similar to PSR 2c.

The world is legal and determinate, but not strictly causal. There are events that are not causally related and processes that are not causally originated. If this is correct, then PSR 3 is a false statement.

From our analysis of different proposals for the formulation of the PSR I conclude that, once all the terms have been conveniently defined, the different statements collapse into the following one (Romero 2016):

- PSR*. Every fact results lawfully from previous facts.

I propose PSR* as the only version of the PSR that is compatible with modern science.

Before discussing the ontological and epistemological status of PSR*, I will briefly comment on the system of all things, to which the principle is applied.

The PSR is equated sometimes to the statement, likely inspired by Hegel, that “reality is rational”. This can adopt occasionally the form (1) “the World is rational” or (2) “the Universe is reasonable”. I submit that all these sentences are nonsense. Reality is a concept: the set of all real entities. As all sets, it lacks of independent existence, it is a fiction, albeit a convenient one. The word ‘rational’, to the contrary, qualifies a type of behavior: the one that is guided by reason, i.e. by cogent thinking. Sets do not think, so reality cannot be rational, hence (1) makes no sense. The world, on the other hand, can be understood as the system of all events; the Universe, as the system of all things. Both world and Universe are concrete entities, but the faculty of thinking, and of thinking reasonably and rationally, is not among their known

[2] $\forall x \; Px \leftrightarrow \neg\exists x \; \neg Px$.

properties. To the best of our current knowledge, only beings endowed with brains of notable plasticity are able to think. It is difficult to understand what would mean for the Universe to think, and even more difficult for the world. At best, sentences (1) and (2) are false statements. In the worst case, they are not even statements.

Perhaps what is meant by this type of talk is that the world is comprehensible for us, humans. This, in turn, means that we can produce conceptual representations of all aspects of the world. Although we can assume we can do that as a guiding methodological principle for our research ("there are not forbidden topics"), there is no certainty, I think, that we will ever be able to develop the conceptual tools for a full representation of the world and the means to test such representations (see Rescher 1999). This should not be a hindrance to our attempts at deepening our understanding of reality. It is in this enterprise where the PSR becomes prominent.

I propose that the correct enunciation of the PSR is PSR*: every fact results lawfully from previous facts. This is a general statement about facts and laws. It is a statement neither necessary nor obviously true. Since it claims that laws cover the whole range of facts, it is a metanomological statement. It is a condition upon law statements: they ought to cover all the realm of reality. The epistemological status of such a statement is methodological: it is guiding principle for generating knowledge. In every situation where apparent brute facts seem to appear, the PSR* recommends the search for deeper laws. Any working scientist adopts this principle when an apparent inconsistency appears in the data at hand. Instead of simply assuming brute facts, the responsible scientist proposes a revision of the data or, as a last resource, a modification of the accepted ontology. For instance, the non-conservation of energy, momentum, and spin in some particle decays led the physicist Wolfgang Pauli to postulate the existence of the neutrino in 1930. Recently, the apparent violation of special relativity in neutrino experiments led some scientists to speculate about some exotic explanations and, ultimately, to find a mistake in the interpretation of the experimental data due to some systematics not originally taken into account. In these and many other instances of scientific inquiry the researchers are guided by the non-explicit assumption of PSR*: there must be a lawful explanation of each experimental or observational situation.

Not being the PSR a necessary truth, the theological scruples of some philosophers are groundless. The principle reflects our disposition to solve problems in science, but cannot be used to make direct predictions. It is too a general statement for that. Predictions can be made from law statements plus a set of conditions obtained from information about particular states of affairs. We cannot infer the existence of something, e.g. the neutrino, from the PSR alone. The actual process is that we *propose* the existence of the neutrino to satisfy a well tested law (e.g. momentum conservation). We are *motivated* by the PSR to demand a fully lawful situation. Ultimately, it is the experiment that confirms the existence of the neutrino.

It is important to notice that quantum transitions and other intrinsically probabilistic phenomena are not violations of the PSR* and *do not require* any special interpretation of quantum mechanics. Transitions and decays occur in perfect agreement with the law statements of quantum mechanics. Actually, the probabilistic predictions of quantum mechanics are extraordinarily well corroborated, to the point that most of our modern technology is based on them. I cannot think of a worse attempt to rebut the PSR* than invoking quantum mechanics. Amazingly, some philosophers have tried to do it... in papers written with computers that operate in accordance with the laws of quantum mechanics.

4.5 Model

A *factual model* is the conceptual representation of a mechanism (collection of processes). It can be characterized by a quadruple:

$$M = \langle D, F, I, A \rangle \,, \tag{4.5}$$

where:

- D is a *domain* or reference class of M. It is a set of factual items: things or processes occurring to them.
- F is the *formalism* of M, the set formed by the mathematical expressions used to represent the elements of D.
- I is the *interpretation* of M. It is a set of partial functions for F to the power set of D, that assigns formulas in F to factual items in D.
- A is a set of *assumptions* and data about the objects in D.

A model is not an application of mathematics to reality: it is a mathematization of our ideas about reality. Occasionally we know sufficient mathematics as to build alternative but empirically equivalent models of a given process or mechanism. Every model is symbolic and, as such, has some conventional elements.

Since mathematization involves idealization, models are always defective in some aspect or another. At best, they are good approximations but they should not be confused with reality.

We can model all kind of things and processes: the flow of traffic in a city, the implosion of a star, the formation of a galaxy, a collision of subatomic particles, the development of a given population, the functioning of a muscle, the expansion of the Universe, and so forth. When we conceive these models we resort to a number of scientific theories about nature. Let us then see now what a scientific theory is.

4.6 Theories

A *theory* is a logically organized set of statements concerning objects of some kind. If we introduce a set of statements P, a set of predicates Q, and a domain (reference class) R, a theory is defined by the quadruple:

$$T = \langle P, Q, R, \vdash \rangle \,, \tag{4.6}$$

where $\vdash$ is the entailment relation. A theory then is a context closed under deduction: every statement in the theory is either a premise or a deductive consequence of a set of premises. The premises are called *axioms*, and the consequences *theorems*.

Scientific theories can be classified in purely formal and factual.

If R is formed exclusively by a conceptual objects, then the theory is purely *formal*. If the reference class include some factual items (material systems) the theory is *factual*.

The axioms of a factual theory are classified, in turn, according to their functions in the organization of the system of statements, as (1) formal, (2) semantic, and (3) nomological. The formal axioms establish the relations among some primitive terms: undefined symbols in some languages that usually includes logic of first order and mathematics. The semantic axioms relate some terms of the theory with extra-linguistic objects, fixing the reference class and providing meanings to the different abstract terms. And finally, the nomological statements express regular patterns of events associated with the objects of the reference class. These axioms are the core of the theory and represent factual, objective laws. Every proper theory, contrary to models, should contain law statements.

The presentation of a given theory can contain also many definitions in order to facilitate communication, the explicit base of primitive (i.e. undefined) terms, and a list of the background theories presupposed. Any non-fundamental theory is based on some other theories that are assumed as valid. Even fundamental theories have a background of formal theories (usually several different mathematical theories).

A *subtheory* is a part of a theory that is itself a theory rather than an arbitrary fragment of it. In general: T_1 is a *subtheory* of T_2 iff T_1 is a theory and $T_2 \vdash T_1$.

The subtheory may or may not have a smaller reference class than the theory of which it is a part ($T_1 \subseteq T_2$): all the statements of the former belong in the larger theory but not conversely. Example: particle mechanics is a subtheory of continuum mechanics.

Subtheories should not be mistaken with specific models of things or processes of a certain kind. A model contains specific assumptions that do not occur in a general theory, so it cannot be part of the latter. For instance, a model of the sun includes not only general assumptions and applications of the laws of thermodynamics, electromagnetism, nuclear theory, transport theory, gravitation, etc., but also very specific assumptions about the characteristics of the sun that are unique. These assumptions usually enter into the model as boundary conditions of the model equations.

In general, we obtain models through a number of theories $(T_1, T_2, \ldots, T_n)$ and sets of specific assumptions $(A_1, A_2, \ldots, A_m)$:

$$(T_1 \wedge T_2 \wedge \ldots \wedge T_n) \cup (A_1 \wedge A_2 \wedge \ldots \wedge A_m) \vdash M. \tag{4.7}$$

When we go from general theories to models the reference class shrinks.

General theories, contrary to models, are not expected to make predictions unless considerably enriched with special assumptions and data. We put theories to the test through *consistency analysis* (both internal and with the total network of theories) and by *empirical evaluation of models* obtained from the theories with specific assumptions and data on applications to particular cases.

In addition, theories are made up of concepts and propositions, not perceptions and feelings. Hence, scientific theories lack emotional and observational terms, in particular terms denoting qualia.

Theories are tested through the comparison of model predictions (statements) with *data*. An *empirical datum* is not a fact but a proposition reporting a fact. We always compare propositions with propositions. Since propositions are conceptual objects, they are “theory-laden”. The facts themselves, of course, are theory independent.

More specifically, we can define:

An *empirical datum* is a simple proposition referring to a factual state acquired with the help of empirical operations.

An empirical datum *e* constitutes empirical evidence for or against a proposition *p* iff: (1) *e* has been acquired with the help of empirical operations accessible to public scrutiny, (2) *e* and *p* share referents, (3) *e* has been interpreted in some theoretical framework, and (4) some regular association between the properties represented by predicates in *e* and *p* is assumed.

The mentioned empirical operations usually involve several theories and data manipulation to evaluate errors.

I have already mentioned that truth cannot be attributed to theories but to propositions. Any theory contains an infinite number of propositions and it is not possible to evaluate all of them. However, we can compare theories with identical referents to establish which one is truer than the others in some finite domain of facts.

Other inter-theory relations include:

Equivalence Two theories are equivalent if they have the same predictive power but different structures. They are organized differently. Examples: an undefined notion in one theory is defined in the other, or an axiom in one is proved as a theorem in another.

Theory Improvement One theory is a *revision* of another if it adopts a more powerful formalism that enhances its precision and scope.

Theory Reduction One theory explains or reduces another. For example, a “black -box” theory is explained by a mechanistic one, as when statistical mechanics explains thermodynamics.

Theory Rivalry Two theories about the same domain are inequivalent because they explain differently and lead to different predictions. Eventually, observational or experimental tests and inter-theoretic consistency will make one of the rival theories more adequate to understand and explain the shared domain.

The network of all our scientific theories forms our scientific worldview. Lets us turn now to the concept of science itself.

4.7 Science

Science is the result of a human activity which aims at acquiring true knowledge about the world. It is a complex activity and hence difficult to characterize. It is not the only way of getting human knowledge: we can learn through experience, practicing, try-and-error activities, or by counter-example. We can also learn reading books, going to school, and so forth. Science differentiate from these and other activities in that it is systematic and its results are subjected to a variety of controls. In addition, it is a progressive activity in the sense that scientific knowledge increases with scientific research. There are several indicators of scientific progress including improvement of predictability and augmentation of the human capability to manipulate the environment (science-based technology). Conversely to other forms of knowledge acquisition, science produces conceptual representations of different aspects of reality. These representations are given in the form of *scientific theories* and *models*.

This informal characterization of science can be made more precise, although always in a provisional and perfectible way. We propose to define science as the *set* of the different *fields of scientific research*.

Each field of research, in turn, is characterized by the following items:

- C: a community of researchers. Researchers are individuals with training in research and with specific knowledge.
- S: a society that hosts, or at least tolerates, the activity of those individuals in C.
- D: a domain or collection of items that are studied and researched by the individuals in C.
- G: a general philosophy that is shared by the members of C. For instance, the idea that there exists something to be researched.
- F: a set of formal languages (including first order logic and mathematics) used by researchers to represent the elements of D.
- B: a background of previous scientific knowledge that is shared by the members of C and is necessary to implement their research project.
- P: a collection of problems that the members of C try to solve.
- A: a collection of goals of the members of C with respect to D.
- M: a specific methodology that is used by the members of C to warrant a quality control of the proposed answers to the problems in P.
- E: an ethics common to all members of C.

The research field R, then, can be represented by its 10 components:

$$R = \langle C, S, D, G, F, B, P, A, M, E \rangle \, . \tag{4.8}$$

The elements of each components change with time, hence these components are collections of items, not sets. The research field evolves according to the changes in its components.

Science, then, can be defined as the set of all research fields:

$$S_{\mathrm{ci}} = \{R_1, R_2, \ldots, R_n\}, \tag{4.9}$$

where R_i, $i = 1, 2, \ldots, n$ are the different research fields with different domains D_i, different communities of researchers C_i, different problematics P_i, and so on. Science, obviously, has no nervous system since it is a concept. Hence, science cannot be morally responsible for any act. Only individuals with an evolved nervous system can be considered responsible for something. This is, the members of C can be responsible for some activities, not science. Because of a similar reason, science cannot cause nothing. Only events can cause events. Of course, the actions of scientists are events, and these events result in the evolution of science.

Notice that science is *not* equivalent to scientific knowledge. The scientific knowledge is the total knowledge of the members of C. This knowledge can be learned by other individuals in different ways.

4.8 The Limits of Science

Are there limits to the knowledge of nature that can be achieved through science? Science is a systematic and self-corrective activity aimed at gathering true knowledge, and it is undoubtedly the best method we have for that. But are there questions beyond its scope? Are there unsolvable problems? Is science increasing our knowledge of the world in such a way that it tends to a final and complete representation of nature?

To answer questions about nature using science, we first have to ask those questions. But questions always have presuppositions that are embedded into a preexisting state of knowledge. The progress of science not only provides answer to those questions, but sometimes (actually quite often) changes our background knowledge in a way such that old questions become meaningless and new ones arise. The dynamics of scientific research is such that no linear accumulative increase of knowledge is produced (Bunge 1998a,b; Rescher 1999). Rather, knowledge can collapse and re-expand in new directions. Entire sets of questions, once quite meaningful, suddenly *dissolve* (nobody cares now, for instance, about the structure of the phlogiston or the properties of the electromagnetic aether). We should not ask, therefore, whether the scientific enterprise can answer all questions about nature that can be posited at a given moment, since it very well be the case that many of such questions might be illegitimate inquiries with respect to a future well-established body of knowledge. New answers and solutions to new problems change the assumptions for the formulation of further questions. As we deepen in our understanding of the world, new problems and questions emerge, that were never glimpsed before. Every successive state of knowledge has associated a new set of valid questions. There is no reason for thinking that this is a convergent process.

Because of the self-corrective methodology ingrained in scientific research, scientific knowledge is always defeasible and transitory. There is no final scientific theory as long as the scientific method remains valid. We can only aspire to obtain ever better partial and tentative representations of reality. The scientific image of the world is always provisional and tentative. There is not a "final truth" to which our theories tend. The reason is simple: we are who attribute truth to our statements about nature. Certainty is not among the options when we assign truth value on the basis of limited evidence (see Chap. 2).

In addition to the above consideration, I want to remark that the expansion of scientific knowledge goes in a direction of increasing complexity. This can be seen not only in the tremendous growth of the scientific literature and the diversification of specialized journals, but also in the overwhelming technicality of new approaches, formalisms, and theoretical frameworks. Nature is certainly not simple. Ontological simplicity is just a convenient myth to think beyond details, but there is not the slightest support for such a thesis. Natural science is not bound to any principle of simplicity (Bunge 1963).

Finally, we can ask whether is it possible within a given theoretical framework to pose questions that are impossible to be answered *in principle*. In other words, are there, as the Schoolmen called them, *insolubilia*? Are there questions that science, in principle, cannot answer? In the realm of empirical research there is nothing that can be legitimately posed and not researched. For instance, if we ask about the simultaneous position and momentum of an electron, we are formulating an illegitimate question since according to the best theory about electrons, quantum mechanics, these particles *do not have* simultaneously these properties. If we ask, instead, what is there in the interior of a black hole, we are asking a valid question. Although the black hole interior is inaccessible to experiments or observations from the outside, questions about the interior can be answered using theoretical tools such as general relativity or theories of quantum gravity. If there were questions whose resolutions are beyond science, then they hardly can be considered scientific questions. Conversely, scientific questions are in principle (although not necessarily in practice) answerable.

Some scientists, especially particle physicists, use to talk about "theories of everything" or "final theories". By this they seem to mean a unique theoretical framework from which all questions might be in principle answerable. I doubt that such an enterprise make any sense at all. If we have learnt something about nature, it is that there are different levels of composition and organization, and there are emergent properties at each level (see Chap. 3). Hence, even if a unified theory of all physical interactions might be formulated, this would not imply that it can be used to get answers to all questions. Even at the physical level of complex systems from stars or galaxies to cryogenic liquids and solids, reality would still offer an inexhaustible source of puzzlement. Not to mention the problems to explain and understand all higher levels and the entities that populate these levels: chemical, biological, social... Moreover, an alleged "theory of everything", even if correct in its formulation of the basic physical laws, would say nothing about the initial and boundary conditions necessary to solve the equations that express such laws. Final theories, to use an expression due to Steven Weinberg, belong to the realm of dreams (Weinberg 1992).

4.9 Technology

Technology is related to our capacity to manipulate the environment. Not necessarily all technology is based on science. Technology is older than science. For instance, some apes and primitive human communities ignore science, but use some simple tools. Dolphins and whales have developed languages, i.e. conceptual tools for communication. Pre-scientific civilizations have achieved significant technological developments including urbanized cities, roads, weapons, and so forth. It is clearly not enough to characterize technology as the ability to change and produce goods in a planned way. Tradition, oral transmission, and practical knowledge are not enough to create fusion reactors, cell phones, send robots to Mars, create vaccines, or build airplanes. A scientific element is missing.

Technology based on scientific knowledge is a human activity aimed at designing, developing, and constructing *artifacts*, i.e. things that can be controlled and used to specific goals. Technology also deals with the planning of human activities with the aim of controlling various processes, always on the basis of the available scientific knowledge.

Specifically, we can define the *concept* of scientific technology as a set formed by all *specific technologies* T_i:

$$T_i = \langle C_i, S, D_i, F, E, P, A, O, M_i, V \rangle , \tag{4.10}$$

where:

- C_i is a community of technologists. These are individuals that have been trained to design, construct, and control artificial systems on the basis of scientific knowledge.
- S is a society that hosts (or at least is not hostile with) the members of C_i.
- D_i is the domain of T_i, i.e. the set of things T_i deals with.
- F is the set of formal theories that can be used by in C_i.
- E is the set of scientific theories along with the relevant data used by the members of C_i to reach their goals.
- P_i is the specific problematic that should be solved by those in C_i.
- A is the total technological knowledge available to individuals in C_i.
- O_i is the set of final goals of the technologists in C_i.
- M_i is the collection of methodological rules and instructions adopted by the members of C_i. M_i evolves with time; its rules must always be verifiable and justifiable.
- V is the value system (axiology) adopted by the persons of C_i, which is based on the ethics shared by the society S.

Scientific technology includes not only the many engineerings but also medicine, didactic, normative epidemiology, regulative economy, law, and all disciplines of social planning. Since scientific technology is based on science, it can be perfected with the help of research.

4.10 Pseudoscience and Pseudotechnology

As most human products, science and technology can be faked: there are activities and artifacts presented or offered as scientific or technological which actually are not. Being modern science and technology quite complex, it is not a simple task to identify impostures (for different recent attempts at demarcation criteria see Mahner 2007 and Pigliucci and Boudry 2013). In general, a simple demarcation criterion fails because a simple rule cannot take into account the complexity and systemic character of science and technology. For instance, the positivist proposal of considering that the scientific discourse is meaningful whereas pseudoscience is not, fails because many pseudoscientific statements are perfectly meaningful, but utterly false. Moreover, we know they are false because we understand them and we know how to put them to the test. Astrology, for instance, makes lots of meaningful predictions…that are systematically false. Pseudosciences such as astrology, psychoanalysis, and parapsychology are testable and falsifiable; they satisfy Popper's demarcation criterion for science (Popper 1959), yet they are hardcore pseudoscience. Astrology and parapsychology even use, occasionally, mathematical tools in the formulation of their predictions. These activities, however, are pseudosciences because they collide with the bulk of scientific knowledge. In the case of parapsychology, there are also methodological problems, such as a trend to overestimate positive cases, the lack of efficient experimental control, and a lack of a corroborated domain of events to be explained.

Pseudosciences are a threat to the culture of a society. Pseudotechnologies are even worst, since they can be a direct menace to human life. Homeopathy and psychoanalysis are offered as health technologies. Homeopathy in the best case is innocuous, and in the worst can delay a correct diagnosis and allow the advancement of mortal diseases and facilitate the propagation of epidemics. Psychoanalysis can be catastrophic for patients with severe mental illness, such as depression or psychosis. Not relying upon any knowledge of the human nervous system or scientific data on human behavior, psychoanalysis operates in a realm of fantasy where any possibility of cure is absent, except by chance. The domain D_i of psychoanalysis is full of non-existent entities and pseudoconcepts, F is the empty set, E_i does not include neurosciences or experimental psychology, M_i includes methods that either never were tested or are delusory. The most shocking aspect of this pseudoscience is its complete disregard for testing its own assumptions and its lack of concern about any kind of scientific validation though controlled experiments.

Even more dangerous are the economic pseudotechnologies. The implementation of arbitrary economic measurements can lead millions of people to misery and even death. Social sciences are still in their infancy, and precisely because of it the application of policies based on them should be careful and rational.

4.11 Scientific Philosophy

Finally, we may ask for the place of philosophy in our scientific world view. Traditionally, philosophy has been concerned with the most general problems related to the nature of the world and our understanding of it. The kind of philosophy that I advocate for here is scientific philosophy. It is scientific because it considers science the most important way of obtaining knowledge about the world. It is scientific because it proceeds by theories and models. It is scientific because it incorporates the latest results from science. Most importantly, it is scientific because its criterion of truth is found in coherence, both internal and with the results of science. I propose the following, rather informal, definition.

Scientific philosophy is philosophy informed by science that deals with problems relevant to science. It proceeds, like science, using theories that are expressed as hypothetic-deductive systems. These theories are contrasted by their internal coherence and their compatibility with the totality of scientific knowledge. Therefore, theories of scientific philosophy evolve with science. They can and should be refuted and replaced by better theories. Scientific philosophy, moreover, uses accurate formal tools to minimize vagueness. Its main branches are: philosophical logic, philosophical semantics, ontology, epistemology, ethics, and aesthetics.The ultimate goal of scientific philosophy is to articulate the best worldview emerging from the specific sciences (see Reichenbach 1951 for additional discussion and Stadler 2001 for historical aspects).

Scientific philosophy should not be confused with *philosophy of science*. The latter is a branch of epistemology. It deals with the meta-scientific study of the different special sciences. Thus, there exists a philosophy of mathematics, of physics, of chemistry, of neurosciences, etc. Certainly, because of the best method of knowledge is the method of science, the philosophies of special sciences and the general philosophy of science occupy a prominent place within scientific epistemology.

Summing Up *Knowledge* is the result of the process of *learning* by some biological system. It is not related to *belief* and it is not necessarily true. Actually, not all knowledge is propositional: there is motor-sensitive knowledge and perceptual knowledge, in addition to conceptual. *Understanding* is a cognitive operation that consists in the accommodation of data about the world into our conceptual view. There are three ways of understanding: *description*, *subsumption*, and *explanation*. The latter is the deeper one, and consists in exposing the *mechanisms* that produce the activity to be explained. The conceptual representation of a mechanism is a *model*. *Theories* are hypothetical deductive systems of propositions closed under deduction that include *law statements*. With the help of specific conditions, theories are used to construct models, and these used to validate theories. Our network of theories is the result of *science*, a complex human activity designed to systematically increase our knowledge. *Technology* based on science allows to manipulate and control our environment and create artifacts.

The Principle of Sufficient Reason is a metanomological statement that provides a useful guide in the pursuit of scientific knowledge. It is not a law of nature nor a necessary statement. It is, nonetheless, used by scientists in their everyday work, and has been assumed in many of the most important discoveries of science. This is reason enough for a principle of sufficient reason to be well coveted into the toolbox of any serious researcher.

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Chapter 5
Ethics

All animals evaluate some things and some processes. Some of them can learn patterns of social behavior and behave according to them at least part of the time. An animal incapable of evaluating anything would be very short-lived; and a social animal that does not observe the accepted social behavior would be likely segregated or punished by other members of the social group.

These are some facts about values, morals and behavior patterns. They are the starting point of *ethics*: the philosophy of moral behavior.

Normal animals strive to attain or retain a state of well-being. This state, however, is not the same for all. Consequently normal animals value positively, i.e. they find good, anything they need for their well-being and, in the first place, for their survival.

I postulate, following Bunge (1989), that needs and wants—biological, psychological, or social—are the very roots of values. The function of norms is to protect such values, i.e. to facilitate the satisfaction of the associated needs. I also postulate that we are driven by our values and constrained by our norms, not only by external factors.

Not all values are on the same footing. There are *primary*, *secondary*, and even *higher order values*, according to the level of needs or wants they originate in.

Correspondingly, there are basic *rights* and *duties* for animals living in society, namely those rights and duties associated with basic values. Similarly, there are higher order—i.e. less important—rights and duties, i.e. those that correspond to higher order values.

5.1 Values

In the real world *there are no values in themselves*, anymore than there are shapes, motions, of mathematical functions in themselves. Instead, *there are organisms that evaluate certain things* (among them themselves) when they, as well as the things

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valued, are in certain states or undergo certain changes. In other words, *whatever is valuable is so for some organisms in certain states*, particularly states of deprivation that originate drives which motivate action.

Values are not things, states of things, or processes in things: these can only be *value-bearers* or objects of valuation. *Values are fictions attributed to objects and processes of certain kinds by organisms of certain types and in certain states*. More specifically,

Definition An item a is valuable in its aspect b for organism c with goal e, in the circumstance d, and in the light of the body of knowledge f iff a satisfies a need of c.

In short, value judgments involve at least binary relations: they are of the form Vab, $Vabc, \ldots, Vabcd \ldots n$. If we succeed in quantifying values, the relation becomes a function from n-tuples of objects to numbers. For example: $V(a, b, c, d, u) = v$, where u is a suitable unit, and v the numerical value c attributes to a in its aspect b and stance d.

The general form of a real function representing values is $V : A \times B \times \ldots N \times U \rightarrow \Re$, where A is a collection of value bearers, B a collection of organisms, and the remaining factors in the Cartesian product, up to N, may be collections of things, properties, states, or processes, whereas U is a set of units, and $\Re$ is the set of real numbers. Quantifiable values are exceptional: rarely animals can or wish to take the effort to quantify their assignation of values.

I distinguish two levels or degrees of need: primary and secondary, and shall define the corresponding concepts in terms of the notion of deficit or deficiency, i.e. whatever is lacking to achieve optimal survivorship.

Definition Let x be a biological, psychological or social deficit of a being b in circumstance c. We call x

1. a *primary need* of b in c iff meeting x is necessary for b to stay alive under c;
2. a *secondary need* of b under c iff meeting x is necessary for b to keep or regain health under c;
3. a *basic need* iff x is a primary or a secondary need.

Definition Let x be a thing, a property of a thing, or a process in a thing. We attribute x

1. a *primary value* for human beings in circumstance c if x contributes to satisfying at least one primary need of any humans, in any society, when in circumstance c;
2. a *secondary value* for human beings in circumstance c if x contributes to meeting at least one of the secondary needs of humans under c in their particular society;
3. a *tertiary value* for human beings in circumstance c if x contributes to meeting at least one of the legitimate wants (or desires or aspirations) of humans in circumstance c;
4. a *quaternary value* for human beings in circumstance c if x contributes to meeting a fancy;
5. a *basic value* if x has either a primary or a secondary value.

Definition An object x is *good* for a human being b in circumstance c if x has a primary, secondary, tertiary, or quaternary value for b.

Definition An object x is *bad* for a human being b in circumstance c if x avoids the realization of primary, secondary, tertiary, or quaternary values for b.

Tertiary and quaternary values are not universal, whence something good for someone (for fulfilling ternary or quaternary needs) may be bad for someone else (with different needs).

I remark that *nothing is good in itself*, i.e. regardless of any evaluating subjects and in all circumstances. For example, there was nothing good or bad in the universe before the first animals emerged.

The following implication chain summarizes the situation:

No needs → no values → no good or bad.

Neither there is evil. There are just some things, states, and processes considered evil by some people under some circumstances. Evil is neither a force to be fought nor an entity to be avoided. It is just a way to name some actions. To fight against evil is pointless. We can only act upon things and we can only influence concrete processes. The only way to eradicate evil is acting upon persons or events we consider evil for some reason.

According to the needs that motivate valuations, we can differentiate between bio-values (basic) and psycho-values (mere desires).

Discrepancy between bio-values and psycho-values can be a source of internal conflict and suffering for the individual that evaluates.

Notice that, for instance, food is not a value. It is an item that we valuate, i.e. valuation is a mental operation by which we attribute value to needed or desired items. The value in itself is a fiction, like truth. We can value extremely harmful things, such as narcotics, out of ignorance or conditioning.

Value judgments can be justified or criticized, rather than accepted or rejected dogmatically, when they are rooted to basic needs or legitimate wants. In this case they can be shown to be true or false with respect to some valuation system. Thus consider the following propositions.

1. Freedom is good for allowing us to exercise our rights.
2. Honesty is good for promoting cooperation.

These statements can be justified or criticized in the context of social science and for specific societies.

5.2 Axiology

Axiology is the theory of values and valuations.

The axiology I propose is materialistic because it considers conscious valuation as a brain process partially conditioned by social circumstances as well as inner biological and psychological needs. Then, in this axiology the statement ‘V is valuable' should be translated into 'there is at least one individual for which objects with the property V meet some needs or wants'.

Clearly, *the more we know, the better we evaluate*.

Human social behavior requires some *rules* or *norms* that are called *morals*. The goal of morals is to help realize (or inhibit) the adherence to some human values. Morals, then, are dependent on what is valuable in a society for the individuals living in it.

When a rule is written and enforced by an authority is called a *legal duty*. If it is of free acceptance, it is a moral. What is not a legal duty is a legal right. *A moral right is the right to meet a basic need*.

Everyone living in a society has some duties and some rights.

An action is said *morally wrong* if it hinders some individual to achieve a moral right. Conversely, it is *morally right* (or correct), if it helps some individual to exercise a moral right. Special cases such as when an action hinders an individual from achieving a moral right but at the same time enables other individuals to reach a greater moral right deserve special analysis in the context of the optimization of the rights of the whole social group (see Bunge 1989).

We use to say that a person is *morally responsible* for an action *b* or for the consequences of not acting in some circumstance iff she knows right from wrong, is fully conscious of the intentions that triggered the action (or blocked it), and is not under external compulsion.

We are morally responsible not only for our intentional or deliberate actions but also for *faults of omission*, such as negligence or failure to act at the right moment. Whoever is in charge or control of an event, the outcome of which is beneficial or harmful to others, is responsible for that event or for the failure to trigger it.

