# Reductionism, Emergence and Levels of Reality

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## The Importance of Being Borderline

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*To the glorious memory of Ludwig Boltzmann who struggled against the stream of his time*

# Foreword

Newton's third law does not apply to the interaction between philosophers ('them') and physicists ('us'). It has usually been asymmetrical, with 'us' influencing 'them', without 'them' acting on 'us'. In a way this is natural, because the raw material that philosophers study are the discoveries and theories of science and the interactions between scientists, while the primary preoccupation of physicists is not the study of philosophy or philosophers. I do not deny that there have been eminent scientists (Einstein, Poincaré, Bohr…) who have pondered on the philosophical significance of the scientific picture of the world, and much of what they said has been immediately appreciated by practicing scientists. But their wise intellectual interventions have usually been outside the philosophical mainstream.

This book by Sergio Chibbaro, Lamberto Rondoni and Angelo Vulpiani (CRV) is an exception. Although their day job is the practice of theoretical physics, they have something genuinely new to say about the physicist's picture of the world, that should be of interest to philosophers. Their focus is on what has long been studied by philosophers as 'the problem of reduction'. This concerns the relations between different levels of description of physical phenomena.

Optics is a good example. Light can be described in terms of the rays of geometrical optics, as interfering waves, as electromagnetic fields, or as the photons of quantum field theory. These are levels of increasing generality; each encompasses phenomena described at the previous levels and also includes new phenomena that were unexplainable earlier. But the concepts and mathematical expressions of these levels are very different, and moving between them is almost always challenging. It is far from straightforward to derive the formula relating the object and image of a simple lens by starting from the field operators of quantum optics supposedly the deepest of our current pictures of light.

This illustrates a wider difficulty. One can have a general theory—or even, as some envisage, the theory of everything—which stubbornly resists attempts to employ it to explain phenomena that were well understood at more elementary levels: at the more sophisticated level, they are emergent. This was cleverly caricatured in Ian McEwen's novel *Solar*: a string theorist, caught by his wife in a compromising situation with another woman, tries to reassure her: "Darling, I can explain everything". It often happens that theories claiming great explanatory reach are in fact powerless to explain many particular phenomena. A political analogy comes to mind: the ideologist who loves all humanity but behaves badly to every individual person he encounters.

The resolution of these difficulties starts from the observation that the theories of physics are mathematical, and relations between them involve limits as some parameter vanishes: wave optics ‘reduces to’ geometrical optics when the wavelength is negligibly small, quantum physics ‘reduces’ to classical physics when Planck’s constant can be neglected, etc. Therefore understanding relations between levels must involve the study of limits, that is, mathematical asymptotics. And the central reason why ‘reduces to’ is so problematic is the fact that the limits involved are usually singular. These singular limits should be not regarded as a nuisance, and certainly not as deficiencies of the more general theories. On the contrary, they should be embraced with enthusiasm, because they are responsible for fundamental phenomena inhabiting the borderlands between theories—phenomena at the forefront of physics research, such as critical phenomena in statistical mechanics, fluid turbulence and the universal statistics of the energy levels of highly excited quantum systems.

CRV fully appreciate these ideas; hence their subtitle *The Importance of Being Borderline*. And they explore them in depth and in detail. There are some philosophers who have grasped the significance of singularities in mathematical asymptotics for the understanding of theory reduction—Robert Batterman and Alisa Bokulich come to mind—but they remain a minority. The value of CRV’s account is that it is the first full-length and wide-ranging exposition of this point of view by physicists who are sensitive to the concerns of philosophers.

Bristol, UK, December 2013 Michael Berry

# Preface

Considerate la vostra semenza:
fatti non foste a viver come bruti,
ma per seguir virtute e canoscenza

(Consider your origin;
you were not born to live like brutes,
but to follow virtue and knowledge)

Inferno, Canto XXVI Dante Alighieri

The attempt to explain the sensible world in terms of a few unifying principles has been a constant of scientific thought since the times of the Presocratic philosophers, who believed to have identified several fundamental elements of which the world had to be made: air for Anaximenes; water for Tales; and air, water, earth and fire for Empedocles. Subsequently, Pythagoras tried to interpret everything sorting out of relationships among integer numbers.

In the fifth century B.C. Democritus boldly hypothesised that reality, which appears so varied and changeable, is nothing but a collection of indivisible and eternal parts, or *atoms*. In one of the few fragments which has survived to our times, the fundamental hypothesis of Democritus can be quite clearly summarised:

Reason: *Sweet exists by convention, bitter by convention, heat by convention, cold by convention, color by convention; but atoms and the void exist in truth.*

Over the centuries, despite the ups and downs, the doctrine of Democritus, has been a landmark of science, and in physics there has been a great deal of progress thanks to the clear distinction that has been made between subjective perception and objective reality. Currently, for example, it is understood how apparently subjective properties such as temperature and colour can be unambiguously understood in terms of physical objective quantities, such as molecular motion and the vibrations of the electromagnetic field.