Only individuals can be morally responsible, for the simple reason that only individuals are conscious. In other words: there is no such thing as collective moral responsibility. All there can be, is the sharing among all the members of a group in a given responsibility. Therefore, collective reprisals are immoral. It is mistaken to shift responsibility from the individual to the society ("the system", "the establishment"). Society has no brain, a necessary condition for thought and consciousness.

A *moral code* is an ordered system of norms specifying what is right and what is wrong for a group of individuals. While some such norms regulate interpersonal activities, others guide the behavior of individuals. Every moral code is supplemented with meta-moral (or ethical) norms stating that such and such norms are superior to such and such other norms.

A rationally and empirically tested moral code will be superior to one that is irrational, based on superstition, and imposed by propaganda. A scientifically-oriented morality takes into account the findings of science in order to propose moral codes designed for specific societies where individuals have specific needs and wants. As society evolves, so moral codes should evolve. No moral is forever.

5.3 Free Will

Free will is a very fuzzy concept. Sometimes it is defined as behavior not caused or behavior that is not related to the previous state of the universe or the organism. This hardly makes any sense. Although there are events that are not caused, all events occur in accordance with laws. A probabilistic event is not undetermined: it is determined by a probabilistic law. A neutron decay, for example, is not an instance of free will. It is just a natural event that follows a regular pattern of nature. Since according to our current scientific view whatever occurs, occurs lawfully, free will, if it is something at all, it cannot be beyond the scope of natural laws (see Wegner 2003; Harris 2012).

Free will is sometimes associated with moral responsibility. If person x commits freely an act b, then x is responsible for the consequences of b. This sounds reasonable, but... what is the difference with pure causation? If x causes b, then x is part of the causes of all consequences of b. Usually, some people think that x is responsible if the behavior of x is itself *uncaused*. This is a completely unscientific view of human behavior. Human (animal, in general) actions are the results of complex processes that involve billions of neurons and other cells in the organism, as well as sophisticated molecules, neurotransmitters, hormones, external inputs, and much more. All these elements contribute to generate extremely complex processes, many of them in the brain, many unconscious, that result in the specific actions of an individual. Since the nervous system is plastic, previous interactions of the organism with the environment, past internal experiences, state of knowledge, and conditioning can be exceedingly relevant to the final behavior. Any definition of free will based on science cannot ignore these facts.

In particular, free will cannot be free from the laws of nature. Volition acts are not uncaused: simply we are not aware of the complex processes that occur in us when a volition appears. In words of Schopenhauer, although we can do what we want, we cannot want what we want. If we were different, with a different brain and a different history, our volitions surely would be different as well. There are many experiments that show (e.g. Libet et al. 1983) that our brain makes decisions *before* we are aware of them. If we think that is our consciousness which makes the choices, we are wrong. We are not aware of most of the happenings in our brain. Consciousness seems to be very useful for some activities, but it is harmful for others, which require a high level of automation (e.g. Eagleman 2011).

So, how can we define free will in a meaningful way? This is a tentative proposal:

Definition An action a by an organism x in the state s is *free* if

1. a is the result of a volition of x.
2. x is not compelled to perform a by uncontrolled external or internal conditions.

Definition A *volition* of an organism x is a brain process that results in the formation of a goal for x.

Then, free will is the capability of an organism to act purposefully without compulsion or coercion. This does not mean that the behavior is uncaused. It only implies that the organism acts according to its own constitution and not impelled by alien events. Actually, when we expect somebody to act by free will, we expect a behavior in accordance with what we know of the person, his or her past, knowledge, and current state. When someone starts to behave in totally unpredictable way, we suspect that he or she can be affected by alien causes or some brain problem. Of course, people surprises us all the times, but this is not because their behavior is uncaused. They surprise us because we are unaware of the causes of their behavior.

Free will, in this interpretation, is not an entity but a disposition to act in some specific way.

5.4 The Ontological Status of Goods, Values, and Morals

In Sect. 5.1 I mentioned that we value objects and processes if we think or feel that they are good to us. And they are good if they meet some need. When we value some thing x, we *attribute* to it a fiction that we call the value of x. The value is not in the thing; it is in our brain. It is a convenient way to express our need of x. There are not values in themselves. There are only valuable things for some organisms in some specific conditions. A very same thing might be very valuable to an individual A and completely indifferent to another B. This difference is not in a failure of B to appreciate x, but in the different needs of B. Clearly, the value was attributed by A to x. Since it is common that in a given society many individuals have similar needs, they tend to valuate similar things in a similar way, and hence the illusion might come that the values exist by themselves. Education, knowledge, indoctrination, and whatever might affect our brain and body can influence the way we valuate. Hence the importance of education for learning to valuate in a way that be in accordance with our goals. Conditioning, manipulation, propaganda, and social or emotional pressure can force some of us to valuate positively extremely harmful things (see Winn 2012).

Similarly, morals do not exist independently of the human beings that codify and follow them. Morals are not given by God, found through research, or received by sudden illumination. Morals are invented as social artifacts to coordinate and guide social behavior. For this reason, morals should be adapted to each society and should evolve with the society. In advanced societies, this evolution should be planned to match the evolving needs of the individuals.

5.5 Ethics

Ethics is meta-moral, i.e. the study and design of morals to satisfy the needs and wants of the individuals of some society. Ethical theories (i.e. hypothetic-deductive systems about the nature, roots, and functions of moral norms) should be evaluated in the light of science: i.e. through internal consistency and experience.

The experience will come from empirical studies of the effects of specific morals onto well-defined groups of individuals and societies. Testing ethical theories, then, requires multidisciplinary work that should involve social scientists and scientific psychologists.

In addition to a scientific ethics, there is an ethics of *scientific research*. This ethics fixes moral rules for doing science. Any adequate definition of the concept of science must include a reference to its moral code, which is designed to encourage and protect the search for truth, i.e. the pursuit of adequate representations and models of reality. The success of scientific research crucially depends on obtaining true data, the formulation of true hypothesis, and the design of efficient methods to test theories and models. Hence, truth is a value for any moral code of scientific research. This will imply moral rules such as:

- Be as clear as possible.
- Do not hide relevant data.
- Do not alter data for your convenience.
- Check your results for truth.
- Give proper credit to other researchers.
- Do not plagiarize.
- Seek expert criticism and advice.
- Do not inflate your results.
- Do not withhold information.
- ...

There are many more specific rules that should be developed for special sciences like "do not make experimental animal suffer", "treat fairly your assistants", and many more. Any research institution should make explicit the moral code it is adopting, as well as the ethics on which the code is based.

Basic scientists are responsible in regards with the moral duties implied by the codes adopted in their organizations, so they can be blamed if they cheat, lie, and mistreat their students, among other things. But they are not responsible for the uses of technology based on the knowledge they generate. The responsibility for this is on the technologists that develop the artifacts, the bureaucrats, businessmen, and politicians that order the construction of the artifacts, and those that decide their use. If a politician decides to use an artifact (from an atomic bomb to a social plan) that results in a harm that is morally reproachable, then the responsibility is on the politician, on those who instrumented the action, and (in a democratic state) on those who voted for the politician.

Science cannot be blamed for the bad uses of technology made by politicians and other individuals that dispose how to use knowledge to create technological tools that are misused. The tools themselves are morally neutral, since only actions (and their agents) and facts can be considered moral with respect to some moral code. A missile can be used to kill or to divert an asteroid. What makes an action good or bad is the use somebody makes of the artifact, not the artifact itself. Technology is a means, not an end in itself (for ethics of technology see Bunge 1989).

5.6 Metaethics

Moral facts are facts considered as of moral significance in some moral system. More specifically, they are facts that belong to the reference class of a moral code. There are moral facts, then, not in absolute terms, but with respect to a given moral code. The *moral code* itself is a system of moral norms. An *ethical theory* is a theory about a moral code. It deals with its justification, meaning, coherence, etc. Finally, *metaethics* is the study of the concepts used in ethical theories. It deals with the clarification of concepts such as those of norm, code, ethical theory, moral responsibility, good and wrong, free will, and many others. Also, metaethics studies the relations between ethics and morals, and those of the latter with actions. For an introduction to metaethics see Fisher (2014).

5.7 Action

Actions can be *intentional* or *unintentional*. Intentional actions are motivated by a goal, and executed by some means. The means are as important as the goal. Not all means are equal. A moral action should adopt means that minimize the morally wrong impact on any sensible individual. This can be achieved with adequate scientific planning. Impulsive, thoughtless actions often are extremely harmful. They should be avoided in a civilized society and in personal life.

Since there may be alternative means for attaining a given goal, we ought to choose the means optimizing the total value $V(i, m, f)$, rather than just the difference between the values of the initial and final states. Notice that optimization is not the same as maximization. In many cases optima lie between minima and maxima. For a quantitative theory of action that adopts optimization see Bunge (1989).

Any responsible action requires at leat three components: knowledge, courage, and goal. Without knowledge we cannot know what is the best way to proceed. Without courage we may waver in implementing our actions. Without a goal or reason, our action is pointless.

Summing Up All organisms with needs valuate some items. Values are fictions attributed by the organisms to those items. There are basic values or *bio-values*, and non-basic values or *psychological values*. In some cases the latter can be strongly influenced by the social context of the individual to the point that talk also of *social values*. *Morals* are norms imposed in a society to enforce values that are considered desirable (goods). *Good* and *wrong* do not exist by themselves. They are the result of our valuations. *Ethics* is meta-moral theory: the study, justification, and design of morals. *Metaethics* is the study and clarification of the concepts of ethics and the relations of ethics and morals. *Action* should be regulated by ethics within a society. Ethics, in a rational society, should be scientifically conducted to lead to the optimal rules of behavior, and hence, to establish what is good and wrong for individuals in the context of that society.

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Chapter 6
Aesthetics

In the previous chapter I have said that we value objects and processes if we think or feel that they are good to us. And I maintain that they are good if they meet some need. The value has no independent existence, it cannot be found in the evaluated object because it is not there: it is in our brain. To state that something is good is a convenient way to express our need of it. Similarly, I claim that there are not beautiful things, there are just things deemed beautiful by some individuals in some context at some instant. And things are considered beautiful because they produce a positive aesthetic experience in the individual. The task of philosophical aesthetics is to elucidate the nature of this experience, as well as the related concepts of aesthetic appreciation, art, work of art, and other meta-artistic ideas.

Art is the result of a human activity. As any product of what human beings do, art can be studied using the tools of science and philosophy. The outcome is *scientific aesthetics*. Art, certainly, is not scientific, but its investigation can be scientific. In what follows I will outline an art theory that might be regarded as yet another branch of scientific philosophy. I will start with the aesthetic experience that is the root of our appraisal of art.

6.1 Aesthetic Experience

Any account of aesthetic experiences has to address at least the following two questions: what it means for x to be an experience; and what it means for an experience to be aesthetic.

As any other human experience, the aesthetic experiences are processes taking place in the human body, especially in the brain. These processes are triggered by interactions with an object (either artwork or a natural item) and depend on its objective properties, the art-related knowledge of the individual, his or her emotional and physical state, the ambient conditions, and the disposition of the subject. Other factors might be revealed by further neurological research based on functional magnetic

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resonance, magnetoencephalography, and electroencephalography performed while a subject is exposed to different types of artworks and aesthetic objects. So far, it seems that the aesthetic experience involves the activation of sensorimotor areas of the brain along with core emotion centers, and reward-related centers (e.g. Di Dio and Gallese 2009; Brattico and Pearce 2013). The aesthetic experience seems to be a multilevel and complex process that exceeds the mere cognitive-sensorial analysis and appreciation of artworks and relies upon viscermotor and somatomotor resonances in the beholder with major emotional centers, such as the insula and the amygdala, involved. The nature and depth of the experience depends strongly on the knowledge, training, and life-style of the subject, along with the external physical conditions (environment, illumination, ambient temperature). The aesthetic experience, then, emerges from the relationships among a sentient subject, an object, and the context in which they are embedded (Langer 2016).

The concepts of aesthetic experiences and aesthetic values are linked to each other by means of the following logical necessity (Dorsch 2000):

> An experience of an object is aesthetic if and only if it ascribes a value to the object, and that value is aesthetic.

Any person unable to have aesthetic experiences will be indifferent to aesthetic judgments. Beauty is not found, it is experienced.

6.2 Beauty

The aesthetic appreciation of different types of objects leads to aesthetic judgements. We say that an object, event, or process is *beautiful* iff it produces in us a particular kind of positive aesthetic experience. An experience is said positive if, under ideal conditions, makes the subject feel good and creates a desire to continue or repeat the experience. Specifically,

Definition An item a is aesthetically valuable in its aspect b for organism c in the circumstance d, and in the light of the body of knowledge f iff a produces a positive aesthetic experience in c.

I notice that an individual might have a positive aesthetic experience but the cause might not be deemed as beautiful. For instance, some objects might cause disgust or even repulsion, but nevertheless they might trigger cognitive and other brain processes regarded as aesthetically valuable and positive by the individual.[1] So, the relation between positive aesthetic experiences and beauty is not a one-to-one relationship. Beauty is just a subset of all possible aesthetically positive experiences

[1] Examples include Alexandrian sculpture, French realist, naturalist, and decadentist literature, anti-war novels written in the 1920s by some outstanding French, German, and Austrian writers, whose main aim was to provoke revulsion, not pleasure, and much of contemporary plastic arts, among many other examples.

for an individual. The distinctive characteristics of the elements of the subset is that they induce an experience that is not only deem positive, but delectable for the subject.

Aesthetic judgments involve relations of the form $Vabcd \ldots n$. If we succeed in quantifying aesthetic values, the relation becomes a function from n-tuples of objects to numbers. For example: $V(a, b, c, d, u) = v$, where u is a suitable unit, and v the numerical value c attributes to a in its aspect b, on the basis of a knowledge f and in the stance d.

The general form of a real function representing values is $V : A \times B \times \ldots N \times U \rightarrow \Re$, where A is a collection of objects of aesthetic appreciation, B a collection of individuals, and the remaining factors in the Cartesian product, up to N, may be collections of things, properties, states, or processes, whereas U is a set of units, and $\Re$ is the set of real numbers. As it occurs in ethics, quantifiable aesthetic values are exceptional. Usually, only art critics and aestheticists care for doing such quantitative assignation. Partitions of the set B caused by different background knowledge or differences in conditions and other variables explain differences in value attribution by different critics to the same objects.

Beauty is simply the set $\mathcal{B}$ of all objects deem beautiful by an individual b, under conditions c, at a given instant t. The intersection of $\mathcal{B}_i$ for objects of class x in a group G of individuals $i = 1, \ldots, n$ in a society C is the *ideal of beauty* of x in that group.

Not only artworks can be aesthetically valuable. Landscapes, human faces, natural objects, animals, technological artifacts, scientific theories, and many other items can be regarded objects of beauty.

6.3 Art and Artworks

'Art' is a polysemous word with multiple referents. It is used to refer to artworks, but also to describe the activity of artists, the evaluation of works of art, their distribution, exhibition, and more. Many of these activities are associated with institutions, foundations, universities, schools, and commercial organizations. The concept of art is clearly multileveled and complex. Attempts to find necessary and sufficient conditions for any x to be 'art' are usually deficient because of the huge variety of activities that are considered as art (music, dancing, photography, sculpture, painting, drawing, cinema, drama, poetry, and so on). Moreover, within each specific art, many different movements, sometimes even opposed in both method and content, can be identified. Finding common elements is achieved only at the price of oversimplifications in such a way that counterexamples are always found (see, e.g., Meskin 2008 and Davies 2013).

I think that the best approach to a definition of art is to start observing the kind of activities that we consider art, finding their more salient features, and then proceed to formulate a tentative characterization. The definition that I will offer, therefore, is provisional, descriptive, and perfectible. It should be improved to fit the facts, if necessary. This is the same approach we have adopted with other complex human products as science and technology. For similar views see Langer (2016).

First of all, let me remark that whatever art is, it is the result of human activity. These activities involve artists, i.e. persons with special training and skills that can create artifacts (both material and conceptual) that are judged as artistic by other people, including experts and at least some public. A work of art may be not recognized as such by part of the public and even it might be rejected by some experts. This sometimes leads to the formation of different schools and artistic movements. Since movements are more homogeneous than art in general, I will attempt at a characterization of the former first.

A specific art movement A_i can be represented by 11 components as:

$$A_i = \langle C_i, S, D_i, F_i, O_i, B_i, T_i, M_i, E_i, P_i; V \rangle , \tag{6.1}$$

where:

- C_i is a community of artists. These are individuals that can design and construct artificial objects (either conceptual or material) called artworks or perform representations of works of art.
- S is a society that hosts (or at least is not hostile to) the members of C_i.
- D_i is the set of artworks.
- F_i is the set of material resources accessible to the members of C_i for creating, exhibit, and trade their works or execute performances (it includes workshops, theaters, art galleries, museums, etc.).
- O_i is the set of artistic goals of the members of C_i.
- B_i is the total knowledge available to individuals in C_i to achieve their goals.
- T_i is the specific technical means available to those in C_i (it includes musical instruments, writing equipments, film industry, painting technology, and so on).
- M_i is the collection of rules, prescriptions, conventions, and instructions adopted by the members of C_i in connection with the movement A_i.
- E_i is the set of experts that make aesthetically sound judgments about objects in D_i in accordance with the rules of M_i.
- P_i is a collection of individuals that are exposed to the effects of the artworks created by the artists of C_i (the 'public').
- V is the value system (axiology) adopted by the persons of C_i, which is based on the ethics shared by the society S.

Some comments are in order. An artistic movement is a material social system according to our characterization. Artistic movements can interact with other subsystems of a society and play an active role shaping historical processes. Artists, critics, and public in general are linked by complex relations that go beyond the mere production and passive perception of artworks. Artistic ideas can pervade influential groups in a society and may help to shape the worldview of large social systems in some historical periods, as it was the case of Romanticism. Romanticism was an artistic movement, mostly literary and musical, that originated in Europe toward the end of the eighteenth century as a reaction to the Enlightenment and the

Classicism in the arts. It affected most aspects of intellectual life. Even scientists were influenced by versions of the *Naturphilosophie* of Johann Gottlieb Fichte, which would lead to German idealism and Hegel. Hegel in turn had a strong impact on Engels and Marx, with the subsequent social and historic implications. Another prominent example of an art movement with global impact is the Renaissance, which was a broad cultural movement that exceeded the arts and affected every aspect of human society.

As any material system, art movements evolve with time. Hence, strictly speaking, the components of the proposed representation of art systems are sets only at a fix moment t. Otherwise, they are collections of individuals and not formal sets.

The existence of a group of experts is important for the emergence, consolidation, production, distribution, and general dynamics of an artistic movement. Experts play an important role in the legitimation of artists and their works. They are essential to evaluate, distribute, exhibit, and foster works of arts. Experts are (or should be) well-aware of the artistic conventions M_i and hence help in the self-regulation of art movements. Notice that the experts may be institutions besides individuals. In the case of extremely innovative artists whose conceptions and creations are not recognized as art by most of the public, experts usually make a decisive contribution to the consolidation or rejection of the new trends.

The group of individuals called 'the public' is the ultimate addressee of artworks. A number of them are expected to have aesthetic experiences when confronted with the works of arts. In the limiting case the set P_i has only one member: the artist. If the public is formed only by the artist and no expert ever recognizes the artistic nature of the artifact, then it cannot be objectively claimed that the artifact is an artwork. It will be only claimed as a piece of art by the 'artist' and his or her claim will remain entirely subjective.

The set of conventions and rules M_i regulate and guide the production of artworks. Usually these conventions are not explicit, so part of the task of the experts is to elucidate them. Since rules are conventional, exceptional authors can break them with various results. When the outcome of these experiments leads to new aesthetic experiences in a significant group of people, a new movement with new conventions emerges.

Works of arts are artifacts, i.e. human constructions (see next section). They can be material, such as paintings and sculptures, conceptual as literary works, written music, or processual as musical performances and stage plays. Conceptual artwork includes fictional work such as novels, and processual art may encompass works as live exhibitions, drama representations, etc. All artistic works are created with some goal (O_i) by the artist. The goal is related to the kind of aesthetic experience the artist seeks to arise in the public. These experiences are not necessarily positive, in the sense that some artists might look for producing anxiety, concern, even horror in their public within a valid aesthetic context (e.g. a movie).

From our characterization of an artistic movement it is clear that aesthetic statements and judgments can be perfectly objective but they are always relative to a certain aesthetic valuation system, which is conventional. That is, there are no aesthetic properties of artworks; we assign an aesthetic value to the attributes of a certain artifact relative to an often implicit system of valuation. Of course, it would be preferable if these value systems were formulated in a clear and consistent way and available to public scrutiny. It is the task of aesthetic research to endow each art movement of a well-defined set of valuation rules in order to make possible objective and contrastable statements of value. Such rules might be in part conventional and in part based upon biological dispositions and cultural preferences. This is the only way to discuss things such as the literary value of a poem or the cultural importance of a film. The same cultural product can have different objective aesthetic values regarding different valuation systems. If these are stated explicitly together with the valuation, then objective communication on aesthetic issues is possible. A meta-aesthetics should then be developed in order to offer selection criteria among the different aesthetic systems.

Once we are in possession of a tentative definition of art movement, we can define art as the set of all art movements.

$$\mathcal{A} = \{x/x = A_i,\ i = 1, \ldots, n\}.$$

Then, art is a concept, not a material system, at least in the aesthetic theory I am presenting here. The study of art is the study of art systems, i.e. artistic movements. Each movement has its own specific features, with its artworks, rules and conventions, public, experts, etc. What they share is the basic structure defined through expression (6.1) above.

6.4 The Ontology of Art

What kind of entities should exist in order to legitimately say that there is art in a given society? If the answer includes 'works of art', then what sort of entities are works of art? Are they physical objects, ideal kinds, imaginary entities, or something else? What is common among such disparate objects as a stage performance, a novel, a symphony, and a painting? How many ontological types of works of art there are? These are the central questions of the ontology of art. They are not easy questions, as the surprisingly large number of views on possible answers shows (see Thomasson 2004, for a review).

We may start considering the reference class of our concept of art given by expression (6.1). The collection of arguments of the predicates that appear in our characterization of art movement (and hence in that of art) includes people (artists, experts, and critics), works of arts, material objects such as instruments, cameras, and dresses, conceptual constructions as rules, axiological systems and conventions, a society, and brain processes such as ideation, knowledge, and volitional acts. We have already dealt with these kind of objects in the previous chapters, so I will focus on works of art here.

The traditional views on the ontological nature of artworks fall in three broad groups. Those who think that works of art are essentially physical objects (e.g. Wollheim 1980), those who think of artworks as mental or imaginary (e.g. Collingwood 1958; Sartre 1966), and those who see them as abstract entities (e.g. Currie 1989). As noted by Thomasson (1999, 2004), these views are at odds with common sense beliefs and usual practices related to the arts. In particular, contrary to the traditional conception of abstract entities, works of art come into existence at definite moments (we can say, for instance, that Ludwig van Beethoven's Piano Sonata No. 8 in C minor, Op. 13, commonly known as Sonata Pathétique, was written in 1798) and they exist only on planet Earth. But contrary to pure physical objects, they might exist solely as brain processes (I think here in "The Secret Miracle", a short story by Jorge Luis Borges[2]). Thomasson (1999) proposes, and I subscribe, that works of art are *cultural artifacts*, i.e. intentional constructions (either material or conceptual) created by human beings with the goal of producing aesthetic experiences. Hence, artworks are not independent of humans in the sense that they are created by intentional activities, and exist only as long as socio-cultural actors are aware of them. Works of music and literature, for instance, are created by the authors at a certain time and context, and then reproduced by a variety of means, including printed books, pdf files, audio books, sheet-musics, performances, recitations, etc. The artwork will last till the last score, recording, printing or memory of it be obliterated or forgotten.

In short, the existence of art is possible only if a number of material entities interact. Among them, we can mention artists that create artworks, public, and experts. The creation and interaction processes also require material means such as theaters, paintings, art galleries, books, musical instruments, and much more. Works of arts are human products, cultural artifacts, that once created can exist independently of its creator, but not of all human beings. Art needs both the intention of the artist and the sensibility of the public in order to exist.

Summing Up Aesthetic experiences are a type of biological processes mediated by the senses that occur in certain (evolved) organisms, mainly involving the brain. These processes depend on both the external stimulus produced by the object (either natural or artificial) and the state of the organism. If the experience is positive, the organism deems the aesthetic object as aesthetically valuable (e.g., as beautiful). Aesthetic experiences are the roots of aesthetic valuations. There are not beautiful things or events in themselves: aesthetic values, as all values, are fictions attributed

[2]The main character of the story is a playwright named Jaromir Hladík, who is living in Prague when the city is occupied by the Nazis during World War II. Hladík is arrested and charged with being Jewish as well as opposing the Anschluss, and sentenced to die by firing squad. During his execution God allows him a whole year of subjective time while everything else, including his body, remains motionless. Working from memory, Hladík mentally writes, expands, and edits a play, the artwork of his life, shaping every detail to his full satisfaction. Finally, after a year of labor, he completes the piece; only a single epithet is left to be written, which he chooses: time begins again and the fire from the rifles of the squad kills him. No one else will ever know that he finished his work and created the play.

to some objects by some organisms in a particular state. Artistic movements are material socio-cultural systems that include artists, experts, critics, and the many material and conceptual items associated with their specific activities. Art is simply the class of all art movements. Each of these movements includes some conventions with respect to which artistic judgements are done. Works of arts are cultural artifacts, i.e. human constructions produced in a cultural context within a society, whose goal is to induce some kind of aesthetic experience in the beholder. Artworks can be material, such as paintings and sculptures, conceptual such as literary works, processual as musical plays, or mixed, as a stage performance. Aesthetics is the philosophical study of aesthetic experiences and art. Art is not scientific, but aesthetics can become so.

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Part II
Specific Topics

Chapter 7
Mathematical Fictionalism

Nominalism is sometimes defined as the doctrine that there are not abstract objects (e.g. Field 1980). The opposite view is called Platonism. An object is abstract if and only if it is non-spatial and causally inefficacious. Why should anybody think that there are such mysterious objects? A powerful reason is offered: mathematics refer to them and there are true mathematical propositions about them. According to Quine (1960), if we are going to accept mathematics (and nobody in his or her right mind would not), we are committed to the existence of abstract entities. No one doubts that the following proposition is true: "There is a prime number greater than 3 and smaller than 7". Then, the argument goes, there is something, called '5', that exists. And '5' is an abstract object: it is located nowhere and has no causal influence on anything. Similarly, mathematical objects such as sets, series, functions, manifolds, vectors, tensors, an so on are abstract objects. An ontology populated by infinite mathematical entities is considered objectionable by nominalists. If there is an entity called 'Paul' in the world, should we also accept the existence of the infinite objects '{Paul}', '{{Paul}}', '{{{Paul}}}', and so forth? Once one abstract object is accepted, an ontological inflation seems unavoidable.

The usual nominalist response to this situation consists in a reformulation of mathematics in order to eliminate the quantification over abstract objects (Goodman and Quine 1947; see Burgess and Rosen 1997, and Balaguer 1998 for reviews). But, as Quine later pointed out, in the end it results indispensable to quantify over classes (Quine 1960). The indispensability of mathematics for science led to a program of moderate Platonism: ontological commitment should be restricted to just those entities that are indispensable to our best theories of the world (Quine 1960; Putnam 1971; Colyvan 2001). These entities seem to be classes, sets, or categories.

Some authors (e.g. Field 1980) accept Quine's criterion of ontological commitment but refuse to include classes as real abstract entities. They have produced different nominalistic reformulations of mathematical theories applied by physics. Others (e.g. Azzouni 2004) accept that quantification over mathematical objects and relations is indispensable to our best theories of the world, but think that this fact offers no reason to acknowledge the existence of the corresponding entities on

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an equal foot with material objects. These latter authors consider that existential quantification is not sufficient for ontological commitment (see Chap. 3, Sect. 3.3).

In what follows I will present an alternative view on the status of mathematical concepts. I will argue that the referents of mathematical theories are *conceptual artifacts*, i.e. human constructions created in the framework of a mathematical context. My position might be dubbed as *formal fictionalism* and is closely related to what I have already said in Chaps. 2 and 3. Before proceeding with my characterization of mathematical objects, I will first say a few things on the nature of mathematics itself.

7.1 The Nature of Mathematics

I hold that mathematics is the science of formal systems endowed with a purely conceptual interpretation (a similar view was proposed by Curry 1951; Curry, however, dispenses with interpretations, conceptual or not). Mathematics, I maintain, consists of a collection of formal systems which have as reference class pure conceptual objects. I will define these objects in the next section. Formal systems were introduced in Chap. 2. They can be characterized as follows.

Definition A *formal system* S is the triplet

$$S = \langle \Sigma, R, O \rangle \,, \tag{7.1}$$

where:

- Σ is the set of primitive terms of the system.
- R is the set of rules that provides explicit instructions about how to form valid combinations of the elements of Σ.
- O is a set of objects that are denoted and represented by the elements of the system.

The set R can contain two disjoint subsets[1]:

$$R = S_{\mathrm{y}} \cup S_{\mathrm{e}}, \tag{7.2}$$

where

- $S_{\mathrm{y}} \equiv$ set of syntactic rules,
- $S_{\mathrm{e}} \equiv$ set of semantic rules.

[1] In Chap. 2 we discussed formal systems as languages, so we added a set of pragmatic rules.

The syntactic rules specify how valid combinations of elements of Σ can be obtained and the semantic rules relate symbols to objects of some kind.[2] The semantic rules provide the system with *an interpretation*. An uninterpreted formal system is a *logistic system*.

Definition A *mathematical system M* is a formal system such that the semantic rules relate symbols in the system to *conceptual artifacts* (see next section for a definition of 'conceptual artifact').

In a formal system, a statement is true if and only if it is derivable in the system. Mathematical statements, then, are true in a system iff they can be proved in such system. Notice that a statement such as $AB - BA = 0$ can be true in some systems (e.g. real arithmetics) and false in others (e.g. in the theory of matrices).

At a fundamental level, all mathematical systems are on a par. There can be at most pragmatical reasons for preferring one system over another. Inconsistent systems can prove all statements and therefore are useless. So when a system is found to be inconsistent, it must be modified. From Gödel's incompleteness theorems result that a system sufficiently strong as to include the arithmetics cannot prove its own consistency; but as far as the system is not proved inconsistent, it can be used in mathematics.

Formal systems, and hence mathematics, are human constructions which are (1) exact, since precise formation rules of their formulas are made explicit, and (2) conceptual, since they are independent of any material object (with the exception of the human beings that create them). Formal systems, therefore, exist only to the extent that there are people capable of thinking them. This does not mean that they are subjective. They are perfectly impersonal and inter-subjective since any person can resort to the formation rules of the system and can check the validity of all statements.

The meaning of mathematical terms is two-dimensional, consisting of a reference class (purely conceptual, formed by mathematical objects) and a well defined sense (the class of all terms that are formally connected with the term at issue). The theory of meaning developed in Chap. 2 holds for mathematical languages and can be used to prove that mathematical theories are exempted of vagueness. This is the main reason of the huge usefulness of mathematics in factual sciences: it provides an exact framework to express our ideas about the world.

When a physical theory appeals to mathematical tools to represent some aspect of reality, some rules are added to those of the mathematical background theory. These are semantic rules that relate mathematical objects to extra-linguistic objects, i.e. material entities. Thus, in some application of vector analysis, for instance, it might be specified that a vector field represents the distribution of velocities in a fluid, whereas in another application the same field might represent an electric field. There is a semantic thickness in physical theories that is absent from pure mathematics.

[2]The pragmatic rules introduced in Chap. 2 are necessary to specify how a language should be used.

The proposed interpretation of mathematics sheds light on the nature of mathematical knowledge. Such knowledge is not about supra-physical, abstract entities which are accessible only to some people by intuition. Mathematical knowledge is knowledge of the implications of our postulates in formal systems. This knowledge is a priori in the limited sense that it can obtained without any appeal to the external world beyond the formal system itself. In the case of physical theories, on the contrary, the truth criterion of the factual propositions is the correspondence with facts (see Chap. 2). This dichotomy between formal and factual statements is the key to an understanding of the role of mathematics among the different sciences. Since its reference class is purely formal, mathematics has nothing to say about the world. Because of the same reason, mathematics can be applied to express our thoughts about the world in an exact way. But this can be done only if mathematical theories are enriched with semantical axioms that link mathematical objects to factual items (Chap. 4).

7.2 Mathematical Objects as Conceptual Artifacts

What are the objects that are referred to by the statements of a mathematical system? I already claimed that they are *conceptual artifacts*. An artifact is a human construction. We have found artifacts before, in our discussions of technology and art. In technology the artifacts are objects designed with a purpose: they are tools to perform some tasks. There are material artifacts, such as hammers and spaceships, or social artifacts, such as laws or morals. In the arts, artifacts usually have a material and a conceptual component. They are designed to induce an aesthetic experience in some individuals. I have maintained that works of arts are cultural artifacts. Similarly, the artifacts of mathematics are complex concepts created by definition or by suitable characterization within a formal system. They are a kind of *fiction*, but, contrary to the fictional characters in novels, they are rigorously introduced through formal systems. So, mathematical fictions are fully characterized by constitutive axioms within the mathematical theory where they are set in.

Essentially, mathematical objects are ontologically on a par with artistic and mythological creations; the difference is contextual: mathematical objects are introduced through theories that are both formal and consistent (in the sense that they do not include contradictions), whereas artistic and mythological fictions are presented in an informal way through novels, narratives, movies, stories, legends, and so on. We can define a mathematical object as follows (see Bunge 1985, 1997):

Definition An object x of a consistent formal system S is a *conceptual artifact* iff there is a set C such that $x \in C$ and C is specified in S.

The specification is implemented through some of the axioms of S. This definition is open to a straightforward criticism: it invokes a conceptual artifact, namely the set C (e.g. Torretti 1982). But for any set C there will be another formal system S' such that $C \in C'$. What about the set of all sets of conceptual artifacts?

Since such a set cannot be consistently formulated, it is not a conceptual artifact. Then, there is no circularity in our definition. Conceptual artifacts can be introduced *only* through their characterization in *consistent* formal theories.

Conceptual artifacts can be quantified over within a mathematical theory, but there is no ontological import associated with such quantification. As we have seen in Chap. 3, the inclusion of an object in the domain of a bound variable only expresses absence of contradiction. In order to assume some ontological commitment with an object, we need to express such a commitment through a predicate. Of course, we are free to act 'as if' the mathematical constructs would have independent existence of human beings (Vaihinger 1911). This is something usually very convenient because of the economy of language implied.

Despite of being human creations, mathematical objects are not arbitrary or purely subjective. Mathematical objects, as conceptual artifacts, are bound by the axioms of the mathematical theories where they are introduced. Any person that masters these theories can attain knowledge of these conceptual objects. In complex theories, not all implications of the axioms can be initially discerned. Hence, research of mathematical systems is necessary to elucidate the relevant consequences of the fundamental postulates. The mathematician not only invents new formal systems, but mainly looks for the implications of already proposed theories. In doing so, the researcher appeals to both invention and discovery. Invention of original ways of establishing a proof and discovery of unforeseen implications of some axioms.

The view of mathematics as a formal research field that refers to conceptual artifacts is a form of *fictionalism*. This is because conceptual artifacts are formal fictions. There are many forms of fictionalism (e.g. Fine 1993; Thomasson 1999; Yablo 2002; Kalderon 2005; Bueno 2009; Sainsbury 2010; Salis 2014). Some versions of fictionalism plainly reject the reference class of mathematics (e.g. Field 1980). I think that this is wrong; mathematics is not a theory about no subject. Mathematics is about mathematical objects, in the same way as a novel is about some fictional characters. Mathematics does not make any ontological commitment to its referents.

The truth of mathematical statements is not determined by correspondence with mathematical 'facts' because there are not mathematical facts.[3] Truth in mathematics is established by fitting a statement coherently within a mathematical system. Mathematical knowledge, then, is a priori knowledge. This does not mean that single mathematical statements are tautologies, as held by some logical empiricists. Consider, as an example, the following statement: "the Cauchy problem for any partial differential equation whose coefficients are analytic in the unknown function and its derivatives, has a locally unique analytic solution" (Cauchy-Kowalevski theorem). This statement is true in the theory of partial differential equations, but it is not a tautology: it is not possible to establish its correctness just by inspection of the statement itself. We need to investigate the full theory in order to produce a proof

[3] Conceptual objects do not change.

of the theorem. The proof does not resort to extra-mathematical knowledge, but it goes far beyond a mere semantical or logical clarification of the terms involved. In general, mathematical statements refer to mathematical objects and attribute them some properties. Whether the statement is correct or not must be determined by formal proof within the context of the corresponding mathematical theory.

7.3 Why Mathematics Can Be Applied to Reality?

If mathematical objects are conceptual fictions, why they can be applied to describe real objects and processes in the world? The answer is precisely because pure mathematics is ontologically neutral, mathematical ideas are portable across research fields. Mathematical concepts, being formal and exact, can be used with profit to represent certain features of real things in our theories. It is not that we apply mathematics to reality, but rather that we can make our ideas about reality more exact through their mathematization. An exact language based on mathematics has a greater expressive power to describe with precision the world than a mere natural language, which is infected with vagueness and imprecision.

Not all mathematical theories are useful to formulate ideas about the world. For instance, Riemannian geometry had little use in physics before the advent of general relativity. Matrix algebra was scarcely known by scientists before quantum mechanics. Sometimes, physicists even need to invent the mathematical tools they need, as it was the case of Newton. Most mathematical theories, however, are never adopted in theories of the factual sciences. There is not an a priori way to determine whether a given mathematical theory will be useful or not to factual science, because we do not know in advance how the world is. The richer our mathematical theories are, the stronger is our capability of representing reality. Basic research in mathematics, therefore, should be encouraged if we want to expand our understanding of the actual world.

The most basic branches of mathematics, such as arithmetic or plane geometry, were inspired by observations of the natural world around us. Hence their versatility. However, when we move away from the realm of the common sense, these tools might be inadequate and others of higher complexity become necessary.

The construction of mathematical models and theories of factual items requires, in addition to the mathematical formalism, an empirical domain and semantic rules that provide the correct interpretation (i.e. that relate mathematical constructs to facts). So, a same formalism can be applied to the mathematization of our ideas in different fields and factual domains. For instance, the same differential equations can express the continuity of charge, mass, or energy. A vector field can represent the velocity of a fluid or an electromagnetic field. The same wave equation can be found in the description of the propagation of perturbations in fluids, elastic bodies, or fields. And so on. We can keep the mathematical apparatus but change the factual domain and the semantic rules with the result of a different physical theory. The ontological commitment of a theory, then, is not given by the mathematical objects that appear in it, but by these semantic rules.

Summing Up Mathematics is the science of formal systems with a conceptual reference class. Mathematical theories are creations of the human beings. They are characterized by their exactness and formal structure. Mathematical statements refer to mathematical objects that are conceptual fictions. Hence, mathematics has no ontological import. Because of that, mathematical theories can be used to formulate exact theories about different aspects of the real world. Ontologically neutral mathematical theories are connected to the world through a set of semantic rules. It is through these rules that our theories acquire their factual content.

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Chapter 8
Philosophical Problems of Quantum Mechanics

8.1 Introduction

Quantum Mechanics (QM) is a fundamental physical theory about atomic-scale processes. It was formulated in the first decades of the twentieth century by many of the most distinguished physicists of that time. The accordance of this theory with experimental results is remarkable. The physical interpretation of the different mathematical constructs that appear in the formalism of QM, however, raised unprecedented controversies. From this intellectual conflict, numerous interpretations of QM emerged. To name just a few: the Copenhagen interpretation, the de Broglie-Bohm theory, interpretations based on Quantum Logic, Time-Symmetric theories, the Many-Worlds interpretation, statistical interpretations, and realistic ones (for a review of QM interpretations and their historical context, see Bunge 1956 and Jammer 1974).

The most accepted and spread interpretation of QM is the Copenhagen interpretation, proposed by a Niels Bohr and Werner Heisenberg in 1927. The popularity of this view is such that the interpretation is presented in many textbooks as an integral part of the theory. The Copenhagen interpretation is, however, implicitly influenced by subjective and pragmatic philosophy and is extremely confusing from an ontological point of view. Semantic and epistemic vagueness abound in it and have resulted in serious misunderstandings that are often repeated in textbooks and elsewhere.

In this chapter I shall apply many of the formal and philosophical tools presented in the first part of the book to clarify several interpretation problems of QM. Among other topics I shall discuss the issue of determinism in QM, the nature of the so-called "uncertainty relations" (Heisenberg's inequalities), the alleged collapse of the wave function, the EPR paradox, the ontology of QM, and quantum entanglement. First I shall provide an informal presentation of the main features of the theory. Then, a full formal axiomatization of QM will be offered (the reader not interested in technical questions can skip these sections). In the final sections of the chapter I shall deal with the philosophical problems mentioned above.

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8.2 Outline of QM

The referents of QM are particular physical systems called *quantum systems*. The states of a quantum system are represented by a non-unique, normalized, mathematical function $\psi(\overline{x}) \in H$ called *wave function*, where $\overline{x}$ denotes the position of a point in Euclidean 3-dimensional space, and H stands for a Hilbert space.[1] The wave function is a fundamental mathematical tool for calculating the values of the different properties of the quantum system.

Unlike classical theories, quantum states are represented by complex functions in Hilbert space, where a summation operation is defined. This fact, and the linearity of the dynamic equations of QM, imply that the Principle of Superposition holds at the level of states. Consider, for instance, the wave functions $\psi_+(\overline{x})$, $\psi_-(\overline{x})$ that represent the state of an electron with its spin up and down, respectively. Then, the wave function

$$\psi(\overline{x}) = \frac{3}{5}\psi_+(\overline{x}) + \frac{4}{5}\psi_-(\overline{x}) \tag{8.1}$$

represents a plausible state of the quantum system that is a superposition of the spin-up and spin-down electron. For empirical confirmation of such counterintuitive feature of QM called *quantum entanglement*, see Schlosshauer (2007), p. 21.

The values of properties of a quantum system can be calculated with self-adjoint operators $\widehat{A}(t) : H \longrightarrow H$, acting upon the corresponding wave functions. But, unlike classical systems, quantum systems may not have precise or sharp values for their properties. Instead, we can calculate the average $\langle\widehat{A}\rangle$ of a certain property by

$$\langle\widehat{A}\rangle = \langle\psi|\widehat{A}|\psi\rangle. \tag{8.2}$$

The *inner product*[2] of two states is defined by:

$$\langle\psi|\phi\rangle = \int \mathrm{d}\overline{x}\, \psi^*(\overline{x}) \cdot \phi(\overline{x}). \tag{8.3}$$

The spread $\Delta_\psi \widehat{A}$ of the average is

$$\Delta_\psi \widehat{A}^2 = \langle\widehat{A}\rangle^2 - \left\langle\widehat{A}^2\right\rangle. \tag{8.4}$$

If the spread $\Delta_\psi \widehat{A}$ of a certain property of a quantum state $\psi_k(\overline{x})$ is null, then the property takes a sharp value λ_k. The corresponding state $\psi_k(\overline{x})$ is called an

[1] A Hilbert space is an abstract vector space possessing the structure of an inner product that allows lengths and angles to be measured. Hilbert spaces are complete in the sense that there are enough limits in the space to allow the techniques of calculus to be used.

[2] In this definition the symbol $*$ designates the conjugate-complex of the wave function.

eigenstate of the operator $\widehat{A}$, λ_k is its eigenvalue, and they satisfy:

$$\widehat{A}\psi_k(\overline{x}) = \lambda_k \psi_k(\overline{x}). \tag{8.5}$$

Under certain conditions, the values λ_k may constitute a countable set, i.e. the values of the property may be quantized. This is another specific feature of QM.

Because of the Superposition Principle, quantum states are not exclusive. Given an eigenstate $\psi_k(\overline{x})$ of certain self-adjoint operator $\widehat{A}(t)$, the propensity p_k of any quantum system in a state $\psi(\overline{x})$ to take the value λ_k is

$$p_k = |\langle\psi|\psi_k\rangle|^2, \tag{8.6}$$

where $0 < p_k < 1$.

Finally, QM has an evolution equation that describes how properties change with time. The equation reads:

$$\frac{d\widehat{A}}{dt} = \frac{i}{\hbar}(\widehat{H}\widehat{A} - \widehat{A}\widehat{H}) + \frac{\partial \widehat{A}}{\partial t}, \tag{8.7}$$

where $\widehat{H}$ denotes a particular operator called Hamiltonian of the system. This equation is called Heisenberg's equation. An alternative, equivalent, formulation of the theory can be obtained adopting time-independent operators to represent the properties and a time-dependent wave function $\psi(x) = \psi(\overline{x}, \ t)$ that obeys the Schrödinger's equation:

$$\widehat{H}|\psi(x)> = \frac{i}{\hbar}\frac{\partial|\psi(x)>}{\partial t}. \tag{8.8}$$

The two pictures only differ by a basis change with respect to time-dependency, which corresponds to the difference between active and passive transformations. The equivalence was proved by Schrödinger (1926) and Eckart (1926), although this has been later questioned (see Muller 1997a,b; see also the interesting paper by de Gosson 2014). By the time of von Neumann book (von Neumann 1955 (1932)) the equivalence was well established.

8.3 Axiomatization of QM

The informal presentation of some basic ideas of QM is not enough to shed light on the controversial issues of the theory. As any theory, QM can be presented as an hypothetical-deductive system. A fully axiomatic formulation of QM has plenty of advantages when compared with other approaches. First, in an axiomatization, all the presuppositions of the theory are explicit. This is very important to clarify the foundations of the theory. Second, in the axiomatic format there is no place for doubts about the arguments of the functions that appear in the statements. In this way, possible erroneous identification of the physical referents can be avoided. Third, the meanings are assigned by semantical axioms, and not by context. This excludes the frequent mistakes originating in an abuse of analogy. Finally, the axiomatic formulation paves the way to the deduction of new theorems and the elimination of pseudo-theorems, because it clarifies the structure of the theory.

The proliferation of interpretations in the case of QM is partially the result of semantical confusions arising from the non-explicit nature of the presuppositions. The standard axiomatization of QM (von Neumann 1955) has semantical contradictions, because it contains predicates that are not related to the primitives that constitute the basis of the theory (Bunge 1967a, 1973). Bunge has carried out a realistic axiomatization of QM, from which it is possible to deduce the standard theorems of the non-relativistic theory (Bunge 1967b). In what follows I present an updated version of Bunge's axiomatics based on Perez-Bergliaffa et al. (1993, 1996). This axiomatics includes several improvements:

1. The theory is formulated in an abstract way, in the sense that it does not depend on any particular representation or picture, and presents the Schrödinger equation, the Heisenberg equation, and the Hamiltonian of a free microsystem as theorems.
2. The use of group theory enhances the role played by symmetries in QM.
3. The mass and the charge are eliminated from the generating basis. Both properties are introduced by means of operators.
4. The spin is brought out directly from the rotational symmetry of the system.
5. The theory of generalized functions developed by Gel'fand and Shilov enables to treat all the operators on an equal footing by the use of the equipped Hilbert space.
6. Bargmann's super-selection rules are presented as theorems.
7. EPR paradox can be solved in this context with no harm to realism.

In the next subsection I describe some tools to be used in the axiomatization. Then, the axiomatization itself is presented: background, definitions, axioms, and theorems. Only after the axiomatic formulation has been made explicit I will discuss the philosophical aspects.

8.3.1 Tools

I give next some mathematical and physical concepts that will be used in the axiomatic core of the theory.

8.3.1.1 The Galilei Group

The proper Galilei group (Bargmann 1954) contains temporal and spatial translations, the pure Galilei transformations, and spatial rotations. A general element of the group has the form

$$g = (\tau,\ \vec{a},\ \vec{v},\ R) \tag{8.9}$$

where τ is a real number, $\vec{a}$ and $\vec{v}$ are arbitrary vectors, and R is an orthogonal transformation. If $\vec{x}$ is a position vector and t is the time, a transformation belonging to the Galilei group is

$$\vec{x'} = R\vec{x} + \vec{v}t + \vec{a}$$
$$t' = t + \tau$$

The multiplication law is given by

$$\begin{aligned} g_1 g_2 &= (\tau_1, \vec{a}_1, \vec{v}_1, R_1)(\tau_2, \vec{a}_2, \vec{v}_2, R_2) \\ &= (\tau_1 + \tau_2, \vec{a}_1 + R_1\vec{a}_2 + \tau_2\vec{v}_1, \vec{v}_1 + R_1\vec{v}_2, R_1R_2) \end{aligned}$$

The unit element of the group is

$$e = (0, 0, 0, 1) \tag{8.10}$$

and the inverse element of g is

$$g^{-1} = (-\tau, -R^{-1}(\vec{a} - \tau\vec{v}), -R^{-1}\vec{v}, R^{-1}) \tag{8.11}$$

Inönu and Wigner (1953) showed that the basis functions of the representations of the Galilei group cannot be interpreted as wave functions of physical microsystems, because it is impossible to construct well-localized states or states with a definite velocity with them. Moreover, Hamermesh (1960) pointed out that the position operator can only be constructed in the case of nontrivial ray representations.

Bargmann (1954) demonstrated that the physical representations of the Galilei group are obtained from the unitary ray representations of the universal covering group of the Galilei group. The exponents of these physical representations have the form

$$\xi(\overline{g_1}, \overline{g_2}) = \frac{1}{2}\{\vec{a}_1 \cdot R_1\vec{v}_2 - \vec{v}_1 \cdot R_1\vec{a}_2 + \tau_2\vec{v}_1 \cdot R_1\vec{v}_2\} \tag{8.12}$$

where $\overline{g_1} = (\tau_1, \vec{a}_1, \vec{v}_1, R_1)$, $\overline{g_2} = (\tau_2, \vec{a}_2, \vec{v}_2, R_2)$ are elements of the universal covering group. To these elements correspond the unitary operators $\hat{U}(\overline{g_1})$ and

$\hat{U}(\overline{g_2})$ such that

$$\hat{U}(\overline{g_1})\hat{U}(\overline{g_2}) = e^{i\xi(\overline{g_1},\overline{g_2})}\hat{U}(\overline{g_1},\overline{g_2}) \tag{8.13}$$

It is possible to construct a local group $\tilde{G}$ in the form

$$\tilde{G} = (\theta, \overline{G}) \tag{8.14}$$

where $\theta \in \mathcal{R}$ and $\overline{G}$ is the universal covering group of the Galilei group G. We say that $\tilde{G}$ is a nontrivial central extension of the universal covering group $\overline{G}$ of the Galilei group G by a one-dimensional Abelian group.

The structure of $\overline{G}$ is locally determined by the structure of its Lie algebra. The commutation relations among the elements of the basis of the algebra can be calculated from the composition laws of G. For the generators of spatial translations ($\hat{P}_i$) and the generators of pure Galilei transformations ($\hat{K}_i$), the commutator is identically zero; if we compute this commutator for the elements of the physical representation (Lèvy-Leblond 1963) we get $[\hat{K}_i, \hat{P}_j] = \hat{M}\delta_{ij}$. We carry out the central extension of $\overline{G}$ imposing this latter relation, in such a way that $\hat{M}$ is the element of the Lie algebra of the one-parameter subgroup used in the extension. This extension is central because $\hat{M}$ commutes with all the other elements of the algebra, and it is nontrivial because $\hat{M}$ appears on the right side of some commutation relations. The physical representations are then the representations of the algebra of the central extension of $\overline{G}$.

In the axiomatic formulation to be presented, the commutation relations of the algebra of $\tilde{G}$ are explicitly postulated, and the generator of the algebra of the one-parameter subgroup is identified with the mass operator $\hat{M}$.

Let us turn now to the equipped Hilbert spaces and Gel'fand's theorem.

8.3.1.2 Equipped Hilbert Spaces

As is well known, not all the physically important operators appearing in QM have eigenfunctions with finite norm. That is the case of the position operator $\hat{X}$ and the linear momentum operator $\hat{P}$. In a consistent axiomatic frame, all the eigenfunctions of operators associated with physical properties should belong to a common space. The Hilbert space $\mathcal{H}$ contains only normed vectors. It is then necessary to introduce an extension: the equipped Hilbert space $\mathcal{H}_e$. This is not really a space, but a triplet, given by

$$\mathcal{H}_e =< \mathcal{S},\ \mathcal{H},\ \mathcal{S}' > \tag{8.15}$$

where $\mathcal{S}$ is a nuclear countable Hilbert space (see Gel'fand and Shilov 1967), i.e. a space of well-behaved functions, $\mathcal{H}$ is the ordinary Hilbert space, and $\mathcal{S}'$ is a space isomorphic to the dual of $\mathcal{S}$ (the distributions, such as Dirac's delta, are in $\mathcal{S}'$). These three spaces satisfy

$$\mathcal{S} \subset \mathcal{H} \subset \mathcal{S}' \tag{8.16}$$

The following theorem, due to Gel'fand and Shilov (1967), that I reproduce without proof, states the necessary conditions to operate on $\mathcal{S}'$ in the usual way:

Theorem *Let $\mathcal{H}_e =< \mathcal{S},\ \mathcal{H},\ \mathcal{S}' >$ be an equipped Hilbert space. If the symmetric and linear operator $\hat{A}$ acting on the space $\mathcal{S}$ admits a self-adjoint extension $\overline{\mathbf{A}}$ on $\mathcal{H}$, then $\overline{\mathbf{A}}$ admits a complete system of eigendistributions $\{e_r\}$ in $\mathcal{S}'$ with real eigenvalues.*

I now define the action of the operators $\hat{X}$ and $\hat{P}$ on $\mathcal{S}$ (in the corresponding representation) in the following way:

$$\hat{X}\phi_r(x) = x\phi_r(x) \tag{8.17}$$

$$\hat{P}\phi_r(p) = p\phi_r(p) \tag{8.18}$$

where $\{\phi_r\}$ is a complete set. The extension of the operators (required by the theorem) can be achieved following Gel'fand and Shilov (1967).

Gel'fand's theorem then enables the use of eigenfunctions of infinite norm within the formal structure of the theory.

Every axiomatic formulation should make explicit its background (i.e. the set of all presuppositions of the theory), its basis of primitive concepts (i.e. the set of non-defined concepts that compose the derived concepts according to the building rules in the background), its axioms, and its conventions.

There are three kinds of axioms in a physical theory: formal axioms, physical (or nomological) axioms, and semantical axioms. The formal axioms are of a purely mathematical type and they refer only to conceptual objects. The physical axioms represent objective physical laws. The semantical axioms establish the relations among symbols, concepts, physical objects and properties of physical objects; in this way they characterize the meaning of the primitives and they set the reference class of the theory.

I next give the background of a formulation of non-relativistic quantum mechanics for one microsystem (T_{QM}).

8.3.2 Formal Background

$\mathbf{P_1}$ Two-valued ordinary logic.
$\mathbf{P_2}$ Formal semantics (Bunge 1974a,b; Chap. 2).
$\mathbf{P_3}$ Mathematical analysis with its presuppositions and generalized functions theory.
$\mathbf{P_4}$ Probability theory.
$\mathbf{P_5}$ Group theory.

8.3.3 Material Background

P_6 Chronology.
P_7 Euclidean physical geometry.
P_8 Physical theory of probability.
P_9 Dimensional analysis.
P_{10} Systems theory.
P_{11} Classical electrodynamics.

8.3.4 Remarks

By chronology I understand the set of theories of time. I adopt here a theory for the local time in which a function is defined such that it maps pairs of events related to a given reference system into a segment of the real line (Bunge 1967a).

The theory of systems deals with physical systems and the relations among them (a physical system is "…anything existing in spacetime and such that it either behaves or is handled as a whole in at least one respect"). This theory has been axiomatized by Bunge (1967a) and its basis of primitive concepts includes the physical sum or juxtaposition ($\dot{+}$), and the physical product or superposition ($\dot{\times}$), see Chap. 3 for additional details.

Finally, the inclusion of classical electrodynamics will allow, by means of the axiom $\mathbf{A}_{42}$, given below, the study a microsystem under the influence of an external classical field. The removal of $\mathbf{P}_{11}$ causes the axioms $\mathbf{A}_{37}$, $\mathbf{A}_{38}$, and $\mathbf{A}_{42}$ to be meaningless.

Let's turn now to the generating basis.

8.3.5 Generating Basis

The conceptual space of the theory is generated by the basis B of primitive concepts, where

$$\mathrm{B}=\{\Sigma,\ \overline{\Sigma},\ \mathrm{E}_3,\ \mathrm{T},\ \mathcal{H}_e,\ \mathcal{P},\ \ \mathrm{A}, \mathrm{G}, \hbar\}$$

The elements of the basis will be semantically interpreted by means of the system of axioms of the theory, with the help of some conventions.[3]

[3]I use an informal notation (with the risk of committing language abuses) instead of exact logical notation that would obscure the physics of the problem. Some unusual symbols and their meaning: $\hat{=}$ ("…represents…"), / ("…such that…"), $\tilde{=}$ ("…isomorphic to…").

8.3.6 *Definitions*

D₁ $eiv\ \hat{A} \stackrel{\text{def}}{=}$ eigenvalue of $\hat{A}$.
D₂ $[\hat{A}, \hat{B}] \stackrel{\text{def}}{=} \hat{A}\hat{B} - \hat{B}\hat{A}$.
D₃ $\Psi \stackrel{\text{def}}{=} \{\alpha|\psi_0> : (\alpha \in \mathcal{C}$, with $|\alpha| = 1) \wedge (|\psi_0> \in \mathcal{H}$ is a fixed vector$)\}$ is a ray in $\mathcal{H}$.
D₄ If $|\psi> \in \Psi \subset \mathcal{H} \Rightarrow |\psi>$ is a representative of Ψ.
D₅ If the spectrum of $\hat{A}$ is continuous $\Rightarrow$
$<\psi|\hat{A}|\phi> \stackrel{\text{def}}{=} \int da\,db\ <\psi|a><a|\hat{A}|b><b|\phi> = \int da\,db\ \psi^*(a)\,A_{ab}\,\phi(b)$.
D₆ If the spectrum of $\hat{A}$ is discrete $\Rightarrow$
$<\psi|\hat{A}|\phi> \stackrel{\text{def}}{=} \sum_{i,j}\ <\psi|a_i><a_i|\hat{A}|b_j><b_j|\phi> = \sum_{i,j}\ \psi_i\ A_{ij}\ \phi_j$.
D₇ $\Psi \cdot \Phi \stackrel{\text{def}}{=} |<\psi|\phi>|$.
D₈ $\mathcal{U} \stackrel{\text{def}}{=} \{\alpha\hat{U}_0\ : (\alpha \in \mathcal{C}$, with $|\alpha| = 1) \wedge (\hat{U}_0$ is a fixed unitary operator on $\mathcal{H})\}$ is a ray operator on $\mathcal{H}$.
D₉ If $\hat{U} \in \mathcal{U} \Rightarrow \hat{U}$ is a representative of $\mathcal{U}$.
D₁₀ If $(|\psi> \in \Psi) \wedge (|\psi'> \in \Psi) \wedge (|\psi'> = e^{i\theta}\,|\psi>) \Rightarrow |\psi'> \stackrel{\text{def}}{=}$ gauge transformed by a gauge transformation of the first kind of $|\psi>$.

8.3.7 *Axiomatic Basis*

T_{QM} is a finite-axiomatizable theory, whose axiomatic basis is:

$$\mathcal{B}_A(T_{QM}) = \bigwedge_{i=1}^{42} \mathbf{A_i}$$

where the index i runs over the axioms. In what follows semantic axioms are indicated by '(SA)'.

8.3.8 *Axioms*

Group I: Space and Time

A₁ $E_3 \equiv$ tridimensional euclidean space.
A₂ $E_3 \hat{=}$ physical space. (SA)
A₃ $T \equiv$ interval of the real line R.
A₄ $T \hat{=}$ time interval. (SA)
A₅ The relation $\leq$ that orders T means "before to" $\vee$ "simultaneous with". (SA)

Group II: Microsystems and States

A₆ $\Sigma, \overline{\Sigma}$: non-empty, denumerable sets.

A₇ $\forall \sigma \in \Sigma, \sigma$ denotes a microsystem. In particular, σ_0 denotes absence of microsystem. (SA)

A₈ $\forall\, \overline{\sigma} \in \overline{\Sigma}$, $\overline{\sigma}$ denotes environment of some system. In particular, $\overline{\sigma}_0$ denotes the empty environment, $<\sigma, \overline{\sigma}_0>$ denotes a free microsystem, and $<\sigma_0, \overline{\sigma}_0>$ denotes the vacuum. (SA)

A₉ $\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma}$, $\exists\, \mathcal{H}_e / \mathcal{H}_e =< \mathcal{S},\ \mathcal{H},\ \mathcal{S}' > \equiv$ equipped Hilbert space.

A₁₀ There exists a one-to-one correspondence between physical states of $\sigma \in \Sigma$ and rays $\Psi \subset \mathcal{H}$. (SA)

Group III: Operators and Physical Quantities

A₁₁ $\mathcal{P} \equiv$ non-empty family of functions on Σ.

A₁₂ $\mathrm{A} \equiv$ ring of operators on $\mathcal{H}_e$.