The grand theory of Democritus was visionary but faced major challenges, because the total objectivity that seems so attractive in the development of a unified conceptual framework poses problems that are difficult to solve. Much as one can be firmly convinced that the ultimate essence is represented by atoms, certain questions cannot be avoided: only through our senses, and with the mediation of appropriate technological tools that are conceptual extensions of our senses, can one hope to reveal the atomic structure of matter.

This was already clear to Democritus; here, as in his dialogue, the Senses respond to Reason:

*Wretched mind, after receiving from us your knowledge, do you try to overthrow us? The overthrow will be your downfall.*

The founder of atomism formulated in a very clear fashion the problem that will be discussed in this book: the issue of reduction in physics. The idea, in its simplest form, is that *the whole is nothing more than the sum of the parts*; that is, the behaviour of things is directly determined by the properties of their elementary constituents. The properties observed at the level of the whole are related to the properties at a lower level of observation, which hence seem to be more fundamental. For example, the motion of a fluid can be related to that of its molecules, or, climbing much higher in the hierarchy of levels, consciousness can be related to the behaviour of neurons. Reductionism is then the activity concerned with the relation between different theories that attempt to describe different levels of reality, or different levels of observation, and, through a qualitative leap consisting of many simplifications, ultimately to relate the different sciences: psychology, physiology, biology, chemistry and physics.

Reductionism, or more generally the relationship connecting the different sciences, is perhaps one of the few issues of the scientific culture which has been also considered in literature. How can one forget the bewildered Mr. Palomar, immortalised by Italo Calvino, who muses over the sea, cheese, the flight of birds and the meadows:

*The lawn is a collection of grasses—this is how the problem must be formulated that includes a subcollection of cultivated grasses and a subcollection of spontaneous grasses… The two subcollections, in their turn, include various species, each of which is a subcollection, or rather it is a collection that includes the subcollection of its own members, which are members also of the lawn and the sub-collection of those alien to the lawn… is "the lawn" what we see or do we see one grass plus one grass plus one grass…? What we call "seeing the lawn" is only an effect of our coarse and slapdash senses; a collection exists only because it is formed of discrete elements. There is no point in counting them, the number does not matter; what matters is grasping in one glance the individual little plants, one by one, in their individualities and differences* (Calvino 1983).

It is clear that Mr. Palomar, and not only he, is continually oscillating between the two opposite points of view that see the lawn either as the sum of so many blades of grass or as something more than just all the individual seedlings. The reality certainly shows a complicated (or complex?) structure of relations, and the dream of a unified interpretation of all phenomena in terms of several simple laws, from which all can be deduced, has attracted and continues to attract almost anyone who has genuine philosophical and scientific interests.

Reductionism seems also to be one of the few topics still capable of stirring peremptory and robust discussions among dedicated scholars. As example, we propose three contributions with significant titles, respectively by Atkins, Midgley and Edelman: *The Power of Science Limitedness; Reductive Megalomania* and *Individual and Soul Memory: Against Silly Reductionism*, included in an interesting volume that collects the opinions of authors having different points of view (Cornwell 1995).

Pondering the difficulties faced in the attempt to show that the behaviour of real systems can be deduced from simple laws, the ‘hard-core’ reductionists, who have their stronghold in high-energy physics, typically acknowledge obvious technical problems, but insist that reduction is in principle possible and conceptually correct. This radical reductionism is sometimes shared by scientists working in other branches of science. The well-known chemical-physicist Atkins claims that a true scientist has to be reductionist and that an anti-reductionist point of view is necessarily obscurantist: *Theism (and the implicit rejection of reductionism) is a system of knowledge based on ignorance, and that twin of ignorance, fear*.

Atkins champions a certain vulgate which tends to equate the radical reductionist with the ‘hard-core’, true lovers of the mathematical and hard sciences, such as physics, who do not indulge in extra-scientific considerations, like those concerning morality and religion. In contrast, anti-reductionists would be incurable romantic people, who complain about the cold rationality of ‘official science’. Nevertheless, the very same source (Cornwell 1995) collects papers by scientists of impeccable reputation, like Dyson, Chaitin and Edelman, whose positions are clearly non-reductionist.

In fact, the state of affairs is rather complex. For instance, the Italian philosopher Severino (1997), contrary to folkloristic vulgarisations, believes that reductionism is one of the pillars of religion:

> “reductionism” is not the enfant terrible of present-day scientific, physicalistic culture: the desire to connect something to its origin—especially the desire to connect the world to its divine origin—is reductionism. Theology is the fundamental form of reductionism. Indeed, theology reduces the essence of the world to God, in the same fashion that in science, one day, reductionists will reduce all human reality to movements of elementary particles.