A₁₃ $\forall\, \mathcal{A} \in \mathcal{P}$, $\mathcal{A}$ designates a property of $\sigma \in \Sigma$. (SA)

A₁₄ $(\forall\, \mathcal{A} \in \mathcal{P})\ (\exists\, \hat{A} \in \mathrm{A} / \hat{A} \hat{=} \mathcal{A})$. (SA)

A₁₅ (Hermiticity and Linearity)
$(\forall\, \sigma \in \Sigma) \wedge (\forall\ t/t = t_0$ with t_0 fixed$) \wedge (\forall \hat{A} \in \mathrm{A} / \hat{A} \hat{=} \mathcal{A},\ \mathcal{A} \in \mathcal{P})$ if $|\psi_1>,\ |\psi_2> \in \mathcal{H}_e \Rightarrow$

1. $\hat{A} : \mathcal{H}_e \rightarrow \mathcal{H}_e / \hat{A}[\lambda_1|\psi_1> + \lambda_2|\psi_2>] = \lambda_1 \hat{A}|\psi_1> + \lambda_2 \hat{A}|\psi_2>$ with $\lambda_1, \lambda_2 \in \mathcal{C}$
2. $\hat{A}^{\dagger} = \hat{A}$ on $\mathcal{H}$.

A₁₆ (Probability Densities)
$(\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma}) \wedge (\forall \hat{A} \in \mathrm{A} / \hat{A} \hat{=} \mathcal{A},\ \mathcal{A} \in \mathcal{P}) \wedge (\forall\, |a> \in \mathcal{H} / \hat{A}|a>= a|a>) \wedge (\forall\, |\psi> \in \Psi \subset \mathcal{H}$ that corresponds to the state of σ when it is influenced by $\overline{\sigma})$:
$<\psi|a><a|\psi> \equiv$ probability density for the property $\mathcal{A}$ when σ is associated to $\overline{\sigma}$
(i.e. $\int_{a_1}^{a_2} <\psi|a><a|\psi>\ da$ is the probability for σ to have an $\mathcal{A}$-value in $[a_1, a_2]$). (SA)

A₁₇ $(\forall \sigma \in \Sigma) \wedge (\forall \overline{\sigma} \in \overline{\Sigma})$ the ray Ψ corresponding to a state of σ is the null ray on the border of the accesible region for the system $\sigma \dot{+} \overline{\sigma}$.

A₁₈ $(\forall \sigma \in \Sigma) \wedge (\forall \hat{A} \in \mathrm{A}) \wedge (\forall a / eiv\ \hat{A} = a)$ a is the sole value that $\mathcal{A}$ takes on σ, given that $\hat{A} \hat{=} \mathcal{A}$. (SA)

A₁₉ $\hbar \in \mathcal{R}^+$.

A₂₀ $[\hbar] = LMT^{-1}$.

Group IV: Symmetries and Group Structure

A$_{21}$ (Unitary Operators)
$(\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma}) \wedge (\forall \hat{A} \in \mathrm{A} / \hat{A} \hat{=} \mathcal{A},\ \mathcal{A} \in \mathcal{P})$ if $\exists\, \hat{U}/\hat{U}^{\dagger} = \hat{U}^{-1} \Rightarrow \hat{A}' = \hat{U}^{\dagger}\hat{A}\hat{U} \hat{=} \mathcal{A}$. (SA)

A$_{22}$ $\forall\ <\sigma, \overline{\sigma}_0> \in \Sigma \times \overline{\Sigma}\ \exists\ \hat{D}(\tilde{G})$, unitary ray representation of some central non-trivial extension of the universal covering group $\bar{G}$ of a Lie group G by a one-dimensional Abelian group on $\mathcal{H}$.

A$_{23}$ The Lie algebra $\mathcal{G}$ of the group G is generated by $\{\hat{H},\ \hat{P}_i,\ \hat{K}_i,\ \hat{J}_i\} \subset A$.

A$_{24}$ (Algebra Structure)
The structure of $\tilde{\mathcal{G}}$, Lie algebra of $\tilde{G}$ is:

$$[\hat{J}_i, \hat{J}_j] = i\hbar\epsilon_{ijk}\hat{J}_k \qquad [\hat{J}_i, \hat{K}_j] = i\hbar\epsilon_{ijk}\hat{K}_k \qquad [\hat{J}_i, \hat{P}_j] = i\hbar\epsilon_{ijk}\hat{P}_k$$
$$[\hat{K}_i, \hat{H}] = i\hbar\hat{P}_i \qquad [\hat{K}_i, \hat{P}_j] = i\hbar\delta_{ij}\hat{M}$$

$$[\hat{J}_i, \hat{H}] = 0\ [\hat{K}_i, \hat{K}_j] = 0\ [\hat{P}_i, \hat{P}_j] = 0\ [\hat{P}_j, \hat{H}] = 0$$

$$[\hat{J}_i, \hat{M}] = 0\ [\hat{K}_i, \hat{M}] = 0\ [\hat{P}_i, \hat{M}] = 0\ [\hat{H}, \hat{M}] = 0$$

where $\hat{M}$ is an element of the Lie algebra of a one-parameter subgroup (which is used to extend $\overline{G}$).

A$_{25}$ G is the Galilei group.

A$_{26}$ $\hat{H}$ is the time-translations generator.

A$_{27}$ $\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma},\ eiv\ \hat{H} = E$ represents the energy value of σ when it is influenced by $\overline{\sigma}$. (SA)

A$_{28}$ $\hat{P}_i$ is the generator of spatial translations on the Cartesian coordinate axis X_i.

A$_{29}$ $\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma},\ eiv\ \hat{P}_i = p_i$ represents the i-component of the linear momentum of σ. (SA)

A$_{30}$ $\hat{J}_i$ is the generator of spatial rotations around the Cartesian coordinate axis X_i.

A$_{31}$ $\forall\ <\sigma, \overline{\sigma}> \in\ \Sigma \times \overline{\Sigma},\ eiv\ \hat{J}_i = j_i$ represents the i-component of the angular momentum of σ. (SA)

A$_{32}$ $\hat{K}_i$ is the generator of pure transformations of Galilei on the axis X_i.

A$_{33}$ $\hat{M}$ has a discrete spectrum of real and positive eigenvalues.

A$_{34}$ $\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma},\ eiv\ \hat{M} = \mu$ represents the mass of σ. (SA)

A$_{35}$ $\forall\ <\sigma, \overline{\sigma}> \in\ \Sigma \times \overline{\Sigma}$, if $\hat{X}_i \overset{\text{def}}{=} \frac{1}{\mu}\hat{K}_i$, then $eiv\ \hat{X}_i = x_i$ represents the i-component of the position of σ. (SA)

Group V: Gauge Transformations and Electric Charge

A$_{36}$ $(\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma})\ \exists\ \hat{Q} \in \mathrm{A} / (\hat{Q} \neq \hat{I}) \wedge ([\hat{Q}, \hat{A}] = 0\ \forall \hat{A} \in \mathrm{A})$.

A$_{37}$ $\hat{Q}$ has a discrete spectrum of real eigenvalues.

A$_{38}$ $\hat{Q}$ is the generator of gauge transformations of the first kind.

A$_{39}$ $\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma},\ eiv\ \hat{Q} = q$ represents the charge of σ. (SA)

A$_{40}$ There exists one and only one normalized state with $eiv\ \hat{Q} = 0$, named the neutral state.

A$_{41}$ There exists one and only one normalizable state, named vacuum, that is invariant under $\hat{D}(\tilde{G})$ and under gauge transformations of the first kind.

A$_{42}$ If $\sigma \in \Sigma$, $eiv\ \hat{M} = \mu \neq 0$, $eiv\ \hat{Q} = e$ and $< A_0, \vec{A} >$ are the components of an electromagnetic quadripotential that represents the action of $\overline{\sigma} \neq \overline{\sigma}_0$ on $\sigma \Rightarrow$

$$\hat{H} = \frac{1}{2\mu}(\hat{\vec{P}} - \frac{e}{c}\vec{A})^2 + \frac{e}{c}A_0 - g_l\frac{\hbar e}{mc}\vec{B}.\hat{\vec{\sigma}}$$

where $\vec{B}$ has the usual meaning that follows from **P**$_{10}$, $\hat{\vec{\sigma}}$ is specified in **T**$_{13}$ and g_l is the gyromagnetic factor of the microsystem.

8.3.9 Remarks

From the axioms, it can be seen that the algebra $\mathcal{S}$ of the symmetry group S of T$_{QM}$ for $< \sigma, \overline{\sigma}_0 > \in \Sigma \times \overline{\Sigma}$ consists of two ideals: an 11-dimensional ideal corresponding to the central extension of the algebra of the universal covering group of the Galilei group by a one-dimensional Lie algebra, and a one-dimensional Abelian ideal corresponding to the U(1) algebra, whose generator is $\hat{Q}$. Stated mathematically, S=$\tilde{G}\otimes$U(1).

In the case of $\sigma \neq \overline{\sigma}_0$, the group of symmetries will depend on the explicit form of $\hat{H}$, and its algebra will be some sub-algebra of $\mathcal{S}$.

The theorems will show that the physics is mainly contained in the commutation relations given in **A**$_{24}$.

8.3.10 Definitions

D$_{11}$ Non-degenerated spectrum of an operator $\hat{A}/\hat{A}|\phi >= a|\phi >$ (with given boundary conditions) where $\hat{A} \in$ A and $|\phi > \in \Phi \subset \mathcal{H} \stackrel{\text{def}}{=} \{a\}/(\forall a \in \{a\}\ \exists\ |\phi > \in \{|\phi >: \hat{A}|\phi >= a|\phi >\}) \wedge (\{a\} \cong \{|\phi >\})$.

D$_{12}$ Component of $|\psi >$ along $|\phi_k > \stackrel{\text{def}}{=} < \phi_k|\psi >= c_k$.

D$_{13}$ $< \hat{A} > \stackrel{\text{def}}{=} < \psi|\hat{A}|\psi >$.

D$_{14}$ $\Delta\hat{A} \stackrel{\text{def}}{=} \hat{A} - < \hat{A} >$.

D$_{15}$ $(\Delta\hat{A})^2 \stackrel{\text{def}}{=} < (\hat{A} - < \hat{A} >)^2 > = < \hat{A}^2 - < \hat{A} >^2 >$.

D$_{16}$ $\|\psi\|^2 \stackrel{\text{def}}{=} < \psi|\ \psi >$.

D$_{17}$ $\hat{S}_i \stackrel{\text{def}}{=} \frac{\hbar}{2}\hat{\sigma}_i$.

D$_{18}$ $\hat{L}_i \stackrel{\text{def}}{=} \epsilon_{ijk}\hat{X}_j\hat{P}_k$.

D$_{19}$ Time evolution operator$\stackrel{\text{def}}{=}$ $\hat{U}(t,t_0)/(\hat{U}(t,t_0)\hat{U}(t,t_0)^\dagger = \hat{I}) \wedge (\hat{U}(t,t')\hat{U}(t',t_0) = \hat{U}(t,t_0)) \wedge (\hat{U}(t_0,t_0) = \hat{I}) \wedge (\hat{A}(t) = \hat{U}(t,t_0)^\dagger\hat{A}(t_0)\hat{U}(t,t_0))$.

8.3.11 Some Theorems

In this section I give some illustrative theorems that can be deduced from the axioms.

T$_1$ (Probability Amplitudes)
The probability that the property $\mathcal{A}$ represented by a non-degenerate operator $\hat{A}$ of the composed system $\sigma\dot{+}\overline{\sigma}$ in the state Ψ takes a value $a_k \in \{a_{k_1}, a_{k_2}\}$ is given by

$$P(a_k) = \sum_{k\in\Delta k} |c_k|^2$$

$$\Delta k = \{k_1, k_2\} \text{ where } c_k = <\phi_k|\psi> \text{ and } |\phi_k> \text{ is an eigenvector of } \hat{A}$$

Proof See Bunge (1967a), p. 252.

T$_2$ Under the same conditions of **T**$_1$, the average of $\hat{A}$ is:

$$<\hat{A}> = \sum_k |c_k|^2 a_k$$

Proof From **P**$_4$ and **T**$_1$.

T$_3$ $(\forall <\sigma,\overline{\sigma}> \in \Sigma \times \overline{\Sigma}) \wedge (\forall \hat{H} \neq \hat{H}(t)/\hat{H}$ is the generator of temporal translations) the time evolution operator is:

$$\hat{U}(t,t_0) = exp\{-\frac{i}{\hbar}\hat{H}(t-t_0)\}$$

Proof Using **A**$_{24}$ and **A**$_{26}$.

T$_4$ (Schrödinger equation)
If $|\psi>_t = \hat{U}(t,t_0)|\psi>_{t_0} \in \Psi$ is a representative of the state of $\sigma \in \Sigma$ when σ is influenced by $\overline{\sigma} \in \overline{\Sigma}$ then $|\psi>_t$ satisfies:

$$\hat{H}|\psi>_t = i\hbar\frac{\partial|\psi>_t}{\partial t}.$$

Proof From $\mathbf{T}_3$.

$\mathbf{T_5}$ $\forall <\sigma, \overline{\sigma}_0> \in \Sigma \times \overline{\Sigma},\ \hat{H} = \frac{\hat{p}^2}{2\mu}$.

Proof From $\mathbf{A}_{24}$.

$\mathbf{T_6}$ $\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma}$ the properties $\mathcal{A}, \mathcal{B} \in \mathcal{P}$ take definite values at the same time if and only if the associated operators $\hat{A}$ and $\hat{B}$ have the same eigenvectors.

Proof Using $\mathbf{D}_{14}$.

$\mathbf{T_7}$ The operators $\hat{A}$ and $\hat{B}$ of $\mathbf{T}_6$ have a common basis of eigenvectors if and only if they commute.

Proof Using $\mathbf{D}_5$.

$\mathbf{T_8}$ (Heisenberg's Inequalities)
$(\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma}) \wedge (\forall\, |\psi> \in \mathcal{H}) \wedge (\forall\, \{\hat{A}, \hat{B}, \hat{C}\} \subset \mathrm{A}\, / \hat{A} \hat{=} \mathcal{A},\ \hat{B} \hat{=} \mathcal{B},\ \hat{C} \hat{=} \mathcal{C}$ with $\{\mathcal{A}, \mathcal{B}, \mathcal{C}\} \subset \mathcal{P})$ if $[\hat{A}, \hat{B}] = i\hat{C} \Rightarrow$

$$(\Delta\hat{A})^2 (\Delta\hat{B})^2 \geq |\hat{C}|^2/4.$$

Proof Using $\mathbf{D}_{12}$, $\mathbf{D}_{14}$, Schwartz's inequality, and the definition $\hat{F} = \hat{A}\hat{B} + \hat{B}\hat{A}$.

Corollary *If* $[\hat{X}_i, \hat{P}_j] = \hbar\, \delta_{ij}\, \hat{I}$ *then*

$$\Delta\hat{X}_i\ \Delta\hat{P}_j \geq \hbar/2.$$

$\mathbf{T_9}$ (Heisenberg's Equation)
$(\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma}) \wedge (\forall \hat{A} \in \mathrm{A}\, / \hat{A} \hat{=} \mathcal{A}, \mathcal{A} \in \mathcal{P})$:

$$\frac{d\hat{A}}{dt} = \frac{i}{\hbar}[\hat{H},\ \hat{A}].$$

Proof From $\mathbf{D}_{18}$ and $\mathbf{T}_3$.

Corollary *if* $[\hat{H}, \hat{A}] = 0 \Rightarrow \hat{A}$ *represents a constant of motion.*

$\mathbf{T_{10}}$ $(\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma}) \wedge (\forall\, |\psi> \in \mathcal{H}) \wedge (\forall \hat{A} \in \mathrm{A}\, / \hat{A} \hat{=} \mathcal{A}$ with $\mathcal{A} \in \mathcal{P}) \wedge (\forall \hat{H} / [\hat{H}, \hat{A}] = i\hat{C})$:

$$\Delta\hat{H}\ \tau_A \geq \frac{\hbar}{2}$$

with $\tau_A = \Delta\hat{A} / |d <\hat{A}> /dt|$.

Proof From $\mathbf{D}_{12}$, $\mathbf{T}_8$ and $\mathbf{T}_9$.

$\mathbf{T_{11}}$ If $\hat{J}_i$ is the spatial rotations generator around the axis $x_i \Rightarrow$

$$[\hat{J}^2,\ \hat{J}_i] = 0.$$

Proof Using $\mathbf{A}_{24}$.

$\mathbf{T}_{12}$ If $|j,\ m>$ is an eigenstate of $\hat{J}^2$ and $\hat{J}_3$ then

$$\hat{J}^2|j,\ m>= \hbar^2 j(j+1)|j,\ m>$$
$$\hat{J}_3|j,\ m>= \hbar m|j,\ m>$$

with $-j \leq m \leq -m,\ j$ half-integer.

Proof From $\mathbf{A}_{24}$ and $\mathbf{T}_{11}$, using $\hat{J}_{\pm} = \hat{J}_1 \pm i\hat{J}_2$.

$\mathbf{T}_{13}$ (Spin)
If $j = 1/2 \Rightarrow \hat{\vec{J}} = (\hat{J}_1,\ \hat{J}_2,\ \hat{J}_3) = \frac{\hbar}{2}\hat{\vec{\sigma}}$, with $\hat{\vec{\sigma}} = (\hat{\sigma}_1,\ \hat{\sigma}_2,\ \hat{\sigma}_3)$, and

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Proof From $\mathbf{D}_5$ and $\mathbf{T}_{12}$, using $\hat{J}_{\pm}$.

$\mathbf{T}_{14}$ $\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma},\ \hat{\vec{J}} = \hat{\vec{L}} + \hat{\vec{S}}$.

Proof From $\mathbf{D}_{17}$, $\mathbf{D}_{18}$ and $\mathbf{A}_{24}$.

$\mathbf{T}_{15}$ (Superselection Rules)
$\forall <\sigma, \overline{\sigma}> \in \Sigma \times \overline{\Sigma}$, $\mathcal{H}$ decomposes in mutually orthogonal subspaces whose vectors are eigenvectors of $\hat{M}$. The same is valid for the charge operator $\hat{Q}$.

Proof From $\mathbf{A}_{24}$ and $\mathbf{A}_{36}$.

8.3.12 Remarks

Theorem $\mathbf{T}_5$ gives the form of $\hat{H}$ for a free microsystem; its expression is deduced from the symmetry group (i.e. the Galilei group). The time-translations generator $\hat{H}$ characterizes the Schrödinger's equation ($\mathbf{T}_4$), which in turn enables us to calculate the vectors corresponding to the physical states of the system. It is clear then that the fundamental physical features of the theory are contained in $\mathbf{A}_{24}$.

The theorem $\mathbf{T}_{10}$ should not be taken as the so-called fourth Heisenberg's inequality: $\Delta E \Delta t \geq \hbar/2$, which is meaningless in this formulation. In fact, being t a parameter and not an operator, this relation is not a logical consequence of $\mathbf{T}_8$. In the expression given in $\mathbf{T}_{10}$ only the characteristic time of the statistical evolution of the operator $\hat{A}$ (i.e. τ_A) appears.

The superselection rule ($\mathbf{T}_{15}$) for the mass operator $\hat{M}$ implies the conservation of the microsystem's mass in the processes that can be described within this axiomatic frame (i.e those non-relativistic processes that reduce to a problem involving a microsystem and its environment). This restriction also holds in Galilean Quantum Field Theories: it forbids certain reactions in which annihilation and creation of particles occur. Note that the superselection rule for the mass is a direct consequence of the imposition of physical representations to the Galilei group. In contrast, the corresponding rule for the charge must be presented in a separated axiom.

8.4 Philosophical Issues

The semantical structure of the theory is determined by the semantical rules expressed in the axioms (SA). This set of axioms fixes the factual interpretation of the mathematical formalism, giving the theory a physical status.

The semantical axioms are of two kinds: denotation/designation rules (like $\mathbf{A}_7$ or $\mathbf{A}_8$) that relate symbols and referents in a conventional way, and representation rules (like $\mathbf{A}_{14}$ or $\mathbf{A}_{21}$) that set correspondences between functions (or other conceptual objects) and properties of referents. These latter rules are not conventional. Moreover, they are hypotheses that can be empirically and theoretically tested. This fact permits the discussion of the foundations of the theory, giving to the variety of hypotheses, a variety of rival interpretations. However, in most of the interpretations the semantical axioms are not clearly identified from the rest of the axioms. This facilitates the propagation of interpretation mistakes.

A semantical axiom that usually appears in the standard formulation of the theory is the so-called von Neumman's projection postulate:

> If the measurement of a physical observable $\mathcal{A}$ (with associated operator $\hat{A}$) on a quantum system in the state $|\psi>$ gives a real value a_n, then, immediately after the measurement, the system evolves from the state $|n>$, where $\hat{A}|n>= a_n|n>$.

This postulate interprets the collapse of the wave function as a consequence of the act of measuring the property $\mathcal{A}$. In our formulation of T_{QM} this postulate plays no role. Moreover, it is in contradiction with the rest of the axiomatic core: neither the observer nor the measuring apparatus are present in the background or the generating basis of QM. As a consequence, none of the legitimate statements in the theory can refer to them. Our formulation is objective, realistic, and literal. The microsystem-apparatus interaction must be studied by the quantum theory of measurement, and there are reasons to think that also in this theory the postulate in question can be eliminated and replaced by a non-linear evolution of the system.

If T_{QM} does not say anything about observers and measurements, what is the kind of entities whose existence is presupposed by it? To ask this is to ask for the ontology of the theory. I understand, in what follows, the ontology in the following restricted sense: the ontology of the theory is the factual restriction of the set formed by the union of the domains of all the variables related to logical quantifiers that appear in the axiomatic basis of the theory (by factual restriction I understand a restriction of the domain to the subset formed by all the non-conceptual elements). This is in accordance with what we saw in Chaps. 3 and 7. In the axioms, we quantify on the elements of the generating basis or on conceptual objects generated by it. All the non-conceptual objects of $\mathcal{B}_A$ belong to $\Sigma \bigcup \overline{\Sigma}$.[4] That is why we identify this set with the ontology of T_{QM}. In our restricted sense, the ontology coincides with the reference class of the theory:

$$R_F(T_{QM}) = \bigcup_{i=1}^{42} R_F(\mathbf{A}_i) = \Sigma \cup \overline{\Sigma}.$$

T_{QM} refers then only to microsystems and their physical environments.

8.5 Extension to Systems of Many Components

The axiomatic system presented in Sect. 8.3 can be easily modified to accommodate systems with arbitrary number of components. Let us adopt the following definitions:

D₂₀ $\Sigma_N = \Sigma_1 \times \Sigma_1 \times \ldots \times \Sigma_1$ (N times) is the set of all systems composed by elements of Σ_1.

D₂₁ $\Sigma^* = \{\Sigma_2, \Sigma_3, \ldots, \Sigma_N, \ldots\}$.

Then, let us introduce the following additional axioms (see Perez-Bergliaffa et al. 1996):

$\mathbf{A'_1}$ $\Sigma_1, \overline{\Sigma}$: nonempty numerable sets.

$\mathbf{A'_2}$ $(\forall \sigma)_{\Sigma_1}$ (σ denotes simple microsystem).

$\mathbf{A'_3}$ $(\forall\, \sigma)_{\Sigma = \Sigma_1 \cup \Sigma^*}$ (σ denotes a q-system).

$\mathbf{A'_4}$ $(\forall\, \overline{\sigma})_{\overline{\Sigma}}$ ($\overline{\sigma}$ denotes environment of some q-system).[5]

$\mathbf{A'_5}$ (Product Hilbert Space)
$(\forall < \sigma, \overline{\sigma} >)_{\Sigma \times \overline{\Sigma}} (\mathcal{C}(\sigma) = \{\sigma_1, \ldots, \sigma_n\} \Rightarrow \mathcal{H}_e = \bigotimes_{i=1}^{n} \mathcal{H}_{ei})$.

$\mathbf{A'_6}$ $(\forall\ < \sigma, \overline{\sigma} >)_{\Sigma \times \overline{\Sigma}}\ (\forall |\Psi >)_{\mathcal{H}_e} (\exists U_\Pi)(U_\Pi$ is a representation of a symmetric group Π by unitary operators $\hat{U}_\Pi\ \wedge$

$$\hat{U}_\Pi |\Psi> = \hat{U}_\Pi \{|\psi_1^a> \otimes |\psi_2^b> \otimes \ldots \otimes |\psi_n^l>\}$$
$$= |\psi_{\alpha_1}^a> \otimes \ldots \otimes |\psi_{\alpha_n}^l>$$

where $\{\alpha_1, \ldots \alpha_n\}$ is a permutation P of $\{1, \ldots n\}$).

[4] For the sake of simplicity I am ignoring here space and time. I will discuss in detail the ontological status of space and time, and spacetime, in the next chapter.

[5] In particular, $\overline{\sigma}_0$ denotes the empty environment, $< \sigma, \overline{\sigma}_0 >$ denotes a free q-system, and $< \sigma_0, \overline{\sigma}_0 >$ denotes the vacuum.

A′7 $(\forall <\sigma,\overline{\sigma}>)_{\Sigma\times\overline{\Sigma}}\,(\forall\hat{A})_A\,(\forall|\Psi>)_{\mathcal{H}_e}\,(\mathcal{C}(\sigma)=\{\sigma_1,\dots\sigma_n\}\wedge\sigma_i\overset{id}{\leftrightarrow}\sigma_j\wedge\ |\Psi>=\hat{U}_\Pi|\Psi'>\Rightarrow<\Psi|\hat{A}|\Psi>=<\Psi'|\hat{A}|\Psi'>)$.

Then, in addition to the previous theorems, we get the following ones:

T′1 (Additivity Theorem)

$$(\forall <\sigma,\overline{\sigma}>)_{\Sigma\times\overline{\Sigma}}\,(\forall k)_K\,(\mathcal{C}(\sigma)=\{\sigma_1,\dots,\sigma_n\}\wedge$$
$$[\hat{P}_i,\hat{X}_{jr}]=i\hbar\delta_{ij},[\hat{J}_i,\hat{X}_{jr}]=i\hbar\epsilon_{ijk}\hat{X}_{kr}$$
$$[\hat{P}_i,\hat{P}_{jr}]=0,[\hat{J}_i,\hat{P}_{jr}]=i\hbar\epsilon_{ijk}\hat{P}_{kr}$$
$$[\hat{K}_i,\hat{X}_{jr}]=0,[\hat{K}_i,\hat{P}_{jr}]=i\hbar\delta_{ij}m_r$$
$$(i,j=1,2,3;r=1,2,\dots,n)$$
$$\Rightarrow\hat{P}_i=\sum_{s=1}^n\hat{P}_{is}\wedge\hat{J}_i=\sum_{s=1}^n\hat{J}_{is}\wedge\hat{K}_i=\sum_{s=1}^n\hat{K}_{is}\wedge\hat{M}=\sum_{s=1}^n\hat{M}_s).$$

T′2 $\mathcal{H}_S\oplus\mathcal{H}_A\subset\mathcal{H}_e$ is a vector subspace of $\mathcal{H}_e$.

Corollary (Pauli's Exclusion Theorem) $(\forall <\sigma,\overline{\sigma}>)_{\Sigma\times\overline{\Sigma}}\,(\mathcal{C}(\sigma)=\{\sigma_1,\dots\sigma_n\}\wedge\sigma_i\overset{id}{\leftrightarrow}\sigma_j\Rightarrow|\Psi(\sigma)>\in\mathcal{H}_{\mathcal{PS}})$

T′3 $(\forall <\sigma,\overline{\sigma}_0>)_{\Sigma\times\overline{\Sigma}}\,(\mathcal{C}(\sigma)=\{\sigma_1\dots\sigma_n\}\Rightarrow$

$$\hat{H}=\frac{1}{2}\sum_{i=1}^n\frac{\hat{p}_i^2}{m_i}+\sum_{i<j}[V(r_{ij})+V(\vec{\hat{s}}_i,\vec{\hat{s}}_j)],$$

with

$$V(\vec{\hat{s}}_i,\vec{\hat{s}}_j)=V_1(r_{ij})+V_2(r_{ij})(\vec{\hat{s}}_i.\vec{\hat{s}}_j)+V_3(r_{ij})[3(\vec{\hat{s}}_i.\vec{n}_{ij})(\vec{\hat{s}}_j.\vec{n}_{ij})-\vec{\hat{s}}_i.\vec{\hat{s}}_j],$$

where

$$r_{ij}\overset{\text{def}}{=}|\vec{x}_i-\vec{x}_j|\qquad\vec{s}_i=\frac{\hbar}{2}\vec{\tau}_i\qquad\vec{n}_{ij}\overset{Df}{=}\frac{\vec{r}_{ij}}{r_{ij}}$$

and $\vec{\tau}_i$ are the Pauli matrices).

For proofs, see Perez-Bergliaffa et al. (1996).

Remark 1 The first (second) group of commutation relations in $\mathbf{T}_1$ means that the behaviour of each simple microsystem under a Euclidean motion (instantaneous Galilean transformations) is unaffected by the presence of interactions.

Remark 2 If $\sigma\in\Sigma$ such that $C(\sigma)=\{\sigma_1,\dots\sigma_n\}$, and σ_i interacts weakly with σ_j $\Rightarrow\hat{H}_\sigma=\sum_i\hat{H}_{\sigma_i}+O(\lambda)$, where λ is some coupling constant.

8.6 EPR and Realism

Let $\sigma \in \Sigma$ such that $\mathcal{C}(\sigma) = \{\sigma_1, \sigma_2\} \Rightarrow \hat{P} = \hat{P}_1 + \hat{P}_2$ by $\mathbf{T}_1$. It follows from $\mathbf{A_{28}}$ that $[\hat{X}_1 - \hat{X}_2, \hat{P}] = 0$, and then, from Theorem 8 of Perez-Bergliaffa et al. (1993), the quantities associated with the operators $\hat{X}_1 - \hat{X}_2$ and $\hat{P}$ are simultaneously well-defined and can be measured with as much precision as the state-of-the-art allows.

Let's suppose now that the components σ_1 and σ_2 are far away from each other in such a way that, for the purpose of experiment, they can be considered as isolated. Solving Schrödinger's equation ($\mathbf{T}_4$ of Perez-Bergliaffa et al. 1993) in the center of mass system of σ for a null potential, we find (in the coordinate representation)

$$\Psi(x_1, x_2) = \delta(x - a)e^{ip(x_1+x_2)/2\hbar}, \tag{8.19}$$

where a is the relative separation between σ_1 and σ_2. If we now measure the position of σ_1 we can infer (from the relation $x_1 - x_2 = a$) which value would be found if we measure the position of σ_2 immediately after the first measure has been carried out. Assuming that there is no action-at-distance in a quantum sense (i.e. that two subsystems apart enough from each other can be considered as isolated, an assumption known as locality or separability), the inference of x_2 is made without perturbing σ_2 in any way. It follows then that the position of σ_2 has a definite predetermined value not included in (4). This implies that the description given by QM is incomplete. By the same reasoning, it can be inferred that the lineal momentum of σ_2 has also a definite value, at variance with Heisenberg's inequalities. Then both the position and the lineal momentum of σ_2 have a definite predetermined value: we do not have to work out any additional measure to know them. This clearly contradicts the subjectivistic interpretation of Copenhagen.

The argument given above is a brief account of the so-called "EPR paradox" (Einstein et al. 1935). In short, it states that if locality is accepted in QM then the theory must be incomplete. In other words, the theory must have hidden variables (Bohm 1953). Besides, a theorem due to Bell (1966) shows that the predictions of deterministic, local theories that have hidden variables can be compared, by means of a given class of experiments, with the predictions of QM. Experiments of such a class have been carried out by Aspect et al. (1981, 1982), and their results are in complete agreement with QM.

These results do not affect the realistic philosophy that underlies the present axiomatization. In fact, as it was shown by Clauser and Shimony (1978),

$$\text{(Hidden Variables} \wedge \text{Separability)} \Rightarrow \text{(Bell's inequalities)}$$

It follows that if Bell's inequalities are refuted by recourse to the experiment, then (1) theories with hidden variables are false (i.e. QM is complete) or (2) the theory is non-local or (3) both (1) and (2) are true. The axiomatization I present here assumes non-locality and completeness, so it *predicts* that Bell's inequalities are false. The non-locality originates in the systemic point of view adopted in the background material, while completeness is introduced through the axioms that states that every property of the physical system under study has its mathematical counterpart uniquely defined in the theory.

8.7 Entanglement

Quantum mechanics embraces a kind of action at a distance with a property called entanglement, in which two particles behave synchronously with no intermediary; it is a nonlocal property. For instance, calcium vapor exposed to lasers fluoresces. Excited atoms cascade down to their ground states and they give off light. Each atom emits a pair of photons which travel off in opposite directions. The polarization of these photons shows no preferred direction since the source is unpolarized. The pairs, however, display a striking correlation: each member of the pair always acts as if it has the opposite polarization as its partner. This quantum connection has different properties:

- The quantum connection is unattenuated by distance.
- The quantum connection is discriminating: only particles which have interacted in the past are affected by it. No classical force exhibits this behavior.
- The quantum connection is faster than light, and likely instantaneous. This seems to be incompatible with relativistic spacetime structure.

Everybody knows that Relativity theory forbids something. Not everyone agrees, however, about what is forbidden. There are different possibilities discussed in the literature, as reviewed by Maudlin (1994):

1. Relativity forbids matter to be transported faster than light.
2. Relativity forbids signals to be sent faster than light.
3. Relativity forbids information to be transmitted faster than light.
4. Relativity forbids causal processes to propagate faster than light.

Actually, Relativity just states that subluminal systems cannot become superluminal and viceversa. Hypothetical superluminal tachyons do not violate Relativity's laws. Tachyon theory shows that Relativity *is not* restricted to systems with subluminal speed in order to be consistent. On other hand, violation of Bell's inequalities does not require superluminal matter transport or signalling. Much less of information. Information is a property of languages, not of physical systems, as we have seen in Chap. 3. Contrary to what Maudlin (1994) states, superluminal transmission of information is not required by quantum entanglement. Information has not, and cannot, have any effect upon physical systems.

Aversely to all these views, I have suggested that violation of Bell's inequalities is possible if causation can be non-local.[6] If causation is non-local under some

[6] Non-Local causation is discussed, for instance, by Romero and Pérez (2012).

circumstances, e.g. when a quantum system is prepared in a specific state of polarization or spin, quantum entanglement poses no problem to realism and determinism. Quantum theory describes an aspect of a reality that is ontologically determined and with non-local relations. Under no circumstances the postulates of Special Relativity are violated, since no physical system ever crosses the barrier of the speed of light.

An important caveat is in order here. Causality is relation among events, not among thins. A causal action of a thing A upon a thing X is just an event in thing A that triggers an event in thing B. Hence, causality implies a change of the state of a particular entity. This seems not to be the case of quantum entanglement: when we determined the state of one of the components of the entangled systems, there is no change in the state of the other component. The state of this component does not go, say, from state s_1 to s_2. There is simply a *specification* of the state of the system: of the different states in which the system might be, it always occurs that the state is that corresponding to the initial preparation of the system. Since there is no work on the second, no energy transfer occurs (the energy of the component is exactly the same before and after the specification of its state). The type of causation involved, if any, is not the familiar kind we know from classical physics.

An alternative, also possible view is to hold that there is actually no causal connection between components at all; there are just non-local correlations: once an entangled state has been formed, the system remains intertwined regardless of the spatial separation of the components. Does this contradict common sense? Yes, it does. But certainly it is not the only thing that contradicts our common sense in the quantum world. Quantum theory deals with a realm that is alien to our ordinary experience; common sense has been shaped by our interactions with a different, macroscopic, world, which we call "classic". When we specify the status of the first photon of an entangled unpolarized pair, the state of the second photon is specified as well according to the initial preparation of system (the second photon will be found in a polarization state such that the total polarization of the pair will be zero). Once an interaction has destroyed the interlacing, the components are separated and there are no more correlations. In this view, there is no action of one component of the system upon the other, just non-local correlation. Once the system is formed, some properties remain until some interaction destroys the entanglement (Bunge 2010; López and Romero 2017).

If you want to use entanglement to transmit information faster than light you will fail: there is no way that at the moment the first polarization is measured, the state of the polarization of the first photon is known at the second polarimeter. Such information can only be transmitted at the speed of light, as always. There is also no instantaneous "work" on the second photon made by the first photon. As I mentioned above, there is no change of state of the latter, but rather a *specification* of its state in the second determination. If there is work on the second photon, it is done by the second detector, locally, and not by the first photon.

These considerations invites us to accept the real world as it is: non-local, legal (the laws of quantum mechanics hold), and independent of cognitive subjects: it does not matter whether the second photon is recorded by an instrument or interacts naturally in the absence of any observer. All these processes were occurring naturally in stars long before human beings appear on the earth, and will continue to occur long after each one of us has disappeared.

Summing Up Quantum mechanics refers to quantum systems and their environment. The theory does not include consciousness, human subjects, or detectors. The interaction of quantum systems with detectors is the subject of a different theory: quantum theory of measurement. Quantum systems have properties that are not classical. Sometimes they behave in a similar way to classical systems such as particles or waves, but they are neither of them. Other properties, such as spin, lepton number, or color, have no classical analogous. Entanglement is a property of quantum systems that are prepared in a certain state; this property holds as far as the system does not interact with other systems exchanging energy. Quantum mechanics is a realistic, non-local, deterministic, and probabilistic theory of microphysical objects. Its dynamical equations are lineal, and hence the state functions of quantum objects obey the Principle of Superposition. This results in a phenomenology that sometimes strongly differs from what we know from classical physics and common sense.

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Chapter 9
Quantum Objects

9.1 Introduction

It has been argued that non-relativistic quantum mechanics for systems of many components raises profound challenges to any metaphysics that seeks to explain the world in terms of self-subsistent individuals (e.g. Ladyman and Ross 2007). It is claimed that quantum particles are not individuals since the usual identity criteria used in ontology seem to fail when applied to them. The standard criterion adopted by philosophers on this matter is Leibniz's Principle of Identity of Indiscernibles (PII). This principle asserts the identity of two objects if they have exactly the same properties. Two objects identical in every respect are not two different individuals (see French and Krause 2006 for refinements. Also, see Teller 1983, French and Redhead 1988, and Saunders 2003). Identical particles in classical mechanics, for instance, share the same intrinsic properties but can be distinguished by their trajectories in spacetime. Something similar occurs in everyday life: in a race of several intrinsically identical cars we can still individuate them if we can keep track of their trajectories. So, PII allows us to claim that there are different cars in the race.

In the quantum world things seem to be different. It is not possible in general to assign well-defined trajectories in spacetime to quantum objects. Two photons or two electrons in an entangled state cannot be individuated by singular spacetime features: their location probability densities are the same. If the photons were prepared in a particular state of polarization, this state is characteristic of the pair, not of the components. These considerations also hold if the quantum particles are in a bound state. If we have two electrons, for instance in an helium atom, they have exactly the same position distribution of probabilities. They also share the same energy eigenstate. Not only all intrinsic properties are identical but also all relational properties seem to be indistinguishable. The entangled state function is completely symmetric with respect to both particles, so not even the different spin orientations are useful to individuate the electrons. It seems completely impossible to distinguish

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the two electrons according to any version of the PII. Should we conclude that they are not individuals?

9.2 Identity and the Quantum World

Let us try to characterize the quantum indiscernibility more formally. Quantum particles are usual called 'identical' if they share in common all their constant properties, such as mass, charge, spin and so on: that is, if they agree in all their state-independent or intrinsic properties. The same applies to classical particles. In addition, quantum particles are indistinguishable if they satisfy the so-called indistinguishability postulate (IP).
(IP): All properties represented by operators $\hat{O}$ must commute with all particle permutations $\hat{P}$:

$$[\hat{O}, \hat{P}] = 0.$$

The IP expresses the requirement that no expectation value of any property is affected by particle permutations. So, if Ψ_{12} is a two-particle state and $\hat{P}$ an operator that interchanges the particles 1 and 2, such that $\hat{P}\Psi_{12} = \Psi_{21}$, then the particles are indistinguishable if

$$\langle \hat{P}\Psi_{12}|\hat{O}|\hat{P}\Psi_{12}\rangle = \langle \Psi_{12}|\hat{O}|\Psi_{12}\rangle, \quad \forall \hat{O}, \forall \Psi_{12}.$$

Bosons are then clearly indistinguishable and entangled fermions are as well. Does this entail that they are not individuals? Not necessarily. One can, for instance, adopt a non-standard version of the theory such as Bohm interpretation,[1] where trajectories in spacetime are ascribed to all particles allowing for discernibility and individuation. The price to be paid, in such a case, is the burden of the extra assumptions of Bohm's theory and a more complex formalism, but so far this move is neither hampered by logic nor experience.

One also can resist the conclusion of the PII. Perhaps indiscernibility does not imply identity and lost of individuality. After all, even if the particles are indistinguishable, the number of them is not in question. Might cardinality amount to individuality in the quantum realm? Actually, in some occasions, even in ordinary life, we deal with situations where we adopt cardinality as a criterion for individuality. Imagine that I have a sum of money, say \$ 300. I go to the bank and deposit my bills. Surely, I still have exactly the same amount of money when I check my electronic account, but there is no point in trying to identify some number in my

[1] It would be more correct to consider Bohm's approach to quantum physics as a different theory from QM because additional dynamical variables are considered and new entities introduced, namely the famous pilot wave.

computer with the original bills. I can convert my money into cash if I want. If I do that, the amount will still be the same amount that I deposited. But the individual bills will differ. So, I might say that the continuity in cardinality has preserved the identity of my amount of money, although not that of the individual bills. Perhaps it is possible to say something similar of the system of entangled quantum particles: the system, as a whole, is preserved as an individual, although not the specific components.

Another famous example is Max Black's two-sphere problem (Black 1952): two intrinsically indistinguishable spheres in a fully symmetrical universe are indiscernible. Should we conclude that there is just one sphere? No, there are two spheres in that universe, but they are indistinguishable. Muller and Seevinck (2009) observe: "Similar elementary particles are like points on a line, in a plane, or in Euclidean space: absolutely indiscernible yet not identical (there is more than one of them!). Points on a line are categorical relationals, categorical weak discernibles to be precise. Elementary particles are exactly like points in this regard."

Whether quantum particles are individuals or not depends on what we understand by an 'individual', and as these examples show, the PII is not the only criterion that we can follow in this respect. Quine (1976), for instance, suggests the following criteria:

> A sentence in one variable specifies an object if satisfied by it uniquely. A sentence in one variable strongly discriminates two objects if satisfied by one and not the other. A sentence in two variables moderately discriminates two objects if satisfied by them in one order only. A sentence in two variables weakly discriminates two objects if satisfied by the two but not by one of them with itself.

Based on these ideas, Muller and Saunders (2008) define absolute discernibility in a given language L as follows:

1. Two objects a and b are absolutely discernible in L iff there is a monadic predicate M in L such that $Ma \wedge Mb$ or $\neg Ma \wedge Mb$.
   Additional notions of relative and weak discernibility are given by:
2. Two objects a and b are relatively discernible iff there is an open formula F in two variables in L such that $F(a, b) \wedge \neg F(b, a)$.
3. Two objects a and b are weakly discernible iff there is an open formula F in two variables in L such that $F(a, b) \wedge \neg F(b, b)$.

Let us consider now the following open formula: ' ...has opposite spin in direction z to...' (Saunders 2006). Electrons in the helium atom are weakly discernible in the above sense: we can say that they have not the same spin state, although we cannot say which state corresponds to each of them. This type of weak discernibility is enough for individuation in non-relativistic quantum mechanics (Perez-Bergliaffa et al. 1996), but things go worst if we move to quantum field theory. Quantum field theory (QFT) is the ultimate expression of quantum mechanics so it is important to understand the ontological status of particles in this theory if we want to clarify whether quantum particles are individuals or not.

What we call 'particles' in quantum mechanics are seen merely as excitations of a quantum field in QFT. These excitations or 'quanta' can be aggregated and counted but not enumerated in the sense of labeled. The world, in this view, is a collection of quantum fields existing in spacetime. The vacuum state $|0\rangle$ of these fields can be excited to form a Fock basis of the quantized field:

$$|1_k\rangle = a_k^\dagger|0\rangle. \tag{9.1}$$

Each application of the operator $a_k^\dagger$ adds a quantum excitation to the state k. Successive applications of the operator $a_k^\dagger$ yield:

$$a_k^\dagger|n_k\rangle = (n+1)^{1/2}|(n+1)_k\rangle. \tag{9.2}$$

Similarly, the operator a_k removes quanta:

$$a_k|n_k\rangle = n^{1/2}|(n-1)_k\rangle. \tag{9.3}$$

In Minkowski space, a preferred basis can be constructed using the specific symmetries of this space (the Poincaré group). Then, if $N_k = a_k^\dagger a_k$ is the operator number of particles, we get

$$\langle 0|N_k|0\rangle = 0, \qquad \text{for all } k. \tag{9.4}$$

This means that the expectation value for all quantum modes of the vacuum is zero: if there are no particles associated with the vacuum state in one reference system, then the same is valid in all of them. In curve spacetime this is not valid any longer: general spaces do not share the Minkowski symmetries, and hence the number of particles is not a relativistic invariant. Since in general spacetimes there are different complete sets of modes for the decomposition of the field, a new vacuum state can be defined:

$$\bar{a}_j|\bar{0}\rangle = |0\rangle, \quad \forall j, \tag{9.5}$$

and from here a new Fock space can be constructed. The field $\phi(x)$ can be expanded in any of the two basis[2]:

$$\phi(x) = \sum_i [a_i u_i(x) + a_i^\dagger u_i^*(x)], \tag{9.6}$$

[2]For simplicity I consider a scalar field.

and

$$\phi(x) = \sum_j [\bar{a}_j \bar{u}_j(x) + \bar{a}_j^\dagger \bar{u}_j^*(x)]. \tag{9.7}$$

Since both expansions are complete, we can express the modes $\bar{u}_j$ in terms of the modes u_i:

$$\bar{u}_j = \sum_i (\alpha_{ji} u_i + \beta_{ji} u_i^*), \tag{9.8}$$

and conversely,

$$u_i = \sum_j (\alpha_{ji}^+ \bar{u}_j - \beta_{ji} \bar{u}_i^*). \tag{9.9}$$

The coefficients α_{ij} and β_{ij} satisfy the relations

$$\sum_k (\alpha_{ik} \alpha^* jk - \beta_{ik} \beta_{jk}^*) = \delta_{ij}, \tag{9.10}$$

$$\sum_k (\alpha_{ik} \beta_{jk} - \beta_{ik} \alpha_{jk}) = 0. \tag{9.11}$$

The operators on the Fock space then can be represented by:

$$a_i = \sum_j (\alpha_{ji} \bar{a}_j + \beta_{ji}^* \bar{a}_j^\dagger), \tag{9.12}$$

and

$$\bar{a}_i = \sum_i (\alpha_{ji}^* a_i - \beta_{ji}^* \bar{a}_i^\dagger). \tag{9.13}$$

An immediate consequence is that

$$a_i |\bar{0}\rangle = \sum_j \beta_{ji}^* |\bar{1}_j\rangle. \tag{9.14}$$

Since in general $\beta_{ij} \neq 0$ the expectation value of the operator $N_i = a_i^\dagger a_i$ that determines the number of quanta is:

$$\langle \bar{0} | N_i | \bar{0} \rangle = \sum_j |\beta_{ij}|^2 \neq 0. \tag{9.15}$$

This surprising result means that the number of quanta of the field (particles) is different for different decompositions. Since different decompositions correspond to different choices of reference frames, we must conclude that different observers detect a different number of quanta (particles). These particles activate detectors in some reference systems, but not in others. They are essentially a frame-dependent feature of the field. If we accept the extended idea that whatever exists objectively cannot depend on our choice of a particular reference system, then the assumption that particles are self-subsistent individuals falls apart.

9.3 Ontic Vagueness?

In Chap. 2 we characterized vagueness as a kind of semantical indeterminacy. Some authors have seen in the peculiarities of quantum objects an indication of ontic vagueness. Lowe (1994), for instance, proposes to consider electrons as vague individuals. He points out that if an electron a is captured by an atom in an ionizing chamber in such a way that the atom becomes a negative ion and then it reverts to its previous state by emitting an electron b, there is no objective fact of matter as to whether or not a is the same electron as b. Lowe points out that the impossibility to identify whether $a = b$ is not an epistemic issue but a direct result of the basic laws of quantum mechanics. According to QM the electrons in the atom enter into a entangled state in which although their number is determinate, their identity is not. Therefore, there is no fact about whether the emitted electron is the same electron that was captured: it lost its identity when entered into a quantum superposition with the other electrons. The indeterminacy of $a = b$, Lowe thinks, amounts to a case of ontic vagueness.

There is a well-known argument against the existence of vague objects by Gareth Evans (1978). The argument goes like this: Let us assume for the sake of reductio, that it is indeterminate whether $a = b$, where 'a' and 'b' are precise designators, in a semantical sense. Then b definitely has the property that it is indeterminate whether it is identical with a, but a definitely lacks this property (since $a = a$ is surely not indeterminate), hence it is false that $a = b$, contrary to the assumption that it is indeterminate. The upshot is that if '$a = b$' is indeed indeterminate in truth value, then either 'a' or 'b' or both must be an imprecise designator. Hence, this would be a case of semantic vagueness, not ontic.

Lowe response is that an essential step in the argument is the move from the determinacy of the self-identity of a, say, to the claim that a definitely lacks the property that it is indeterminate whether it is identical with a (which is possessed by b). However, the latter property cannot be determinately distinct from the property of being indeterminate whether the object is identical with b, since the two properties differ only by a permutation of a and b and it is indeterminate whether $a = b$ by assumption. Hence the possession by either a or b of an identity involving property such as these cannot serve to determinately differentiate the two.

French and Krause (2003) argue that there is another kind of vagueness involved, which is associated with the lack of individuality of the particles (something that is not disputed by Lowe). They argue that because in quantum statistical mechanics, arrangements of particles over states which result from permutations of the particles cannot be counted as distinct, contrary to the case of classical statistical mechanics. As a consequence, quantum particles themselves cannot be considered as distinct and they lack of individuality in this sense. The result, they claim, is in accordance with the Fock representation of QFT, where the particles are not labeled. There is an assignment, nevertheless, of definite cardinality to the quantum state of the field, where the number of quantum excitations or 'quanta' corresponds to the number of non-individual 'particles'. Hence, they state that "we can have a determinate number of quantum objects in a given state without these objects possessing definite identity conditions [...] it is because of this lack of self-identity that the objects can be described as vague, in perhaps the most fundamental sense one can imagine."

Although I think that French and Krause are right in their analysis of the lack of individuality of the quanta in QFT, I do not agree with the commitment with ontic vagueness. What QFT clearly shows, as I explained in the previous section, is that what we consider in QM as 'particles' are actually excitations of the field in some specific reference frame. These excitations are then not "objects" as claimed by French and Krause, but relational properties of the field. And they are not vague at all, because the theory is completely clear about how to assign such properties to the field. The fact that the property in question, the number of discrete excitations of the field, is not a relativistic invariant is not enough to state that there is ontic vagueness. We have plenty of relational properties in our physical theories. If we reify them, making a category mistake, we might conclude that velocities are "non-individual objects". According to the best available theory, i.e. QFT, quantum particles are not objects at all, but just a feature of a different entity, the quantum field. The reason why Evans argument fails when applied to quantum particles is that such particles are not entities or objects that exist independently of a specific choice of a reference frame. The clause " '*a*' and '*b*' are precise designators" is false, then the argument cannot proceed. We do not live in a world of particles, we live in a world of fields, where particles appear as modes of excitations in the fields. It might be strange and counter-intuitive to understand particles as properties and not objects, but this should not hinder us if it is implied by well-established physics. Vagueness on these issues still belongs to our thought about the world, and not to the world itself.

9.4 Realistic Quantum Ontology

If particles are not the basic ontological referents of modern physical theories, what should be considered by a scientifically informed realist as the best ontology? Ladyman and Ross (2007) think that if we cannot adopt particles because they are not individuals, then the next step is to move towards structures. According to them a metaphysics of self-subsistent individuals is at odds with physics and should be abandoned in favor of a metaphysics of structures. In this view, what we call individuals are just nodes in the structure and completely dependent on it. This is ontic structuralism, a popular view at the time of writing these lines.

I confess that these arguments are not convincing to me. They seem to be the result of a too strong commitment with standard QM. In QFT particles are not dealt as individuals but as features of the quantum fields and relative to some specific choice of mode decomposition of the field that is frame dependent. Matters of existence should not be solved just counting or individuating with respect to some reference system, but considering true invariant properties and their referents. In this sense it is the energy-momentum complex and its mathematical representation through a second-rank tensor field that provides an objective indicator of independent existence. Contrary to the excitations of the field, that depend on global modes defined over the whole spacetime, the energy-momentum of the field is defined locally through a tensor quantity. For a fixed state $|\psi\rangle$ the results of different detectors when measuring the expectation value $\langle\psi|T_{\mu\nu}|\psi\rangle$ can be related by the usual transformation laws of tensors. In particular, if $\langle\psi|T_{\mu\nu}|\psi\rangle = 0$ in one reference system, the energy density of the quantum field will be zero for any reference. This situation is quite different for particles, that might be detectable or not in the same region of space by different observers in different states. This clearly points out that the ontological import is in the quantum field, not in the particles. And it is not neither in the structure, since the structure emerges from the relations of the fields.

It might be objected that in the case of Minkowski spacetime all fields are in the vacuum state and then $\langle 0_{\mathrm{M}}|T_{\mu\nu}|0_{\mathrm{M}}\rangle = 0$. But an accelerated observer in this spacetime actually should detect thermal radiation (Davies 1975, Unruh 1976). In the accelerated frame it is also valid $\langle 0_{\mathrm{M}}|T^{acc}_{\mu\nu}|0_{\mathrm{M}}\rangle = 0$, so the thermal radiation seems to violate energy conservation. But this is a wrong conclusion originated by considering only a part of the system. The whole system is the accelerated detector plus the field in the vacuum state. The field couples with the accelerated system producing a resistance against the accelerating force. It is the work of the external force that produces the thermal bath measured by the detector in the co-mobil system. The same radiation is not measured by a detector at rest, since it is not coupled with the field. I remind here that a vacuum state of the field does not correspond to the absence of field, but to the absence of discrete excitations of the field. The example just shows the reality of the field, even when there are no excitations. The excitations themselves, the quanta, can be present in one system and not in other, according to the state of the system with respect to the field.

When curvature is present in spacetime, inertial frames will be associated with free-falling systems and in general not unique choice of the vacuum state can be made to express the field. So, different detectors located in different reference systems will detect different numbers of particles. Polarization of the vacuum by event horizons results in Hawking radiation that is detectable in the asymptotically flat region of spacetime, but such radiation is not seen by an observer falling freely into the black hole. In general, there is not simple relation between $\langle N_i\rangle$ and the particle number measured by different detectors (Birrell and Davies 1982). The ontological status of particles in QFT in curve spacetime is that of a complex relational property between fields and detectors. The ontological substratum, however, is provided by the fields. Remove them, and nothing is left: no energy-momentum, no excitations, no expectations, no structure. I conclude that quantum objects are quantum fields over spacetime. In the next chapter I will discuss the status of spacetime itself.

Summing Up Non-relativistic QM for systems with many components provides a strong argument against the individuality of quantum particles. This is fully realized in quantum field theory, where the particles are interpreted as discrete excitations of quantum fields existing over spacetime. These arguments against the individuality of quanta, however, do not entail the existence of vague quantum objects. The ontology of quantum field theory is an ontology of fields. These fields are endowed with definite properties albeit some of them are frame-dependent. Quantum excitations are some of these relational properties, when curvature for spacetime is allowed. Relational features of certain entities do not imply ontic vagueness. At most, some people can talk vaguely about them.

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Chapter 10
Ontological Problems of Spacetime

10.1 Introduction

Discussions about the nature of space and time in Western thought can be traced to the early Pre-Socratic philosophers (Graham 2006; Jammer 2012; Romero 2012). The position of Aristotle, who understood time as a measure of motion, and its contrast with the Platonic view, shaped the ontological controversy of the Hellenistic period, the Late Antiquity, and even the Middle Ages (see Sorabji 1983). It was not, however, until the development of Newtonian physics and the Leibniz-Clarke correspondence (Leibniz and Clarke 2000), that what is now called relationism-substantivalism debate clearly emerged. Crudely, relationism is the metaphysical doctrine that space and time are not material entities existing independently of physical objects. Space and time emerge, according to this view, as a complex of relations among things and their changes (this position has been forcibly defended by Reichenbach 1957, Grünbaum 1973, Bunge 1977, and Perez Bergliaffa et al. 1998, among others). According to relationism, there are spatial and temporal relations among the constituents of the world, but space and time are not things in themselves. On the contrary, substantivalism is committed to the independent existence of space and time, which are considered material substances or even as things or entities. Substantivalism is ontological realism about space and time. The debate between both parties went on during more than 300 years (see the books by Jammer 2012 and Friedman 1983 for arguments supporting both positions).

With the advent of the concept of spacetime (Minkowski 1908) and the General Theory of Relativity (Einstein 1915), the debate underwent such major changes in the meaning of the original terms of both positions that some authors, as Rynasiewicz (1996), claimed that the whole issue was outmoded and ill-directed. Hoefer (1998) has argued, convincingly, that although some aspects of the classical debate might dissolve in the context of contemporary science, the dispute is based on a genuine ontological problem and the debate goes on. I agree. I maintain, however, that the current ontological discussion cannot ignore the related issue of the eternalism-presentism-growing block universe. In this chapter I shall offer a

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view of the topic in which a kind of substantivalism, relationism, and eternalism can coexist on the basis of emergentism, the doctrine that qualitative systemic properties arise from more basic ontological levels devoid of such properties (see Chap. 3). The mechanisms that enforce emergence are composition and interaction. I hold that there is a level for each of the three ontological positions to be considered as a good option for a description of the way the world is.

In what follows, I first give a characterization of the main concepts I am going to discuss and then I place the debate in the context of General Relativity and spacetime ontology. Next, I present a new argument for rejecting presentism, the doctrine that only the present time exists. In my opinion, this is the only of the four ontological views that is completely inconsistent with modern science. The remaining of the chapter is devoted to outline an ontological position about the existence of spacetime. Technical details go to a last section in the form of an appendix of the chapter, so the bulk of the discussion is apt for a broad readership.

10.2 The Controversy

The traditional substantivalism–relationism debate was reshaped by the introduction of General Relativity in 1915. The changing views of Einstein himself on ontological matters helped to generate much confusion in the early interpretations of the theory. Einstein was originally motivated in part by a Mach-inspired relationism (see his debate with de Sitter about the impossibility of empty spacetime, Smeenk 2014). Then, when he was forced to admit that his theory allows for solutions without matter, he shifted to a kind of "ether substantivalism" after 1918 (Einstein 1920; Hoefer 1998) to end espousing a block universe *á la* Weyl, after the early 1920s. Einstein remained a spacetime realist and hardcore eternalist until the end of his life. He wrote to Vero and Bice Besso, referring to the death of his lifelong friend Michele Besso, just 3 weeks before his own death (Fölsing 1998):

> Now he has preceded me a little by parting from this strange world. This means nothing. To us, believing physicists, the distinction between past, present, and future has only the significance of a stubborn illusion.

After a meeting with Einstein in 1950, Karl Popper wrote (Popper 2005, p. 148):

> I had met Einstein before my talk, first through Paul Oppenheim, in whose house we were staying. And although I was most reluctant to take up Einstein's time, he made me come again. Altogether I met him three times. The main topic of our conversation was indeterminism. I tried to persuade him to give up his determinism, which amounted to the view that the world was a four-dimensional Parmenidean block universe in which change was a human illusion, or very nearly so. (He agreed that this had been his view, and while discussing it I called him "Parmenides".)

But at the time of his debate with de Sitter (i.e. towards 1917), Einstein wrote (Einstein 1918a, see also Smeenk 2014):

> It would be unsatisfactory, in my opinion, if a world without matter were possible. Rather, the $g^{\mu\nu}$-field should be fully determined by matter and not be able to exist without the latter.

This was a consequence of his, by then, strong Machian influences, that so well helped him in the developing of Special Relativity. All these shifts of ontological views by the founder of the theory contributed to create some confusion on the metaphysical trenches.

The development, in the early 1920s, of dynamicist philosophical views of time by Bergson, Whitehead, and other non-scientific philosophers helped to resurrect presentism, the Augustinian view that only the present time exists and there is no future or past. Such a doctrine has a profound impact on theological issues and has been defended by Christian apologists (see, e.g. Craig 2008) but also by scientific-oriented thinkers in later years (see, e.g. Bunge 1977).

Substantivalism, relationism, eternalism, and presentism are all different ontological stances, although some of them are closely related. I offer some provisional definitions in order to make some semantical clarifications of importance for the subsequent discussions (see Romero 2017).

- *Spacetime substantivalism*[1]: Spacetime is an entity endowed with physical properties. This position is clearly expressed by Einstein (1920). The exact nature of this entity is open to discussion. I shall defend a view that may be dubbed as 'emergent substantivalism'.
- *Spacetime relationism*: Spacetime is not an entity that can exist independently of physical objects. Spacetime, instead, is a system of relations among different ontological items. The nature of these items is also open to discussion. I shall propose that there is a level where a form a relationism provides an adequate framework for current physics and that this is not in contraction with emergent substantivalism when the latter is applied to a different ontological level.
- *Eternalism [also known as Block Universe (BU)]*: Present, past, and future moments (and hence events) exist. They form a 4-dimensional 'block' of spacetime. Events are ordered by relations of earlier than, later than, or simultaneous with, one another. The relations among events are unchanging. Actually, they cannot change since time is one of the dimensions of the block. I have defended this position in Romero (2012, 2013a, 2017). The reader is referred to these papers as well as to Peterson and Silberstein (2010) and references therein for further arguments.
- *Presentism*: Only those events that take place in the present are real. This definition requires explanations of the terms 'present' and 'real'. Crisp (2003, 2007) offers elucidations. See also the mentioned paper by Craig (2008), and

[1]I follow the modern jargon and adopt the expression "substantivalism" instead of the more traditional (and less awkward) "substantialism". Unfortunately, philosophy and elegance of style not always go together.

Mozersky (2011). Presentism has been subject to devastating criticisms since the early attacks by Smart (1963), Putnam (1967), and Stein (1968). See Saunders (2002), Petkov (2006), Wüthrich (2010), Peterson and Silberstein (2010), Romero (2012, 2015) for up-dated objections.

A position intermediate between eternalism and presentism is the growing block universe proposal, strongly advocated in recent years by cosmologist G.R.S. Ellis. This position holds that past and present events exist, but future moments and events are not real. Reality would be a kind of growing 4-dimensional block, to which events are been added and go from non-existence to present and then to the past. The ultimate motivation for this proposal seems to be in some interpretation of quantum mechanics and a commitment with indeterminism with respect to the future (e.g. Ellis and Rothman 2010, see also Broad 1923). Several of the objections raised against presentism apply to the growing block universe, but I shall not make the case against it here.

10.3 Against Presentism

The Englishman John McTaggart Ellis McTaggart presented a disproof of presentism in his famous paper *Unreality of Time* (McTaggart 1908). He reasoned as follows.

1. There is no time without change.
2. If time passes, events should change with respect to the properties of pastness, presentness, and futureness.
3. A given event, then, should be able to be in absolute sense, past, present and future.
4. These properties exclude each other.

Then: Events do not pass, just are.

There is no passage of time. There is no moving present. The mere idea of a flowing time simply does not make any sense. An additional problem is that if time flows, it should move with respect to something. If we say that there is a super-time with respect to which time flows, then we shall need a super-super-time for this super-time, and we shall have an infinite regress. In addition, there is no flow without a rate of flow. At what rate does time go by? The answer 1 s per s is meaningless. It is like saying that a road extends along a distance of 1 km per each km that it extends!

On the physical side, the theory of special relativity seems not to be friendly to the idea of an absolute present, at least in its usual Minkowskian 4-dimensional interpretation. Special relativity is the theory of moving bodies formulated by Albert Einstein in 1905 (Einstein 1905). It postulates the Lorentz-invariance of all physical law statements that hold in a special type of reference systems, called *inertial frames*. Hence the ‘restricted’ or ‘special’ character of the theory. The equations of Maxwell electrodynamics are Lorentz-invariant, but those of classical mechanics are not. When classical mechanics is revised to accommodate invariance under Lorentz transformations between inertial reference frames, several modifications appear. The most notorious is the impossibility of defining an absolute simultaneity relation between events. Simultaneity results to be frame-dependent. Then, some events can be future events in some reference system, and present or past in another system. Since what exists cannot depend on the reference frame adopted for the description of nature, it is concluded that all events exist. Consequently, presentism, the doctrine that only what is present exists, is false.

The presentist or A-theorist of time might find a way around this argument adopting a different (purely Lorentzian) interpretation of the theory (Crisp 2007; Zimmerman 2011), which relinquishes the concept of spacetime. The problems of this approach have been discussed at length by Saunders (2002), and I do not insist on the topic here. Instead, I prefer to say a few words about the much less discussed issue of the compatibility of presentism with General Relativity.

General Relativity is the theory of space, time, and gravitation proposed by Einstein in 1915 (Einstein 1915). Spacetime is an indispensable ingredient of this theory. A 4-dimensional real and differentiable manifold is adopted to represent spacetime, which is considered as a physical entity (Romero 2014a,b). A rank-2 metric field g_{ab} is defined over the manifold to represent the potentials of the gravitational field (an abbreviation for the metric field of spacetime). Distances over the manifold are given by

$$ds^2 = g_{ab} dx^a dx^b, \tag{10.1}$$

where dx^a is a 4-dimensional differential length vector. The key issue to determine the geometric structure of spacetime, and hence to specify the tidal effects we call gravity, is to find the law that fixes the metric. The metric field is related to matter. The energy-momentum tensor T_{ab} represents the physical properties of material things that interact with spacetime. The curvature of spacetime at any point is related to the energy-momentum content at that point by a set of differential equations. These equations, the Einstein's field equations, can be written in the simple form:

$$G_{ab} = -\frac{8\pi G}{c^4} T_{ab}, \tag{10.2}$$

where G_{ab} is the so-called Einstein's tensor, which is linear in the curvature[2] and non-linear in the metric. It contains all the geometric information on spacetime. The constants G and c are the gravitational constant and the speed of light in vacuum. Einstein's field equations are a set of ten non-linear partial differential equations for the metric coefficients.

[2] The curvature is represented by the Riemann tensor R_{abcd}, formed with second derivatives of the metric (see, e.g. Hawking and Ellis 1973).

A crucial point of General Relativity is that the 4-dimensional spacetime with non-zero curvature is not dispensable anymore. Contrarily to the Minkowskian case, General Relativity is not susceptible of a global Lorentzian formulation. This poses a problem for presentism, because of the relativity of simultaneity implied by the constancy of the speed of light in spacetime. However, for some cosmological models $\mathcal{M}_{\text{st}} =< M,\ g_{ab},\ T_{ab} >$ a kind of ‘cosmic time’ can be re-introduced in spacetime, and some presentists have tried to use it to their advantage.

Thomas Crisp (2007) has proposed a “presentist-friendly” model of General Relativity. He suggests that the world is represented by a 3-dimensional space-like hyper-surface that evolves in a forth dimension (time). This interpretation requires the introduction of a preferred foliation of spacetime at large scales, and to consider the $3 + 1$ usual decomposition for the dynamics of spacetime in such a way that ‘the present’ is identified with the evolving hyper-surface. This situation is depicted in Fig. 10.1.

In order to set up such a model for spacetime, some global constraints must be imposed: there should be a unique foliation into surfaces of constant mean curvature. This is the case, for instance, of the Friedmann-Lemaître-Robertson-Walker metric. This metric is isotropic and homogeneous. General conditions for such kind of metrics require the absence of Cauchy horizons, the fulfilment of the so-called *energy conditions* (Hawking and Ellis 1973), and symmetry constraints. In this kind of metrics, the parameter along which the hyper-surfaces evolve is called ‘cosmic time’.

I confess that I do not see how such ‘cosmic time’ can help the presentist’s cause. The foliation of a manifold is nothing else than a computational device. The selection of a given hyper-surface as ‘present’ is completely arbitrary. A hyper-surface is nothing else than a class of events (i.e. a concept, not a thing), which we decide to specify as initial data for subsequent calculations. Any hyper-surface can be used for this purpose, and since the Einstein’s equations are time-reversible,

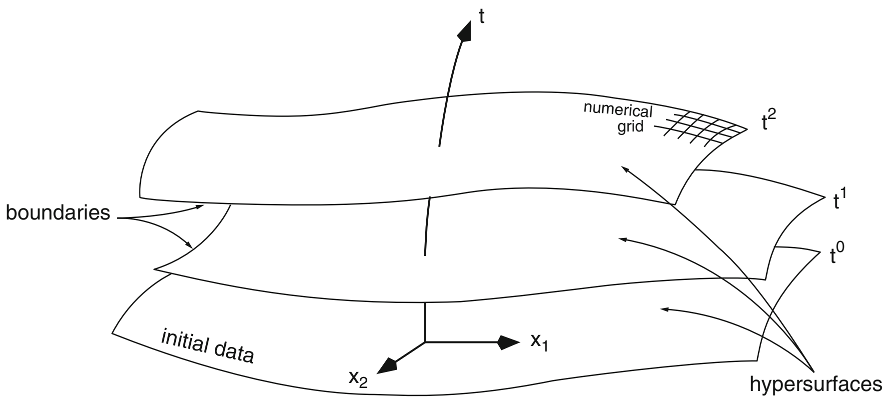

Fig. 10.1 A ‘presentist-friendly’ spacetime: evolving 3-dimensional space-like surfaces in a spacetime with a preferred time-direction

we can compute the evolution with respect to both t and $-t$. There is no reason for thinking that a particular class of events, even if they are all space-like, is the 'present'. Moreover, classes do not flow, as the present is supposed to do.

A similar criticism is valid for the definition of present given by Crisp (2003), who considers that the present is the aggregation of all things (I would say events) with null temporal distance. There are events with null temporal distance in the past of the event of reading this line, which are simultaneous with the landing of Apollo 11 on the moon on July 20th 1969. There is no reason to think that your reading of this line is 'now' and not the events simultaneous with Armstrong's remarkable step: both events form part of aggregates with null temporal distances. Why one aggregate of events is present and the other is not?

There are additional problems related to the actual structure of the Universe if it is supposed to be represented by a smoothly foliable theoretical spacetime model $\mathcal{M}_{\rm st}$. First, there are black holes. Non-spherically symmetric black holes (i.e. rotating or Kerr black holes) have Cauchy horizons. There is no way to compute the evolution of any physical system inside these regions, whatever the external spacetime foliation be. There is no possibility of synchronization between clocks outside and inside the inner horizon of a Kerr black hole. And the evidence for rotating black holes in the Universe is overwhelming (e.g. Romero and Vila 2014). This point cannot be ignored by the presentist (for more arguments based on black holes see Romero and Pérez 2014, and Romero 2014a,b).

Another problem for the 'presentist-friendly' spacetime is that observational data indicate that remote supernovae Type Ia present redshifts that either suggest the Universe is expanding in an accelerated way or it is inhomogeneous. Both possibilities are ruinous for the presentist. The first requires massive violations of the energy conditions in the Universe. These violations can be produced by dark fields with negative energy densities or by gravity with modified dynamical equations. In either case, particle cosmological horizons appear in the Universe, disconnecting different regions and making global time synchronization impossible. On the other hand, if the Universe is inhomogeneous or anisotropic on medium scales, then the Friedmann-Lemaître-Robertson-Walker model is not a fully correct description of spacetime and more complex models should be considered. No foliation of constant curvature is possible with inhomogeneity or anisotropy, with the consequent problem for synchronization.

Zimmerman (2011) has pointed out that in a desperate case of conflict with General Relativity the presentist can abandon Einstein's theory, since one can be sure that relativity is ultimately a wrong theory because it is incompatible with quantum mechanics. I protest. General Relativity is *not* inconsistent with quantum mechanics as it is sometimes loosely stated. The background spacetime of quantum mechanics is flat Minkowskian spacetime. Even in a spacetime with non-zero curvature, quantum mechanical calculations can be performed (Wald 1994). General Relativity is a classical theory, and hence it cannot deal with *quantum interactions of the metric field*. This is something very different from saying that there is incompatibility with quantum mechanics or quantum field theory. What is not known is what a quantum field theory *of gravitation* is. What we actually know is that at the scales that are relevant for the presentist, General Relativity is a well-tested theory. But even if it is replaced by other field theory to better accommodate the phenomenology of dark matter and the apparent universal accelerated expansion, the very same problems I mentioned above will remain. For the presentist, the battle is lost from the beginning: the very concept of spacetime is at odds with presentism. And this is because spacetime is the ontological sum of all events. The mere postulation of spacetime implies a consent to events that can be classified as past or future with respect to some other events. Spacetime is inconsistent with presentism.

Said all that, yet, we all have a kind of feeling that “our time is running out”. Where does this feeling come from? To answer we should look not at spacetime, but into our own brains.

10.4 When Is ‘Now’?

If the present is an instant of time instead of a thing, then the question of “which instant is present?” follows. One possible answer is “now”. But… when is ‘now’?

‘Now’, like ‘here’, is an indexical word. To say that I exist now gives no information on when I exist. Similarly, to say that I am here, gives no information on where I am. There is no particular moment of time defined as an absolute now.

I maintain that ‘nowness’ and ‘hereness’ emerge from the existence of perceiving self-conscious beings in a certain environment. What these beings perceive is *not* time, but changes in things, i.e. events (Bunge 1977). Similarly, they do not perceive space, but spatial relations among things. In particular, we do not perceive the passage of time. We perceive how our brain changes. I claim that there is no present *per se*, in the same way that there is no smell, no pain, no joy, no beauty, no noise, no secondary qualities at all without sentient beings. What we call “the present” is not in the world. It emerges from our interaction with the world.

We group various experienced inputs together as present; we are tempted to think that this grouping is done by the world, not by us. But this is just delusional. I maintain that tenses are not needed and in fact are not wanted by the natural sciences. This idea is clearly expressed by E. Poeppel on the basis of neurological research (Pöppel 1978):

> […] our brain furnishes an integrative mechanism that shapes sequences of events to unitary forms… that which is integrated is the unique content of consciousness which seems to us present. The integration, which itself objectively extends over time, is thus the basis of our experiencing a thing as present.
>
> […] The now, the subjective present, is nothing independently; rather it is an attribute of the content of consciousness. Every object of consciousness is necessarily always now - hence the feeling of nowness.

The perception of motion gives an additional argument against the idea that the present is an instant of time. According to Le Poidevin (2009):

1. What we perceive, we perceive as present.
2. We perceive motion.
3. Motion occurs over an interval.

Therefore: What we perceive as present occurs over an interval.

Recent research in neurosciences lends strong support to these claims. Perception of events outside the brain and the construction of what we call time is a complex cluster of processes that involves different cortical and sub-cortical regions. Distortions in timing can be produced by narcotics, experimental manipulation, strong emotions, and by different brain disorders such as Alzheimer’s disease, clearly indicating a dependence of temporal experience on brain processes. The involvement of sub-cortical areas in external change perception explains why extreme fear and other abnormal emotional states can modify the subjective experience of time (e.g. Stetson et al. 2007).

A very important breakthrough in neurological research about the timing mechanisms operating in the brain was made by Benjamin Libet and collaborators (Libet et al. 1964; Libet 1973). In a series of now classical experiments, Libet et al. demonstrated that there is a time delay of about 0.5 s between the starting of brain stimulation and the appearance of awareness of the stimulus. This shows that awareness of an event happens in the brain when the event is past: what we become aware of has already occurred about 0.5 s earlier. In Libet’s words: “We are not conscious of the actual moment of the present. We are always a little late.” (Libet 2004). The entire battery of sensory stimuli are manipulated by the brain to create a coherent representation of the external world in such a way that we are not aware of any time delay. The subjective ‘present’ is actually a construction made with a manifold of sensory information of events *in the past*.

The motor system does not wait ~ 0.5 s before making its decisions. These are done unconsciously and over spans as short as 10 ms in some cases. Consciousness allows further interpretation and adjustments on the basis of later information (Eagleman and Sejnowski 2000). The actual span required to create a transient representation of the environment can vary from an individual to another, but should take more than 100 ms on average. In Eagelman’s words (Eagleman 2009):

> This hypothesis –that the system waits to collect information over the window of time during which it streams in– applies not only to vision but more generally to all the other senses. Whereas we have measured a tenth-of-a-second window of postdiction in vision, the breadth of this window may be different for hearing or touch. If I touch your toe and your nose at the same time, you will feel those touches as simultaneous. This is surprising, because the signal from your nose reaches your brain well before the signal from your toe. Why didn’t you feel the nose-touch when it first arrived? Did your brain wait to see what else might be coming up in the pipeline of the spinal cord until it was sure it had waited long enough for the slower signal from the toe? Strange as that sounds, it may be correct.
>
> It may be that a unified polysensory perception of the world has to wait for the slowest overall information. Given conduction times along limbs, this leads to the bizarre but testable suggestion that tall people may live further in the past than short people. The

consequence of waiting for temporally spread signals is that perception becomes something like the airing of a live television show. Such shows are not truly live but are delayed by a small window of time, in case editing becomes necessary.

All evidence from neuroscience research points to the hypothesis that 'the present' is a construction of the brain; a construction that is not instantaneous. We do not perceive time; we only are aware of events and can compare the event rate or their clustering in the external world with the rate of activity of our own brain (e.g. Karmarkar and Buonomano 2007).

Any tentative definition of 'present' compatible with modern neurobiology must take into account the role of the perceiving and sentient individual. In the next section I offer some provisional definitions that meet this requirement and distinguish among the different meanings in which the word 'present' is used.

10.5 Defining the Present

Physical events are ordered by the relations 'earlier than' or 'later than', and 'simultaneous with' (Grünbaum 1973). There is no 'now' or 'present' in the mathematical representation of the physical laws. What we call 'present' is not an intrinsic property of the events nor an instant of time, much less a moving thing. 'Present' is a concept abstracted from the relation between a certain number of events and a self-conscious individual. I propose:

Present Class of all events simultaneous with a given brain state.

To every brain state there is a corresponding present. The individual, notwithstanding, needs not to be aware of all events that form the present. The present, being a class of events, is an abstract object without any causal power.

Psychological Present Class of local events that are causally[3] connected to a given brain state.

Notice that from a biological point of view only local events are relevant. These events are those that directly trigger neuro-chemical reactions in the brain. Such events are located in the immediate causal past of those brain events that define the corresponding state. The psychological present is a conceptual construction of the brain, based on abstraction from events belonging to an equivalence class. The present, then again, is not a thing nor a change in a thing (an event). It is a construction of the brain; a fiction albeit a very useful one for survival. Yet, individuals are not necessarily aware of *all* events that are causally relevant for the construction of the psychological present.

Kelly (1882) introduced the concept of 'specious present', which William James elaborated as "the short duration of which we are immediately and incessantly sensible" (James 1893). I propose to update this definition to:

[3]For a complete account of causality as a relation between events see Bunge (1979).

Specious Present Length of the time-history of brain processes necessary to integrate all local events that are physically (causally) related to a given brain state.

The specious present, being related to brain processes, can be different for different individuals equipped with different brains. The integration of the specious present can be performed in different ways, depending on the structure of the brain. It is even possible to imagine integration systems that can produce more than one specious present or even systems that might ‘recall’ the future (see Hartle 2005 for examples based on computers). If biological evolution has not produced such systems, it seems because of the existence of spacetime asymmetric boundary conditions that introduce a preferred direction for the occurrence of processes (Romero and Pérez 2011).

Finally, I introduce a *physical present.*

Physical Present Class of events that belong to a space-like hyper-surface in a smooth and continuous foliation of a time-orientable spacetime.

Since in the manifold model of spacetime every event is represented by an element of the manifold, the introduction of this class does not signal a special time identified with ‘now’. Every space-like hyper-surface corresponds to a different time and none of them is an absolute present ‘moving’ into the future. Actually, naming ‘the future’ to a set of surfaces in the direction opposite to the so-called Bing Bang is purely conventional.

10.6 Some Further Objections Against Presentism

Most of the arguments against presentism are based on the Special Theory of Relativity; see the references cited in the previous section and the discussions in Craig and Smith (2008). Metaphysical arguments can be found, for instance, in Oaklander (2004) and Mellor (1998). Recently, several arguments based on General Relativity have been displayed against presentism. Romero and Pérez (2014) have shown that the standard version of this doctrine is incompatible with the existence of black holes. In Sect. 10.3 I enumerated a number of additional objections based on General Relativity and modern cosmology. Wüthrich (2010) discusses the problems and inconsistence of presentism when faced with Quantum Gravity. Now, I offer a new argument based on the existence of gravitational waves.

The argument goes like this:

P_1: There are gravitational waves.
P_2: Gravitational waves have non-zero Weyl curvature.
P_3: Non-zero Weyl curvature is only possible in 4 or more dimensions.
P_4: Presentism is incompatible with a 4 dimensional world.

Then, presentism is false.

The logic is sound, so let us review the premises of the argument to see whether there is some escape route for the presentist. The truth of P_1 is accepted by the vast majority of scientists working on gravitation. Gravitational waves are a basic prediction of General Relativity (Einstein 1916, 1918b). The Laser Interferometer Gravitational Wave Observatory (LIGO) has directly detected gravitational waves from several merging black hole binary systems and even one neutron star merger (e.g. Abbott et al. 2016a,b, 2017). A space-based observatory, the Laser Interferometer Space Antenna or LISA, is currently under development by the European Space Agency (ESA). Indirect evidence for the existence of gravitational waves is known since long ago from the orbital decay of the binary pulsar PSR B1913+16, discovered by Hulse and Taylor in 1974. The decay of the orbital period is in such accord with the predictions of General Relativity that both scientists were awarded the Nobel Prize in Physics 1993 (see, for instance Taylor and Weisberg 1982). So, P_1 is true.

Premises P_2 and P_3 are necessarily true. Gravitational waves propagate in empty space, where the Einstein's field equations are reduced to:

$$R_{ab} = 0.$$

This expression means that the 10 coefficients of the Ricci tensor are identically null. But the full Riemann tensor[4] has 20 independent coefficients since is a rank 4 tensor. The remaining 10 components are expressed by the Weyl tensor. Then, since the gravitational waves are disturbances in the curvature of spacetime, the Weyl tensor must be non-zero in their presence. If the dimensionality of the world were 3, as proposed by the presentists, the Riemann tensor would have only 6 independent components, and since in 3 dimensions the Einstein's equations in vacuum are reduced to 6, the Weyl tensor must vanish. Only in 4 or more dimensions gravity can propagate through empty spacetime (see Hobson et al. 2006, p. 184, and Romero and Vila 2014, p. 19).

Then, the presentist should either deny that presentism is incompatible with 4-dimensionalism or accept that presentism is false. But presentism is essentially the doctrine that things do not have temporal parts (Heller 1990). Any admission of temporal parts or time extension is tantamount to renounce to the basic claim of presentism: there are no future or past events. I conclude that presentism is utterly false. I shall ignore this position in what remains of this chapter.

10.7 Event Substantivalism and the Emergence of Things

In General Relativity, a specific model representing a sate of affairs is given by a triplet $\langle E, \ \mathbf{g}, \ \mathbf{T} \rangle$, where E is a 4-dimensional, real, differentiable pseudo-Riemannnian manifold, $\mathbf{g}$ is a metric tensor field of rank 2 defined on E, and $\mathbf{T}$

[4]The Riemann tensor represents the curvature of spacetime. See Appendix "Basic Definitions" at the end of this chapter.

is another rank 2 tensor field representing the energy-momentum of the material entities accepted by the theory. Both tensor fields are related by the Einstein's field equations: $G_{ab}(g_{ab}) = \kappa T_{ab}$, where $G_{ab} = R_{ab} - 1/2\, g_{ab} R$ is the so-called Einstein's tensor, a function of the metric field and its second order derivatives. Substantivalism is usually presented within the context of General Relativity in one of two types: manifold substantivalism and metric substantivalism (Hoefer 1996). The former is characterised as the view that the bare manifold represents spacetime (Earman and Norton 1987). The latter, as the view that the metric field **g** represents substantival spacetime (Hoefer 1996).

Two lines of attack on manifold substantivalism have been adopted by philosophers of spacetime and advocates of relationism: the hole argument and the 'absence of structure' argument. The first one was originally conceived by Einstein, and resurrected by Earman and Norton (1987). The second, was presented by Maudlin (1989) and elaborated by Hoefer (1996). Let us briefly review them.

Imagine a situation where the matter distribution is known everywhere outside some closed region of spacetime devoid of matter, the so-called 'hole'. Then, the field equations along with the boundary conditions supposedly enable the metric field to be determined inside the hole. General covariance states that the laws of physics should take the same mathematical form in all reference frames. In two different frames, there are two solutions that have the same functional form and impose different spacetime geometries. If the coordinate systems in these frames[5] differ only after some time $t = 0$, there are then two solutions; they have the same initial conditions but they impose different geometries after $t = 0$. This seems to imply a breakdown of determinism. Then, the manifold substantivalist should abandon determinism if he or she wants to remain a realist about spacetime points represented by the bare manifold (Norton 2014). Nothing observable, however, is made indeterminate by the hole argument, and hence the relationist escapes unscathed.

As noted by Hoefer (1996), the argument outlined above is not conclusive: without the premise that determinism is actually true, the argument has no force beyond the psychological conviction that determinism deserves a fighting chance. I see an additional problem: the substantivalist can claim that there are two types of determinism, namely, ontological and epistemological. The hole argument affects only the second type, since it concerns the predictions of the theory, not its ontological assumptions (i.e. that the points of the manifold represent events). But the existence of Cauchy horizons in many solutions of General Relativity is well established, so the hole argument adds essentially nothing to the epistemic problems of the theory. In any case, the hole argument prevents the univocal identification of bare points of the manifold with spacetime, not spacetime substantivalism.

The second criticism of manifold substantivalism is based on the observation that the manifold, being just a topological structure, has not geometrical properties that are essential to any concept of spacetime (Maudlin 1989). In particular, without

[5]Notice that frames, contrary to coordinate systems, are physical objects.

the metric field is not possible to distinguish spatial from temporal directions or to establish relations of 'earlier than' and 'simultaneous with'. I agree. The manifold by itself has not structure enough as to provide a suitable representation of spacetime. Hoefer (1996) concludes that the metric field **g** is a much better candidate to represent spacetime than the manifold. He observes that the metric field is clearly defined, and distinguishable from the matter field **T**, which represents the contents of spacetime. The metric field cannot be null over finite regions of the manifold, contrary to other fields. If the metric field were just a physical field defined over spacetime, the geodetic motion would not be related to spacetime, but only to this field. Hoefer also remarks that Einstein was of the opinion of that if the metric coefficients are removed, no spacetime survives the operation, since nothing is left, not even Minkowski spacetime. All spatiotemporal properties disappear with the metric. Based on his rejection of primitive identity for the points of the manifold, Hoefer proceeds to identify substantivalism with the claim that the metric represents spacetime and the manifold is a dispensable metaphysical burden.

I concur with the opinion that the metric is indispensable for a representation of spacetime. The metric provides all properties associated with spacetime. The manifold, however, does not seem dispensable to me. The whole spacetime is represented by the ordered pair $\langle E, \ \mathbf{g}\rangle$. The elements of the pair represent different aspects of spacetime. The points of the manifold represent the existing events that form the world, and the metric represents their relational and structural properties. The identification of spacetime with a single element of the pair leads to problems. Instead, the representation of spacetime with $\langle E, \ \mathbf{g}\rangle$ is in accord with the usual practice in science of representing entities with sets and properties with functions (Bunge 1974a,b). It might be argued, as Hoefer (1996) does, that spacetime points have no duration, and hence no trajectories in time, and they do not interact in any way with each other or with physical objects or fields, so it would be weird to assign them any kind of independent existence. My answer to this complaint is that of course points do not interact: they are the elements of the manifold that represent events. Events form the ontological substratum, and they do not move nor interact: change and interaction emerge from their ordering. At the level of analysis of General Relativity, events do not need to satisfy primitive identity neither. Only at a pre-geometric level events can be differentiated by a single property, their potential to generate further events. At the level at which General Relativity is valid, events do not need to be differentiated and it is this very fact that allows us to represent them by a manifold plus the metric. There is then no problem at all with embracing Leibniz Principle (i.e. diffeomorphic spacetime models represent the same physical situation). We can actually define a spacetime model as an equivalence class of ordered pairs $\{\langle E, \ \mathbf{g}\rangle\}$ related by a diffeomorphism. In this class, the manifold provides the global topological properties and the continuum substratum for the definition of the metric structure. The representation of spacetime appears, therefore, as the large number limit of an ontology of basic timeless and spaceless events that can be identified only at a more basic ontological level.

The ontological operation of composition '$\circ$' of events is a binary relation that goes from pairs of events to events. If E is a set of events, and $e_i, \ i = 1, \ldots, n \in E$

represent individual events, then $\circ : E \times E \to E$ is characterised by the following postulates:

- P_1: $(\forall e)_E\ (e \circ e = e)$.
- P_2: $(\forall e_1)_E(\forall e_2)_E\ (e_1 \circ e_2 \in E)$.
- P_3: $(\forall e_1)_E(\forall e_2)_E\ (e_1 \circ e_2 \neq e_2 \circ e_1)$.

We can introduce some definitions:

- D_1: An event $e_1 \in E$ is composite $\Leftrightarrow (\exists e_2, e_3)_E\ (e_1 = e_2 \circ e_3)$.
- D_2: An event $e_1 \in E$ is basic $\Leftrightarrow\ \neg\,(\exists e_2, e_3)_E\ (e_1 = e_2 \circ e_3)$.
- D_3: $e_1 \subset e_2\ \Leftrightarrow e_1 \circ e_2 = e_2$ (e_1 is part of $e_2\ \Leftrightarrow e_1 \circ e_2 = e_2$).
- D_4: $\mathrm{Comp}(e) \equiv \{e_i \in E \mid e_i \subset e\}$ is the composition of e.

Composition leads to a hierarchy of events, with basic events on the lower level and increasing complexity towards higher levels. Reality seems to be organised into levels, each one differentiated by qualitative, emerging properties (see Chap. 3). A level can be defined as a collection of events or things that share certain properties and are subject to some common laws that apply to all of them.

At some point of this hierarchy of events, things can be introduced as classes abstracted from large number of events (see Romero 2013a for formal definitions; a full event ontology is presented in Appendix A at the end of the book). A thing-based ontology allows a simplification in the description of the higher levels of organization of what is, essentially, an event ontology.

Once events have multiplied and composed to a point where they can be represented with a continuum set, General Relativity can be formulated. In the appendix of this chapter, I present General Relativity as a physical theory that emerges from the basic ontological level. The first axiom, of ontological nature, postulates the existence of all events. Form the start, then, the theory can be labeled as 'event substantivalism'. Spacetime is represented by the ordered pair $\langle E, \mathbf{g}\rangle$, not by the bare manifold E or by the metric field $\mathbf{g}$. Spacetime is then an emerging thing from the collection of all events, that can be characterised as an individual endowed with properties (Romero 2012, 2013a).

I close this section offering a brief new argument for spacetime substantivalism. It might be called a 'thermodynamical' argument:

- P_1: Only substantival existents can be heated.
- P_2: Spacetime can be heated.

Then, spacetime has substantival existence.

The logic is clearly sound, so let us briefly discuss the premises. P_1 is a fundamental insight from physics. To heat something is to excite its internal degrees of freedom. It is impossible to heat something that does not exist, because non-existents do not have internal microstructure. Regarding P_2, quantum field theory in curve spacetime clearly indicates that spacetime can be heated and the amount of radiation produced by it can be increased (for instance, by acceleration or gravitational collapse, e.g. Birrell and Davis 1982). I conclude that spacetime has substantival existence.[6]

10.8 Defending Eternalism

The assumption that the collection of all events exists and is represented by a 4 dimensional differentiable real manifold, along with the metric structure of this manifold given by the field **g**, leads to the doctrine we have define as 'eternalism': past, present, and future events exists. In fact, the metric allows to define the separation of any two events, $ds^2(e_1,\ e_2) = g_{ab}dx^a dx^b$, with $d\mathbf{x}$ the differential 4-dimensional distance between e_1 and e_2. According to whether $ds^2 = 0$, $ds^2 > 0$, or $ds^2 < 0$, the events are considered 'null', 'time-like', or 'space-like', respectively. In the first two cases the events might be (but not necessarily are) causally related and the temporal ordering cannot be reversed with a simple change of coordinates. In the case of space-like events, on the contrary, there is no absolute temporal ordering, given the invariance of the theory with respect to the group of general coordinate transformations. Events that are future or past in some system, can be simultaneous in another. If someone claims that a couple of space-like events are present, he or she must accept that there are future and past events (since there will be always a frame transformation that renders them future or past) or negate that existence is invariant under transformations between reference systems. The latter seems to be an impossible step. The existence of future and past events, hence, is implied by substantivalism, i.e. any consistent substantivalist must be an eternalist. The converse is not true.

The existence of space-like events cannot be denied by a presentist, since the existence of all events was assumed from the very beginning, when the existence of the referents of the manifold E was accepted in the formulation of General Relativity (Axiom $\mathbf{P}_1$ in "Axiomatic Ontology of Spacetime" in Appendix at the end of the chapter). The presentist can try to offer a suitable reformulation of General Relativity where all but present events are just convenient fictions, but it is difficult to see how this move will help him or her to escape from the argument from general covariance, since the 'present' is defined as a moving hyper-surface of space-like events. For the eternalist, instead, there is nothing dynamical associated with the 'present': this is just a local relational property; every event of the hyper-surface is present to a person located at that moment and location. The same event is past or future to persons located in the future or the past of the event; there is no intrinsic 'presentness' associated with individual events. All events exists on equal foot for the eternalist.

[6] A similar argument has been made by Bunge (2017) based on the detection of gravitational waves.

The presentist can object that eternalism implies fatalism: the future is fixed and unchangeable. This objection seems to be the main motivation for the postulation of the growing block universe view. The presentist's universe, however, can be as fixed in regards to the future as the block universe of the eternalist. This is because the inevitability of an occurrence depends on the character of the physical laws. If the laws are deterministic, the future of the presentist is still nonexistent, but will exist in a determined way. So the argument can work only if the presentist can prove that ontological determinism is false. The usual move here is to turn to quantum mechanics. There is, however, no help to be found in quantum theory since it does not imply the fall of ontological determinism. Two quantum events can be related by some probability estimated from the deterministic evolution of dynamical objects of the theory (either operators or wave functions, depending on the formulation). Such a relation, from the point of view of the spacetime, is as fixed as any other relation between the events. There is no sudden change of probabilities: the probabilities are just a mathematical measure of the propensity of some events to be related. Besides, mathematical objects like probabilities do not change. In this sense, quantum probabilities are not special: the probability of a dice roll to yield a 3 is 1/6, both before and after the rolling (see Romero 2015, appendix). This does not make less ontologically determined the events of throwing the dice and getting the 3. There is no 'collapse' of the wave function. Wave functions, mathematical objects in the Hilbert space, cannot 'collapse' in any meaningful sense (Bunge 1967, 1973; Perez Bergliaffa et al. 1993). What can change is a quantum physical system, not the probability attributed to the event by quantum mechanics. The evolution of the system, when it interacts, is not unitarian and cannot be predicted by quantum mechanics. It must be studied by a quantum theory of measurements, where each case depends of the specific instrumental set up (see Chap. 8).

I also want to emphasize that quantum mechanics is not a background independent theory: it is formulated on a previously assumed spacetime theory (Euclidean spacetime in the case of non-relativistic quantum mechanics, Minkowskian and pseudo-Riemannian spacetimes in the cases of relativistic quantum mechanics and quantum field theory on curve space). Being a background dependent theory, quantum mechanics imports the ontological assumptions of its background (Rovelli 2004).

The other standard argument against eternalism raised by presentists is that it cannot explain the human experience of time and passing. I have addressed this issue in Sect. 10.4 above and in Romero (2015) so I shall only mention here that modern neuroscience supports the idea that the "passage of time" is a construction resulting from the ordering of brain processes (Pöppel 1988; Le Poidevin 2007; Eagleman 2009).

10.9 Relationism Before Time

Event substantialism regarding spacetime does not preclude relationism at a more basic level. Relations among basic events, or 'ontological atoms',[7] can be the basis from which substantival spacetime emerges.

The manifolds adopted in General Relativity to represent spacetime have a pseudo-Riemannian metric and are compact. A very important property of such manifolds is that they are compact if and only if every subset has at least one accumulation point. These points are defined as:

Definition Let E be a topological space and A a subset of E. A point $a \in A$ is called an *accumulation point* of A if each neighbourhood of a contains infinitely many points of A.

For compact Hausdorff spaces,[8] every infinite subset A of E has at least one accumulation point in E.

If we want to represent events at very small scale, the assumption of compactness must be abandoned. The reason is that any accumulation point implies an infinite energy density, since events have finite (but not arbitrarily small) energy, and energy is an additive property. In other words, spacetime must be discrete at the smallest scale. Arguments for discrete spacetime coming from physical considerations can be found, for instance, in Oriti (2014) and Dowker (2006). Also, notice that the thermodynamical argument for the existence of spacetime presented in Sect. 10.7 implies that there exists a microstructure of spacetime, namely:

- P_1: Spacetime has entropy.
- P_2: Only what has a microstructure has entropy.

Then, spacetime has a microstructure.

A possible path towards discrete spacetime is discussed in Appendix A, Sect. A.5.

10.10 An Ontology Cozy for Science

The current physical view of the world is a collection of quantum fields existing in spacetime. The interaction of these fields is local. The properties of spacetime are represented by what is usually interpreted as another physical field, the Lorentzian metric field defined on the continuum 4-dimensional manifold. This field represents both the geometrical properties of spacetime and the potential of gravity. This

[7] These basic events can be thought as some suitable re-interpretation of Leibniz monads (Leibniz 2005).

[8] A manifold E is said to be Hausdorff if for any two distinct elements $x \in E$ and $y \in E$, there exist $O_x \subset E$ and $O_y \subset E$ such that $O_x \cap O_y = \emptyset$.

dual character makes it unique among all physical fields. The metric tensor field, contrarily to the others, is a classical field with infinite degrees of freedom and background independence. Background-independence is the property that the metric of spacetime is the solution of the dynamical equations of the theory.

When standard quantization techniques are applied to gravity, there appear infinitely many independent parameters needed to correctly define the theory. For a given choice of those parameters, one could make sense of the theory; but since it is not possible to carry out infinitely many experiments to fix the values of every parameter, a meaningful physical theory cannot be determined: gravity is perturbatively nonrenormalizable. The appearance of singularities in General Relativity, however, indicates that the theory is incomplete (e.g. Romero 2013b). Another hint that a quantum theory of gravity should emerge from a discretization of spacetime itself comes from black holes. Quantum field theory in curved spacetime shows that the horizon of a black hole has entropy. But the horizon is just a region of spacetime. Spacetime, hence, has an associated entropy as we have seen. A merely continuum spacetime, with its infinite number of degrees of freedom would have an infinitely large entropy. The finiteness of the black hole entropy, then, points to the existence of a discrete substratum for spacetime.

There is another very important difference between the metric field **g** and the fields of the Standard Model of particle physics. The ten coefficients of metric do not represent a physical field, but a class of properties of a substantival entity: spacetime. It is then incorrect to attribute energy to **g**. Properties do not have energy, only substantival entities have (Bunge 1977). Attempts to construct a well-defined and conserved energy for the metric field fail, and only a (non-unique) pseudo-tensor can be constructed within General Relativity.[9] The reason is that the geometrical properties of spacetime are always locally reduced to those of a flat Minkowskian manifold. Physically, we call this condition 'the Equivalence Principle' (Einstein 1907). Energy should be attributed not to the metric, but to substantival spacetime itself. The energy content of spacetime is related to the number of basic events per unit of volume. This number is minimum for nearly flat spacetime, or when the volume is very small ($\sim l_{\rm P}^3$), but it is never zero. It is not possible to eliminate the energy of spacetime through a transformation of coordinates, in the way the metric field can be made locally Minkowskian; existence cannot be suppressed by a mere coordinate change. I suggest that the average minimum energy of spacetime is measured by the cosmological constant. If there is only one basic event in a Planck cubic volume, the energy of such event would be amazingly tiny: $\sim 10^{-91}$ eV.

The ontological views I advocate are in good agreement with these physical considerations. First, spacetime has substantival existence. It can be formally represented by a continuum manifold equipped with a metric tensor field: $\mathrm{ST} \hat{=} \langle E, \mathbf{g} \rangle$. Second, the existence of spacetime implies the existence of events that are past,

[9] Other theories of gravitation, such as the so-called tele-parallel gravity, allow to define an energy associated with spacetime. However, this can be done only with respect to a well-defined reference system (Combi and Romero 2017).

present, and future. Third, the metric field is not akin other physical fields; it represents the geometrical properties of spacetime and does not have independent existence. And forth, as all large scale entities, spacetime emerges from the composition of more basic existents, that I have called ‘basic events’. I suggest that these ontological views can provide an adequate philosophical background for physical research of gravity and cosmology, both classical and quantum.

10.11 Closing Remarks

Undoubtedly, ontology by itself cannot offer a solution to the problems of quantum gravity. But this is not the task of ontology. What should be expected from ontological theories is a framework suitable for the development of scientific research, with no hidden assumptions or confusing terms; a clarification of the basic concepts of our most general theories about the world and its emergence. It is in this sense that I think that a scientifically informed ontology can pave the way for research through the elucidation of our ideas of space, time, and spacetime.

Summing Up Presentism, the doctrine that only present events and things exist, is false. Substantivalism and relationism are not incompatible views if they apply to different scales. At large scales compared to the Planck length spacetime behaves as a substantival entity endowed with energy. General Relativity describes correctly the interaction of spacetime with other material fields. Spacetime is represented by an equivalent (diffeomorphic invariant) class of ordered pairs of the form $\{\langle E, \mathbf{g}\rangle\}$, where E is a 4-dimensional differential pseudo-Riemannian manifold and $\mathbf{g}$ is a metric field on E. Some basic ontological assumptions behind General Relativity should break down at the Planck length. At this level, spaceless and timeless entities might exist and from their relations spacetime would emerge.

Appendix: Axiomatics

Basic Definitions

I give here some basic definitions used in the two axiomatizations that follow in the next section.

The Einstein’s tensor is:

$$G_{ab} \equiv R_{ab} - \frac{1}{2} R g_{ab}, \tag{10.3}$$

where R_{ab} is the Ricci tensor formed from second derivatives of the metric and $R \equiv g^{ab} R_{ab}$ is the Ricci scalar. The geodetic equations for a free test particle in a curved spacetime are:

$$\frac{d^2x^a}{d\lambda^2} + \Gamma^a_{bc}\frac{dx^b}{d\lambda}\frac{dx^c}{d\lambda} = 0, \tag{10.4}$$

with λ an affine parameter and Γ^a_{bc} the affine connection, given by:

$$\Gamma^a_{bc} = \frac{1}{2}g^{ad}(\partial_b g_{cd} + \partial_c g_{bd} - \partial_d g_{bc}). \tag{10.5}$$

The affine connection is not a tensor, but can be used to build a tensor that is directly associated with the curvature of spacetime: the Riemann tensor. The form of the Riemann tensor for an affine-connected manifold can be obtained through a coordinate transformation $x^a \to \bar{x}^a$ that makes the affine connection vanish everywhere, i.e.

$$\bar{\Gamma}^a_{bc}(\bar{x}) = 0, \quad \forall\, \bar{x},\ a,\ b,\ c. \tag{10.6}$$

The coordinate system $\bar{x}^a$ exists if

$$\Gamma^a_{bd,c} - \Gamma^a_{bc,d} + \Gamma^a_{ec}\Gamma^e_{bd} - \Gamma^a_{de}\Gamma^e_{bc} = 0 \tag{10.7}$$

for the affine connection $\Gamma^a_{bc}(x)$. The left hand side of Eq. (10.7) is the Riemann tensor:

$$R^a_{bcd} = \Gamma^a_{bd,c} - \Gamma^a_{bc,d} + \Gamma^a_{ec}\Gamma^e_{bd} - \Gamma^a_{de}\Gamma^e_{bc}. \tag{10.8}$$

When $R^a_{bcd} = 0$ the metric is flat, since its derivatives are zero. If

$$K = R^a_{bcd}R_a^{bcd} > 0$$

the metric has a positive curvature. Sometimes it is said, incorrectly, that the Riemann tensor represents the gravitational field, since it only vanishes in the absence of fields. On the contrary, the affine connection can be set locally to zero by a transformation of coordinates. This fact, however, only reflects the equivalence principle: the gravitational effects can be suppressed in any locally free falling system. In other words, the tangent space to the manifold that represents spacetime is always Minkowskian.

Axiomatic Ontology of Spacetime

The basic assumption of the ontological theory of spacetime I propose is:
Spacetime is the emergent system of the ontological composition of all events.

Events can be considered as primitives. They are characterized by the axiomatic formulation of the theory. Since composition is not a formal operation but an ontological one, spacetime is neither a concept nor an abstraction, but an emergent entity. What I present here is, then, a substantival[10] ontological theory of spacetime. As any entity, spacetime can be represented by a concept. The usual representation of spacetime is given by a 4-dimensional real manifold E equipped with a metric field g_{ab}:

$$\mathrm{ST} \hat{=} \langle E, g_{ab} \rangle \,.$$

I insist: spacetime *is not* a manifold (i.e. a mathematical construct) but the "totality" of all events. A specific model of spacetime requires the specification of those other fields that can affect spacetime. This specification is done through another mathematical field, called the "energy-momentum" tensor field T_{ab}. Hence, a model of spacetime is:

$$M_{\mathrm{ST}} = \langle E, g_{ab}, T_{ab} \rangle \,.$$

The relation between both tensor fields is given by the field equations. The metric field specifies the geometry of spacetime. The energy-momentum field represents the potential of change (i.e. event generation and density) in spacetime.

We can summarize all this through the following axioms. The axioms are divided into syntactic, if they refer to purely formal relations, ontological, if they refer to ontic objects, and semantic, if they refer to the relations of formal concepts with ontological ones. There are no physical axioms at this level.

The basis of primitive symbols[11] of the theory is:

$$B_{\mathrm{Ont}} = \langle \mathcal{E}, \; E, \; \{\mathbf{g}\}, \; \{\mathbf{T}\}, \; \{\mathbf{f}\}, \; \Lambda, \; \kappa \rangle \,.$$

- **P1: Ontological/Semantic**. $\mathcal{E}$ is the collection of all events. Every member e of $\mathcal{E}$ denotes an event.
- **P2: Syntactic**. E is a C^{∞} differentiable, 4-dimensional, real pseudo-Riemannian manifold.
- **P3: Syntactic**. The metric structure of E is given by a tensor field of rank 2, g_{ab}, in such a way that the differential 4-dimensional distance ds between two events is:

$$ds^2 = g_{ab} dx^a dx^b.$$

[10] An entity x has substantival existence iff x interacts with some y, such that $y \neq x$.

[11] A primitive symbol is a symbol not defined explicitly in terms of other symbols.

- **P4: Syntactic**. The tangent space of E at any point is Minkowskian, i.e. its metric is given by a symmetric tensor η_{ab} of rank 2 and trace -2,

$$\eta_{ab} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}.$$

- **P5: Syntactic**. The symmetry group of E is the set of all 4-dimensional transformations $\{\mathbf{f}\}$ among tangent spaces.
- **P6: Syntactic**. E is also equipped with a set of second rank tensor fields $\{\mathbf{T}\}$.
- **P7: Semantic**. The elements of $\{\mathbf{T}\}$ represent a measure of the clustering of events.
- **P8: Ontological—inner structure**. The metric of E is determined by the following equations:

$$\mathbf{G} - \mathbf{g}\Lambda = \kappa\mathbf{T}, \tag{10.9}$$

  or

$$G_{ab} - g_{ab}\Lambda = \kappa T_{ab}, \tag{10.10}$$

  where G_{ab} is the Einstein's tensor. Both Λ and κ are constants.
- **P9: Semantic**. The elements of E represent physical events.
- **P10: Semantic**. Spacetime is represented by an ordered pair $\langle E,\ g_{ab}\rangle$:

$$\mathrm{ST} \hat{=} \langle E, g_{ab}\rangle .$$

- **P11: Semantic**. A specific model of spacetime is given by:

$$M_{\mathrm{ST}} = \langle E, g_{ab}, T_{ab}\rangle .$$

This theory characterize an entity that emerges from the composition of basic, timeless and spaceless events (see below). On the basis of this theory we can formulate a physical theory about how this entity, spacetime, interacts with other systems and the corresponding dynamical laws. Such a theory is General Relativity. The axioms we should add to obtain General Relativity form our ontological theory are:

- **A.1: Semantic**. The tensor field **T** represents the energy, momentum, and stress of any physical field defined on E.
- **A.2: Physical**. Λ is a constant that represents the energy density of spacetime in the absence of non-gravitational fields. The constant κ represents the coupling of the gravitational field with the non-gravitational systems.

- **A.3: Semantic.** $k = -8\pi G c^{-4}$, with G the gravitational constant and c the speed of light in vacuum.

From $\bigwedge_{i=1}^{11} \mathbf{P_i} \;\wedge\; \bigwedge_{i=1}^{3} \mathbf{A_i}$, all standard theorems of General Relativity follow (see Bunge 1967, Covarrubias 1993).

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Appendix A
Event Ontology

A.1 Introduction

In his *Cratylus*, Plato attributed to Heraclitus the doctrine that change is basic and that "all things are in flux" (DK 22A6).[1] I have argued elsewhere that there is nothing in the extant fragments of Heraclitus that may compel us to think that he denied substance and material things (Romero 2012). A pure event ontology is more in accord with the spirit of some minor Socratic schools, such as the Cyrenaics (see, e.g., the book by Ziloli 2013). Regarding Cratylus himself, little is known beyond what Plato included in his dialog.

The preeminence of Plato and Aristotle during Late Antiquity and the Middle Ages led to a loss of interest in event-based metaphysics in the West. The idea that events are prior to things, nevertheless, has been influential in the East through Buddhism. Both the Theravada and Mahayana traditions of Buddhism emphasize the importance of the *Paticca-Samuppada* ('dependent origination') and *Anicca* ('impermanence') as ultimate features of reality. For all major Buddhist schools the world and the self are a manifold of processes and happenings without a stable essence or intrinsic nature. These processes, for the Buddhist, are causally conditioned and dependent on other events. The whole world is an inter-dependent storm of events that, here and there, cluster giving the illusion of stability and delivering the delusion of being.

In modern Western philosophy, processes regained centrality in the work of Leibniz: his *monads*, which he considered to be the basic constituents of the world, are not atoms but "centres of force", i.e. units of change or activity that compose the processes that form the world. In the early twentieth century two prominent

[1]See also Aristotle: "[Plato] as a young man became familiar with Cratylus and the Heraclitean doctrines that all sensible things are always flowing (undergoing Heraclitean flux)" DK 65A3 (The notation refers to the doxography in H. Diels and W. Kranz, *Die Fragmente der Vorsokratiker*, 6th ed., Berlin, 1951.)

G. E. Romero, *Scientific Philosophy*, https://doi.org/10.1007/978-3-319-97631-0

philosophers advocated for an event ontology: Russell (1914) and Whitehead (1920, 1929). Both formulated programs that considered events as basic individuals. Later process philosophers have defined things as "processual complexes possessing a functional unity instead of substances individuated by a qualitative nature of some sort" (Rescher 1996). Things, in this view, are construed as "manifolds of processes". This project, however, has never been accomplished in a rigorous way and in accordance to modern science.

There have been attempts to use the calculus of individuals of Leonard and Goodman (1940) to provide an outline of a formal ontology of events (e.g. Martin 1978), but the topological structure based on the relation of precedence, attributed to the set of all events, is far too poor to account for some very general features of the world. More structure, in particular a metric structure, is required to deal with the totality of events. This fact was already noticed by Russell (1927), but a full theory was never developed.

Later ontological discussions about events have focused on the characterization of events and their identity criteria. The well-known views of Kim (1973), Brand (1977), and Davidson (1980) invoke spatiotemporal categories and cannot serve as a basis for a constructive theory of spacetime upon basic events. Quine's doctrine of the collapse of the categories of physical objects and events into spatiotemporal particulars (Quine 1960) is not a constitutive, but an eliminative theory. Lombard (1986) and Bunge (1977) understand events as changes in things, and hence they think of them as derivative of an ontology of physical objects. Such ontology, although attractive at some level of description for the physical sciences, presents problems related to the violation of Lorentz symmetry: basic things should have an absolute minimum length. The existence of such a length is incompatible with Lorentz invariance and requires an absolute system of reference, which blocks the path to a relativistic theory of spacetime.

I want to offer in this appendix a more elaborate event ontology and briefly discuss its relevancy for the foundations of spacetime theories. In particular, I want to propose a theory about basic timeless events and their possible place as constitutive elements of the world. The theory might be useful for the foundations of some promising approaches to quantum gravity, such as the causal set program. In any case, the theory I present is a sketch that can be expanded in different ways to provide an ontological framework for different areas in science and philosophy.

A.2 A Theory of Basic Events and Processes

I assume that there are events. My writing and your reading of this line are series of events or processes. Of course, there are people that have denied the existence of events. Parmenides denied events or happenings because for something to happen, something should go out of existence, and something that previously did not exist should appear. But nothing can come from nothing, because what is not does not exist, and what does not exist has no causal power. I have sustained that this is a powerful argument (Romero 2012), but its correct interpretation requires a 4-dimensional approach. Allow me now to accept events.

I consider here events as basic entities, primitive elements of an ontological basis. The full meaning of what I understand by an 'event' will be given by the role played by the term in the proposed axiomatic system. The generating basis of the system is

$$\mathcal{B} =< E, \mathcal{E}, e^0, \star >, \tag{A.1}$$

where E is a set, $\mathcal{E}$ is the collection of all events, e^0 is a fiction called the null event, and $\star$ is a binary operation on E. The meaning of all these symbols will become clear through a set of axioms. In what follows I assume as background knowledge the predicate calculus, set theory, semantics, and real analysis. I adopt standard logical notation. The symbol $\triangleq$ denotes the semantic relation of representation (Bunge 1974a, 1974b, Chap. 3). The symbol $\vdash$ is used to mean 'is a theorem'.

In the following theory events are the only individuals that can be values of bound variables. The first axioms are:

- P_1: $(\forall e)_E \; (e \star e = e)$.
- P_2: $(\forall e_1)_E (\forall e_2)_E \; (e_1 \star e_2 \in E)$.
- P_3: $(\forall x)_{\mathcal{E}} (\exists e)_E \; (e \triangleq x)$.
- P_4: $(\forall x)_{\mathcal{E}} \; (e_1 \triangleq x \wedge e_2 \triangleq x) \Rightarrow (e_1 = e_2)$.
- P_5: $(\exists e^0)(\forall e)_E \; (e^0 \star e = e \star e^0 \equiv e)$.
- P_6: $\neg(\exists x)_{\mathcal{E}} \; (e^0 \triangleq x)$.

A few comments are in order. The first two axioms characterize the operation $\star$ as a binary operation (closed on E), that is idempotent on the same individual. Axiom P_2 states that the set E contains both basic and composed events (see definitions D_1-D_6 below). The axiom P_3 is of semantic nature: it states that for each event occurring in the world there is an element in the set E such that it represents the event. Notice that $\mathcal{E}$ is not a set, as E, but a collection of individuals. P_4 establishes that the representation of events is unique. P_5 introduces e^0, which is a neutral element under operation $\star$ in E. The next axiom states that this individual, e^0, is syncategorematic, i.e. it is a fiction that does not represent any real event; see Bunge (1966) and Chap. 2 for details. It is introduced for formal purposes, in order to endow E with some basic mathematical structure. I emphasize: there are not null events in the world.

After these axioms, I introduce some useful definitions:

- D_1: An event $e_1 \in E$ is composed $\Leftrightarrow$ $(\exists e_2, e_3)_E \; (e_1 = e_2 \star e_3)$.
- D_2: An event $e_1 \in E$ is basic $\Leftrightarrow$ $\neg\, (\exists e_2, e_3)_E \; (e_1 = e_2 \star e_3)$.
- D_3: $e_1 \subset e_2 \;\Leftrightarrow e_1 \star e_2 = e_2$ (e_1 is part of e_2 $\Leftrightarrow e_1 \star e_2 = e_2$).
- D_4: $\mathrm{Comp}(e) \equiv \{e_i \in E \mid e_i \subset e\}$ is the composition of e.
- D_5: $E^0 = E \cup \{e^0\}$.
- D_6: If $e \in E$ is composed by basic events, it is called a *process* and denoted by p.

These definitions give the concept of composition and the relation 'being part of', which depends entirely on the basic operation of composition. A process is any composed event. In what follows I shall use, for simplicity, the word 'event' as meaning ‘basic event’, and ‘process’ for ‘composed event’. Note that both events and processes belong to the collection $\mathcal{E}$ and any e and p are elements of the set E. Also notice that the symbol ‘$\subset$’ is not being used in its standard sense of ‘subset’ but in the ontological (actually mereological) sense of ‘is part of’.

The following theorems are immediate:
$\vdash (\forall e)_{E^0}\ (e^0 \subset e)$.
$\vdash < E^0,\ \star,\ e^0 >$ is a commutative monoid of idempotents.

The structure of a monoid is essentially that of a semi-group with neutral element.

Processes, considered as individuals, have descriptions, such as duration and complexity, and then admit predicates. I use capital letters to denote unitary predicates and relations. There is no need, however, to admit properties as values of the bound variables in the formulation of the event ontology. I shall have some nominalistic scruples on this point. I introduce the operation of abstraction from a collection of individuals. Let us consider a formula with a single variable x that runs *only* over processes: ‘$(- - x - -)$’. This formula can be atomic or complex (i.e. formed by atomic formulae connected by standard logic functors). The formula predicates of each individual x such and such a property. We can abstract a virtual (i.e. fictitious) class from such a formula forming the collection (Martin 1969, p. 125):

$$P = \{y : - - y - -\}.$$

Hence, properties are introduced as classes of individuals sharing descriptions. The identity criterion for properties is immediate.

- D7: $F = G \Leftrightarrow (\forall p)_E(Fp \wedge Gp \Rightarrow Fp = Gp)$.
- D8: $R = S \Leftrightarrow (\forall p_1)_E(\forall p_2)_E \ldots (\forall p_n)_E(Rp_1, \ldots, p_n \wedge Sp_1, \ldots, p_n \Rightarrow Rp_1, \ldots, p_n = Sp_1, \ldots, p_n)$.

The first definition means that two properties are identical if and only if they have the same value for any process that satisfies both. The second definition is just the extension from singular properties to relations among several processes. The identity criterion for events is given by

- P7: $(\forall e_1)_E(\forall e_2)_E(e_1 = e_2 \Leftrightarrow \forall F : Fe_1 = Fe_2)$.

This is Leibniz’s identity of the indiscernibles. It is valid for events of any kind: basic ones and processes.

Given the previous definition of F in terms of collections of individuals (events and processes), the universal quantification does not require second order logic. It follows immediately that
$\vdash (\forall e)_E(e = e)$,
$\vdash (\forall p)_E(p = p)$,
i.e., every event is identical to itself. Trivially, the same is valid for processes.

It is convenient now to define two important relations between processes: *overlapping* and *separateness*. Two processes overlap if and only if they have common events. Two processes are separate if and only if they do not overlap. Formally,

- D_9: $p_1 O p_2 \Leftrightarrow (\exists p_i)_E (p_i \subset p_1 \wedge p_i \subset p_2)$.
- D_{10}: $p_1 \backslash p_2 \equiv \neg(p_1 O p_2)$.

The composition of all actual events and processes is the World (W):

$$\neg(\exists e)_E \neg(e \subset W).$$

There is nothing that is not part of the World. The World, W, should not be confused with the Universe, $\mathcal{U}$, the composition of all things in a thing-based ontology as the one given by Bunge (1977) and Romero (2013) or in Chap. 3. The Universe can change, i.e. events and processes take place in the Universe. The World, the composition of all events, cannot change itself because it is not a thing. In an ontology of events, the totality of events is changeless, otherwise there would be an event not included in the totality, which is absurd. Events do not change, they simply *are*. In the sense used here, the Universe can evolve, but not the World, which is fixed. The World is the maximal processes; it is the process of the Universe (the maximal thing admitted by a thing ontology).

Composition is not an adequate ordering relation. So far, the set E is a mess of elements representing basic events and processes. Some events are part of some processes, but there is no order. I introduce some order now. I want to equip E with a relation that would allow for an ordering among basic events of any given list. I cannot adopt a simple relation of "before than", as Reichenbach (1980), Carnap (1958), Grünbaum (1973), and Martin (1978) did, because not all events can be ordered by such a relation without further specification: we know from relativity theory that such an order can be inverted by choosing an appropriate reference system in the case of space-like events. The World simply is not that way. Not all events can be related to each other by a precedence relation. I need to introduce a stronger structure on the set of all events E, if I want to represent with this set the actual World. To achieve this goal, I stipulate that E is a *metric space*.[2]

- D_{11}: E is a metric space if for any two elements e_1 and e_2 of E, there is number $d(e_1, e_2)$, called the *interval* between e_1 and e_2 in accordance with the postulates:

  M1: $d(e_1, e_2) = 0$ iff $e_1 = e_2$.
  M2: $d(e_1, e_2) + d(e_2, e_3) \geq d(e_1, e_3)$ with $e_3 \in E$.

[2]If a weaker structure such as a causal ordering is imposed, then the ordering will be only partial, and we would be unable to accommodate space-like events in the theory. So I adopt a strong structure for the whole World, and then I shall show how local time can emerge from a partial ordering of time-like events.

Lindenbaum (1926) has demonstrated that from these two axioms it follows that[3]:

$\vdash \ d(e_1,\ e_2) = d(e_2,\ e_1)$.

Only in case that $d^2(e_1,\ e_3) > 0$, there is a precedence relation between e_1 and e_3. I postulate:

- P_8: E is a metric space.

Then,

- D_{12}: The event represented by e_1 *precedes* (or is *earlier than*) the event represented by e_3 iff $d^2(e_1, e_3) > 0$.

In short, $e_1 \prec e_3$. Events such that $d^2 > 0$, $d^2 = 0$, and $d^2 < 0$ are called *time-like*, *null*, and *space-like* events, respectively. Notice that d^2 can be negative since non-Euclidean metrics are possible. For instance, for a Minkowskian metric $ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2$ the interval is an imaginary number if the spatial separation of the events (i.e. the part of the metric with signature $(-, -, -)$ is greater than the temporal one, of signature $+$). For events and processes with non-real intervals the precedence relation can be reversed just choosing an adequate coordinate representation from a different reference system. Hence, precedence is a partial ordering relation and not an absolute one in the context of a general geometry.

Given any event represented by $e \in E$, the *future* of e is the set Fut $= \{e' : d^2(e, e') > 0 \ \wedge \ e \prec e'\}$. Similarly, the *past* of e is the set Past $= \{e' : d^2(e, e') > 0 \wedge \neg(e \prec e')\}$. Every event has its own past and future, that depends on the metric d of the space E.

Some relevant theorems:

$\vdash \ < E,\ \prec >$ is a partially ordered set.

$\vdash \ (\forall e_1,\ e_2)_E\ [e_1 \prec e_2 \Rightarrow \neg(e_2 \prec e_1)]$.

$\vdash \ \neg(\exists e)_E(e \prec e^0 \vee e^0 \prec e)$.

All this can be easily generalized to processes.

Perhaps it is convenient at this point to remind that a set is partially ordered if the following conditions are fulfilled:

- Reflexive: For all $x \in E$, $x \preceq x$.
- Antisymmetric: For all $x,\ y \ \in E$, $x \preceq y \preceq x$ implies $x = y$.
- Transitive: For all $x,\ y,\ z \in E$, $x \preceq y \preceq z$ implies $x \preceq z$.

Here, $\preceq \ \equiv \ (\prec \vee =)$.

Once the set E has been equipped with a metric structure, I can make the fundamental semantic assumption of the event ontology: The World is represented by a metric space. In symbols:

- P_9: $E \hat{=} W$.

[3]For Euclidean spaces it is also the case that $d(e_1,\ e_2)\ \geq 0$.

Here, E is a mathematical construct and W is the composition of all events, i.e. the maximal existent in an event ontology. It follows that
$\vdash \quad \neg(\exists e)_E(e \prec W \vee W \prec e)$.

There is no previous or subsequent event to the World, since simply there is not any event outside W. This implies, in turn, that:
$\vdash \quad E$ is closed.

There is no preceding event to the World. Creation, if is understood as causal relation among events (e.g. Bunge 1979), is not even an option for the World in this ontology.

A final step in the formulation of the event ontology is the formal construction of things out of events and processes. This can be done defining things as classes of processes sharing some properties, P, Q, etc.:

$$X = \langle P,\ Q, \ldots \rangle\, p.$$

This formula is true of all processes that satisfy P, Q, ... In this way things are bundles of events defined by shared properties, which are abstracted from conditions imposed on the events. The thing 'Socrates', for instance, is a cluster of events sharing their occurrence in Greece, previous to such and such other events, including processes like 'talking with Plato', and so on. Note the similarity with the qualitative insight proposed by Russell (1914).

I close this section with the remark that there are two relations in the event ontology I am presenting: a relation of composition, that is basic and allows events to form processes, and a partial ordering relation among the elements of E that is a consequence of the metric structure we attribute to this set. As far as the metric structure is postulated these relations must me considered independent. There is a third relation, causation, that can be introduced at the current level, and is derivative of the way composition acts upon events to produce some processes. I turn to it now (see also Chap. 3).

A.3 Causation

Causation is a mode of process generation based on composition (Bunge 1979). It is not the only way of generating processes. Particle decays, such as those of the muon, and other quantum processes generate series of events without causal origination: the existence of no previous event is necessary for the occurrence of the decay. The event of decay is legal (it occurs in conformity to the probabilistic laws of quantum electro-weak theory), but not causal. I adopt the following definition of causal interaction between events: two events represented by e_1 and e_2 are causally related iff there is at least a process p such that both events are components of p, and there never occurs an instance of p in which $e_2 \subset p$ and $\neg(e_1 \subset p)$. Then, I say that e_1 is a cause of e_2.

$$e_1 \rhd e_2.$$

In other words, the process p involving e_2 can never occur without the existence of e_1. The World is legal and determinate, but not strictly causal. There are events that are not causally related and processes that are not causally originated. They result from spontaneous (although lawful) events; for additional details see Bunge (1977, 1979) and Romero and Pérez (2012).

- D_{13}: e_1 is called 'cause' and e_2, 'effect'.
- P_{10}: $(\exists e_1)_E(\exists e_2)_E\ (e_1 \rhd e_2)$.
- P_{11}: $\neg(\exists e)_E\ (e \rhd e)$.
- P_{12}: There are events that belong to the same process but are not causally related.

P_{10} states that some events, but not all, are causally related. P_{11} postulates that no event is cause of itself (Ulfbeck and Bohr 2001). Also notice that P_{12} allows spontaneous events, like quantum occurrences, to be part of a processes and belong to what is called in the physical literature the "causal past" of a given event.

A.4 Spacetime

I call spacetime to the ontological system formed by all events and processes. It is the World, with all its events and the restrictions on the way events are. Spacetime, then, being an emergent entity from a system of structured events, is substantival. I do not endorse a pure metric or manifold substantivalism as characterized by Hoefer (1996), but a constructive substantivalism that can be reduced to pure event relationalism (Romero 2017, Chapter 10).

The mathematical representation of the World *on large scales* can be improved imposing some additional constraints on the set E. To the metric postulates M1 and M2 I add now the following postulates:

P_{13} : The set E is a C^{∞} differentiable, 4-dimensional, real pseudo-Riemannian manifold.

P_{14} : The metric structure of E is given by a tensor field of rank 2, g_{ab}, in such a way that the differential interval ds between two events is given by: $ds^2 = g_{ab}dx^a dx^b$.

A real 4-D manifold is a set that can be covered completely by subsets whose elements are in a one-to-one correspondence with subsets of $\Re^4$. The manifold is pseudo-Riemannian if the tangent space in each element is flat but not Euclidean. Each element of the manifold represents one (and only one) event. Notice that it is incorrect to say that spacetime *is* the manifold (a position know as manifold substantivalism); spacetime is *represented* by the manifold and its metric structure. We adopt four dimensions because it seems enough to give four real numbers to provide the minimal characterization of an event. We can always provide a set of four real numbers for every event, and this can be done independently of the intrinsic geometry of the manifold. If there is more than a single characterization of an event, we can always find a transformation law between the different coordinate systems. This is a basic property of manifolds.

I have introduced the continuum through the adoption of a manifold structure. This is a major step and I shall come back to the implications of adopting the continuum hypothesis in the next section.

I am ready now to introduce the Equivalence Principle and the specification of the metric through two additional postulates:

P_{15} : The tangent space of E at any point is Minkowskian, i.e. its metric is given by a symmetric tensor η_{ab} of rank 2 and signature -2.

P_{16} : The metric of E is determined by a rank 2 tensor field T_{ab} through Einstein's field equations:

$$G_{ab} - g_{ab}\Lambda = \kappa T_{ab}. \tag{A.2}$$

In these equations G_{ab} is Einstein's tensor, formed by second order derivatives of the metric. In the second term on the left, Λ is called the cosmological constant, whose value—according to observations—is thought to be small but not null. The constant κ on the right side is -8π in units of $c = G = 1$. Finally, T_{ab} represents the energy and momentum of all fields other than the metric itself, and satisfies conservation conditions ($\nabla_b T^{ab} = T^{ab}{}_{;b} = 0$) from which the equations of motion of physical things (i.e. bundles of events) can be derived. The solutions of such equations are the histories of things: 4-dimensional subsets of E. The solutions can be seen as continuous series of events (processes) represented on the manifold E. Einstein's field equations are a set of ten non-linear partial differential equations for the metric coefficients.

Postulates P_{15} to P_{16} given above, with an adequate formal background (Bunge 1967; Covarrubias 1993; Perez Bergliaffa et al. 1998; Romero 2014) imply the theory of general relativity. The conceptual representation of spacetime $\mathcal{ST}$ is given by a 4-dimensional manifold equipped by a metric. In standard relativistic notation:

$$W = \mathcal{ST} \hat{=} \langle E, g_{ab} \rangle .$$

General Relativity, then, can be obtained from our ontology just with some simple additional constraints upon the set E that represents the totality of events. It is a natural extension of the proposed ontology that applies to processes with large number of events, in such a way that they can be represented by continuous functions. I insist on an important point: spacetime *is not* a manifold (i.e. a mathematical construct) but the "totality" (the composition in our characterization) of all events and processes plus some metric structure.

Since the ontic basis of the $\mathcal{ST}$-model is the *totality* of events, the World is ontologically determined. This does not imply that the World is necessarily *predictable* from the model. In fact, Cauchy horizons can appear in the manifold E for many prescriptions of the field T_{ab} (e.g. Hawking and Ellis 1973; Joshi 1993). One thing is the World, and another our representations of it. Not all models of the

World admit full predictability since in many of them the Cauchy problem cannot be well posed.

In the World, objects are 4-dimensional bundles of events (Heller 1990). Beginning and end, are just boundaries of objects, in the same way that the surfaces and boundary layers are limits of 3-dimensional slices of such objects. The child I was, long time ago, is just a temporal part of me. The fact that these parts are not identical is not mysterious or particularly puzzling, since spacetime, although changeless itself, is composed of events. We can understand the intrinsic changes of the World as asymmetries in the geometry of spacetime (Romero 2013).

Although so far I have presented spacetime as a structured system of events and processes, I have not shown that its structure naturally emerges from basic relations among basic events. To exhibit the mechanism that enforces such an emergence, i.e. to construct the metric structure upon an operation such as composition of basic events, is a major problem for any ontology of spacetime, and arguably, the main challenge of most approaches to quantum gravity. Nevertheless, I think that the theory of events I have outlined might help to formalize some promising proposals of constructive spacetime theories such as the so-called causal set approach. In what follows I shall present some preliminary steps towards providing an ontological foundation for such theory, and some hints about how to proceed towards the transition from discrete to continuum representations.

A.5 Discrete Spacetime

As far as we can decompose a given process into more basic events, in such a way that E can be approximated by a compact non-denumerable metric space, the continuum representation for the totality of events will work. But if there are atomic[4] events, there will be a sub-space of E that is countable (or denumerable if it is infinite) and ontologically basic. There is, in such a case, a discrete substratum underlying the continuum manifold, which is, ultimately, a large number approximation. Since the quantum of action is given by the Planck constant, it seems a reasonable hypothesis to assume that atomic events occur at the Planck scale, $l_{\mathrm{P}} = \sqrt{\hbar G/c^3}$. If there are atomic events, a new postulate should be introduced:

$\mathrm{P}_{\text{discrete}}$. Card $(E) < \mathfrak{c}$.

Here c is the cardinality of the continuum $c = 2^{\aleph_0}$. If we accept the continuum hypothesis[5] the set of basic events is numerable. The continuum representation would be only an approximation that is adequate for complex processes and large numbers of basic events. The continuum spacetime is then a large-scale emergent

[4]I use the word 'atomic' in the original Greek sense of $\acute{\alpha}\tau o\mu o\varsigma$, "uncut", "individual", "not decomposable". It should be considered as synonymous of 'basic', introduced in D_2.

[5]The continuum hypothesis asserts that there are no sets whose cardinality is strictly between $\aleph_0$ and $\mathfrak{c}$; it implies that $\mathfrak{c} = \aleph_1$.

property, absent at the more basic ontological level. This is similar to, for instance, considering the mind as a collection of complex processes of the brain, emerging from arrays of 'mindless' neurons. The word 'emergence', in the present context, means apparition of qualitative novelty (Bunge 2003). The postulate $\mathrm{P}_{\mathrm{discrete}}$ says that the cardinality of the set of basic events is not that of the real numbers.

If this view is correct, discrete spacetime should be represented by a theory about the relations among basic events yielding the ontological emergence of spacetime and its geometrical properties (what we call classical gravitation) for large numbers of events. The basic substratum of the World would be purely ontological instead of physical; the physical realm emerges at scales where dynamics makes sense.

Atomic events and their relations can be represented by a partially ordered set (a *poset*, see Bombelli et al. 1987). It can be proved, under some assumptions, that the dimension, topology, differential structure, and metric of the manifold where a poset is embedded is determined by the poset structure (Malament 1977). If the order relation is interpreted as a causal relation, the posets are called *causal sets* (or *causets*). We have already seen that this relation obtains in terms of the basic relation of composition in our ontology.

A given poset can be embedded into a Lorentzian manifold. An embedding is a map taking elements of the poset into points in the manifold such that the order relation of the poset matches the causal ordering of the manifold. A further criterion is needed, however, before the embedding is suitable. If, on average, the number of poset elements mapped into a region of the manifold is proportional to the volume of the region, the embedding is said to be faithful (Sorkin 1990; Walden 2010). The poset is then called *manifold-like*.

A conjecture is usually made to ensure that the same poset cannot be faithfully embedded into two different spacetimes that are dissimilar on large scales. Alternatively, a poset can be generated by *sprinkling* points (events) from a Lorentzian manifold. By sprinkling points in proportion to the volume of the spacetime regions and using the causal order relations in the manifold to induce order relations between the sprinkled points, a poset can be produced that (by construction) can be faithfully embedded into the manifold.

To maintain Lorentz invariance[6] this sprinkling of points must be selected randomly using a Poisson process. Thus, the probability of sprinkling n points (events) into a region of volume V is:

$$P(n) = \frac{(\rho V)^n e^{-\rho V}}{n!}, \tag{A.3}$$

where ρ is the density of the sprinkling.

[6]Lorentz invariance is incompatible with most approaches to quantum gravity and with ontologies based on things, since in a Lorentzian world it is impossible to have an *absolute* minimum length.

A *link* in a poset is a pair of elements $e_1,\ e_2 \in E$ such that $e_1 \prec e_2$ but with no $e_3 \in E$ such that $e_1 \prec e_3 \prec e_2$. In other words, e_1 and e_2 represent directly linked events.

A *chain* is a sequence of elements $e_0,\ e_1, \ldots, e_n$ such that $e_i \prec e_{i+1}$ for $i = 0, \ldots, n-1$. The length of a chain is n, the number of links used. A chain represents a specific type of process.

A geodesic between two poset elements can then be introduced as follows: a geodesic between two elements $e_i,\ e_f \in E$ is a chain consisting only of links such that $e_0 = e_i$ and $e_n = e_f$. The length of the chain, n, is maximal over all chains from e_i to e_f. In general there will be more than one geodesic between two elements. The length of a geodesic should be directly proportional to the proper time along a time-like geodesic joining the two spacetime points if the embedding is faithful.

A major challenge is to recover a realistic spacetime structure starting from a numerable poset. A step in the direction of solving the problem is a classical model in which elements are added according to probabilities. This model is known as classical sequential growth (CSG) dynamics (Rideout and Sorkin 2000). The classical sequential growth model is a way to generate posets by adding new elements one after another. Rules of how new elements are added are specified and, depending on the parameters in the model, different posets result. The direction of growing gives rise to a global time, which does not exist at the fundamental poset event level. In the large number limit, the poset becomes manifold-like. The local time we 'feel' is given by the local causal ordering of the events and not by the global 'cosmic' time.

Another challenge is to account for the remaining referents of General Relativity, namely, gravitating objects. I have proposed above that physical objects can be understood as clusters of processes, and hence they can emerge as inhomogeneities in the growing pattern of events. This conjecture is supported by the observation that whatever exists seems to have energy, and energy is just the capability to change.[7] The most populous the bundle of events is, the larger the associated energy results. In this view, spacetime curvature emerges as well, just as a measure of the number of basic events. Objects, physical things, would be nothing else than clusters of events.

Any object has energy and any object can be defined as the result of a myriad of events. Objects, then, appear as a large number approximation to clusters of events. They inherit energy from the events that form them. In such a context, I can define energy as an additive quantity associated with composition. I postulate:

P_{17} : $(\forall e)_E(\exists \mathcal{W})(\mathcal{W}$ is a real function $\mathcal{W} : E \to \Re)$.

P_{18} : If $\mathrm{Comp}(e) = \{e_1, e_2, \ldots, e_n\}$ then $\mathcal{W}(e) = \mathcal{W}(e_1) + \mathcal{W}(e_2) + \ldots + \mathcal{W}(e_n)$, where all e_i are basic events.

[7] I notice that a thing-based ontology, such as Bunge's, is an emergent ontology of the system here presented, valid for any level well above the Planck scale.

Let us define:

$D_{14}: \ \text{Eff}(e) = \{e_i, \text{ such that } e_i \text{ is an effect of } e\}$
$D_{15}: \ \mathcal{W}(e) \equiv \text{Card [Eff}(e) \text{]: `energy' of } e,$

Then,
$\vdash \ \mathcal{W}(e_1) > \mathcal{W}(e_2) \rightarrow \text{Card [Eff}(e_1) \text{]} > \text{Card [Eff}(e_2) \text{]}.$

In words, if the energy of an event is greater than the energy of another, then the former event produces more events than the latter (its effect is stronger). It is conceivable, but not necessarily true, that all events might have originated in a single, very energetic event. Notice that the effects of an event can be infinite in number, but this does not imply an infinite energy for the chain, since conservation of energy requires that if there are more than a single effect, the energy is divided among the successive events, in a similar way as it occurs in a particle cascade. Insofar as there are more than one basic event, they can be differentiated by their sole intrinsic property (energy) and by their relational properties. Composed events (processes), on the other hand, have emergent properties.

I illustrate the above considerations in Fig. A.1, which shows a Hasse-like diagram (see Dowker 2013). This diagram is a graph-theoretic representation of a finite partially ordered set. The dots represent events and the arrows indicate the asymmetric link between events. Events connected by successive arrows are processes. I have added circles centred at each event. The area of these circles represents the energy of the event. Since energy is conserved, at each level[8] of generation, L_i, the total area in linked circles is constant. I do admit spontaneous basic events: these appear in the graphic without being generated by previous events. Global time emerges in the graph as the direction of growth. For the emergence of spatial dimensions see Perez Bergliaffa et al. (1998). After a large number of levels a continuum manifold is a good representation. The clustering of events giving rise to curvature is pictorially indicated in the upper part of the figure.

The transition from clustering to curvature is mediated by energy. If $E' \subset E$ has n elements, then

$$\mathcal{W}(E') = \Sigma_{i=1}^{n} \mathcal{W}(e_i), \quad e_i \in E', \tag{A.4}$$

and we can introduce an energy density $\rho = \mathcal{W}(E')/V$, where V is the volume of E' in the metric space E. This energy density forms a component of a tensor field on E that is related to the curvature of E by Einstein's field equations. The implementation of this proposal should be elaborated in detail, but the final implication is clear; there is just one, changeless entity: spacetime. I guess Parmenides would approve these speculations.

The World, under the perspective presented here, would be a maelstrom of events; the things, people, the galaxies of the universe, would arise as a pattern in that storm.

[8]Levels are define by space-like classes of events.

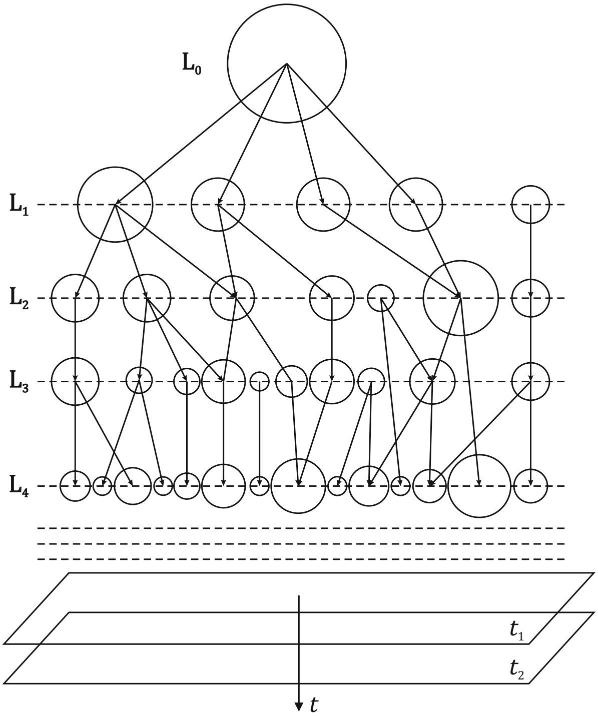

Fig. A.1 Graphic representation of discrete event generation and transition to spacetime. The circles around each event represent energy, defined as the capacity to generate new events. See main text for details

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Appendix B
Boolean Algebra

A Boolean algebra is a six-tuple consisting of a set A, equipped with two binary operations $\wedge$ (called "meet" or "and"), $\vee$ (called "join" or "or"), a unary operation $\neg$ (called "complement" or "not") and two elements 0 and 1 (called "bottom" and "top", or "least" and "greatest" element, also denoted by the symbols $\perp$ and $\top$, respectively), such that for all elements a, b and c of A, the following axioms hold:

- $a \vee (b \vee c) = (a \vee b) \vee c$; $a \wedge (b \wedge c) = (a \wedge b) \wedge c$ (Associativity).
- $a \vee b = b \vee a$; $a \wedge b = b \wedge a$ (Commutativity).
- $a \vee (a \wedge b) = a$; $a \wedge (a \vee b) = a$ (Absorption).
- $a \vee 0 = a$; $a \wedge 1 = a$ (Identity).
- $a \vee (b \wedge c) = (a \vee b) \wedge (a \vee c)$; $a \wedge (b \vee c) = (a \wedge b) \vee (a \wedge c)$ (Distributivity).
- $a \vee \neg a = 1$; $a \wedge \neg a = 0$ (Complements).

G. E. Romero, *Scientific Philosophy*, https://doi.org/10.1007/978-3-319-97631-0

Appendix C
Probabilities

Axioms

A probability space consists of a triplet $\langle \Omega, \ F, \ P\rangle$, where:

1. Ω is a space of points ω, called the sample space and sample points.
2. F is a σ-field of subsets of Ω.[1] These subsets are called 'events'.
3. P is a probability measure on F. Henceforth we refer to P as simply a probability.

- **First axiom**. The probability of an event is a non-negative real number:

$$P(E) \in \Re, P(E) \geq 0 \ \forall E \in F, \tag{C.1}$$

  where F is the event space. In particular, $P(E)$ is always finite, in contrast with more general measure theory. Theories which assign negative probability relax the first axiom.
- **Second axiom**. The probability that some elementary event in the entire sample space will occur is 1. More specifically, there are no elementary events outside the sample space.

$$P(\Omega) = 1. \tag{C.2}$$

  If it is not precisely defined the whole sample space, then the probability of any subset cannot be defined either.

[1] A σ-algebra or σ-field on a set X is a collection Σ of subsets of X that includes the empty subset, is closed under complement, and is closed under countable unions and countable intersections. The pair $(X, \ \Sigma)$ is called a measurable space.

G. E. Romero, *Scientific Philosophy*, https://doi.org/10.1007/978-3-319-97631-0

- **Third axiom**. This is the assumption of σ-additivity: Any countable sequence of disjoint sets (synonymous with "mutually exclusive") events $E_1, E_2, \ldots$ satisfies:

$$P\left(E_1 \cup E_2 \cup \ldots\right) = \sum_{i=1}^{\infty} P(E_i). \tag{C.3}$$

Appendix D
Suggested Readings

In this appendix I offer the reader some suggestions on books that I deem helpful for deeping in the topics of this book. The list is not comprehensive. I have included just some books that I enjoyed and consider very useful. The literature on the matters touched upon in this book is huge, and any selection of a few volumes is personal.

For a comprehensive treatment of most of the issues discussed in this book I strongly recommend Bunge's *Treatise*. For a short general introduction, Rescher's *Philosophical Inquiries*:

- Bunge, M. 1974–1989, Treatise on Basic Philosophy, 8 Volumes, Dordrecht: Kluwer.
- Rescher, N. 2010, Philosophical Inquiries: An Introduction to Problems of Philosophy, Pittsburgh: University of Pittsburgh Press.

Books on Logic and Semantics

- Tarski, A. 1983, Logic, Semantics, Metamathematics, 2nd Ed. Indianapolis: Hackett. A collection of Tarski's major contributions.
- Martin, R.M. 1958, Truth and Denotation, London: Routledge and Kegan Paul. An extremely clear presentation of most major topics in semantics. Very lucid book.
- Boolos, G.S., Burgess, J.P., and Jeffrey, R.C. 2007, Computability and Logic, Cambridge: Cambridge University Press; 5 edition. A good and popular introduction to modern logic.
- Carnap, R. 1948, Introduction to Semantics, Cambridge: HUP. Classic Carnap's book on semantic. A difficult but important contribution.
- Carnap, R. 1958, Introduction to Symbolic Logic and its Applications, New York: Dover. An outstanding treatment of both logic and semantics, with many applications.

G. E. Romero, *Scientific Philosophy*, https://doi.org/10.1007/978-3-319-97631-0

- Geach, P. and Black, M. (eds. and trans.), 1980. Translations from the Philosophical Writings of Gottlob Frege, 3rd ed., Oxford: Blackwell (1st ed. 1952). A translation of Frege's major papers including 'Sense and reference'.
- Tarski, A. 1995, Introduction to Logic: and to the Methodology of Deductive Sciences, New York: Dover (1st ed. 1941). Superb. Still one of the best introductions to logic and its applications.
- Kirkham, R.L. 1995, Theories of Truth. Cambridge, Massachusetts: MIT Press. One of the best surveys of theories of truths.
- Quine, W.V. 1960, Word and Object, Cambridge: MIT Press. A seminal work about the relation between language and the world.
- Niiniluoto, I. 1987, Truthlikeness, Dordrecht: Kluwer. On the concept of truth in science. An important work.
- Keefe, R. 2000, Theories of Vagueness. Cambridge University Press: Cambridge. All aspects of vagueness.

Books on Ontology

- Bunge, M. 2003, Emergence and Convergence, Toronto: University of Toronto Press. A lucid treatment of the two most important ontological processes.
- Lowe, E.J. 2002, A Survey of Metaphysics, Oxford: Oxford University Press. A good overview and starting point.
- Simons, P. 1987, Parts, Oxford: Oxford University Press. Probably the best modern introduction to mereology.
- Küng, G. 1967, Ontology and the Logistic Analysis of Language, Dordrecht: Reidel. Clear and concise.
- Edwards, D. 2014, Properties, Cambridge: Polity Press. Nice overview of current ideas about properties.
- Ladyman, J. and Ross, D. 2007, Everything Must Go, Oxford: Oxford University Press. An vigorous criticism of contemporary metaphysics and a defence of ontic structuralism.

Books on Epistemology

- Bunge, M. 1998, Philosophy of Science: From Problem to Theory, New York: Transaction Publishers.
- Bunge, M. 1998, Philosophy of Science: From Explanation to Justification, New York: Transaction Publishers. Along with the previous entry, comprehensive treatment by a philosopher-scientist who knows the business.
- Rescher, N. 2003, Epistemology, New York: State University of New York Press. A good overview from America's leading pragmatist.

- Rescher, N. 2000, Nature and Understanding. Oxford: Oxford University Press. Another excellent, science-informed volume by Rescher, with many original ideas.
- Psillos, S. 1999, Scientific Realism: How Science Tracks Truth, London: Routledge. A superb defence of realism in science.

Books on Ethics

- Schlick, M. 1962, Problems of Ethics, New York: Dover. Schlick classic book is still a highly stimulating reading.
- Kraft, V. 1981, Foundations for a Scientific Analysis of Value. Dordrecht: Reidel. One of the first books to deal with ethics and axiology from a scientific point of view. Excellent.
- Mackie, J.L. 1977, Ethics: Inventing Right and Wrong. Harmondsworth: Penguin. Classic but not free of problems. Nevertheless, an interesting reading.
- Rescher, N. 2014, A System of Pragmatic Idealism, Volume II: The Validity of Values, A Normative Theory of Evaluative Rationality, Princeton: Princeton University Press.
- Harris, S. 2010, The Moral Landscape. New York: Free Press. Controversial and well-argued.

Books on Aesthetics

- Graham, G. 1997, Philosophy of the Arts. London: Routledge. A nice introduction.
- Agassi, J. and Jarvie, I. 2008, A Critical Rationalist Aesthetics. Amsterdam: Rodopi.
- Saw, R.L. 1972, Aesthetics: An Introduction. London: The Macmillan Press. Another useful introduction.
- Kivy, P. (ed.) 2003, The Blackwell Guide to Aesthetics. Oxford: Blackwell Publishing Ltd. Good survey. The chapter on the ontology of art is particularly good.
- Thomasson, A., 1999, Fiction and Metaphysics, Cambridge: Cambridge University. An important source on fictionalism.

Books on Philosophy of Mathematics

- Beth, E.W. 1964, The Foundations of Mathematics, New York: Harper and Row. Outstanding, clear, comprehensive. An essential book.

- Curry, H.B. 1951, Outlines of a Formalist Philosophy of Mathematics, Amsterdam: North Holland Publishing Company.
- Bostock, D. 2009, Philosophy of Mathematics. West Sussex: Wiley-Blackwell. One of the best introductions.
- Mayberry, J.P. 2000, The Foundations of Mathematics in the Theory of Sets. Cambridge: Cambridge University Press.
- Benacerraf, P. and Putnam, H. (eds.) 1983, Philosophy of Mathematics: Selected Readings (2nd Edition). Cambridge: Cambridge University Press. A classic anthology with many outstanding papers.

Books on the Philosophy of Quantum Mechanics

- Jammer, M. 1974, The Philosophy of Quantum Mechanics: The Interpretations of QM in historical perspective. New York: John Wiley and Sons. Excellent overview.
- Mauldin, T. 2011, Quantum Non-Locality and Relativity, West Sussex: Wiley-Blackwell. A clear introduction to EPR and non-local effects in quantum mechanics.
- Jammer, M. 1966, The Conceptual Development of Quantum Mechanics. New York: McGraw Hill. Indispensable to understand the evolution of quantum mechanics.
- Lewis, P.J. 2016, Quantum Ontology: A Guide to the Metaphysics of Quantum Mechanics. Oxford: Oxford University Press. A well-informed introduction.
- Bunge, M. 1967, Foundations of Physics. New York: Springer. This books contains a rigorous axiomatization of elementary quantum mechanics and many insightful remarks of the theory.

Books on the Spacetime Philosophy

- Price, H. 1997, Time's Arrow and Archimedes' Point. Oxford: Oxford University Press. Perhaps the best book on the direction of time.
- Earman, J. 1989, World Enough and Space-Time. Cambridge (Ma): The MIT Press. Absolute and relational theories in perspective.
- Nerlich, G. 1994, What Spacetime Explains? Cambridge: Cambridge University Press. Contains many arguments for substantivalism.
- Friedman, M. 1983, Foundations of Space-Time Theories. Princeton: Princeton University Press. A classic and highly recommendable reading.
- Oaklander, L.N. 2004, The Ontology of Time. Amherst: Prometheus Books. Arguments against presentism.

Index

G. E. Romero, *Scientific Philosophy*, https://doi.org/10.1007/978-3-319-97631-0