Feigenbaum, one of the “fathers” of chaos theory, similarly maintains in an interview reported in (Horgan 1997), that: *many physicists like the idea of final theories because they use it to replace God.* Finally the words of Laughlin and Pines (2000) are particularly poignant: *The belief on the part of many that the renormalisability of the universe is a constraint on an underlying Theory of Everything rather than an emergent property is nothing but an unfalsifiable article of faith.*

If the most radical reductionist point of view was correct, the relationship between the different scientific disciplines would be of strictly inclusive type: chemistry contained in physics, biology in chemistry and so on. Eventually, only one science, indeed just a single theory, would survive, since all the others would eventually be embedded in the Theory of Everything. Is the current coexistence of different sciences a mere historical parenthesis which will end when the Theory of Everything has been worked out?

At the same time, it seems that at every moment in history, some have doubted the possibility of a unified description of nature, and not only among scientists of little formalised disciplines, i.e. with a mathematical apparatus less advanced than that of physics, such as biology. For instance, in 1856, the young Maxwell addressed the Cambridge Apostles, stating: *perhaps the "book", as it has been called, of nature is regularly paged; if so, no doubt the introductory parts will explain those that follow, and the methods taught in the first chapters will be taken for granted and used as illustrations in the more advanced parts of the course; but if it is not a 'book' at all, but a magazine, nothing is more foolish than to suppose that one part can throw light on another* (Campbell and Garnett 1882).

Laughlin and Pines (2000) suggest that to refute the radical reductionist approach leads one to propose new categories for those properties which do not appear likely to be reduced to the mere sum of their constituents. The most appropriate category is then that of emergence.

The first purpose of this book is to analyse some aspects of theory reduction in physics and to stimulate some reflection on questions that spontaneously arise in this field:

1. Is there any evidence of actual reduction of theories? Are the examples that are found in books on the philosophy of science too simplistic or not completely correct?
   For example, we shall discuss the reduction of thermodynamics to statistical mechanics, which is considered by many a paradigm case of reductionism. This relation is for others a counterexample. Indeed, the passage from the microscopic level to the macroscopic one is not a simple translation between two different languages, as can be appreciated observing, for instance, that the erratic behaviour of the elementary parts (the molecules) leads to total order.
2. If the microscopic level is essential to determine the macroscopic one, as Weinberg (1987) says when he writes *we understand perfectly well that hydrodynamics and thermodynamics are what they are because of the principles of microscopic physics*, why have we understood hydrodynamics quite well for centuries?
   More specifically, if microscopic laws are truly relevant, how can we explain the possibility of reproducing hydrodynamic behaviour by means of cellular automata that violate several fundamental properties of the microscopic dynamics (e.g. they occur in discrete states and do not follow strictly deterministic rules)?
3. The most extreme reductionists argue that by abandoning research on the Theory of Everything, unification of the sciences would never be achieved and just two alternatives would remain: a devastating fragmentation of applied knowledge and a weak science, like a sort of mysticism based upon sickening mantra along the lines of: *everything is more than the sum of its parts.* Is this really so?
4. What has been endangered by the search for (the) ultimate truth? Has the dream of reductionist reason created any monsters? Is *big science* one such monster? We have built accelerators tens of kilometres in size, to study phenomena that occur on scales of the order of $10^{-20}$ sec. while we do not understand many issues concerning the macroscopic level. In an effort to study smaller and smaller scale phenomena, from those of atomic physics to those of nuclear

physics and elementary particles, physics, the leading science for a long period, has marginalised many important issues, some of which have been recently rediscovered and repopularised.
5. What is the point of embedding science *Y* within science *X*, if predictions concerning science *Y* cannot be made starting from science *X*?

Even some of the most extreme reductionists admit that there are practical, maybe insurmountable, difficulties in performing theory reductions. For instance, after having praised the merits of the Standard Model, Weinberg (1995) states: *It seems that quantum chromodynamics is mathematically self-consistent, but it describes an impoverished universe in which there are only nuclear particles—there are no atoms, there are no people*. Nevertheless, the reductionist approach in its radical forms remains very influential in physics, and Weinberg himself concludes the same paper proposing his dream of an ultimate truth: *Perhaps our best hope for a final explanation is to discover a set of final laws of nature and show that this is the only logically consistent rich theory, rich enough for example to allow for the existence of ourselves*.

The theme of reductionism has been, and still is, the source of many discussions in areas other than physics. In recent times, it has been analysed especially in relation to one of its corollaries, *emergent* properties, which is a traditional theme in philosophy as well as in the biological sciences and those related to them (such as neurology, philosophy of the mind and psychology). As in the philosophy of science, the problem of reductionism typically arises between two completely formalised theories. The motivation of this approach is technically flawless: if the two theories are not even formalised, the problem is just too vague even to be posed. But in doing so, the danger is that the issue is rendered void or uninteresting. However, completely formalised theories are very few, even in physics, and the areas of most advanced research cannot be axiomatised, as mathematics has been,[1] because of the insufficient lack of understanding, which is unavoidable in the early stages of research in any given field.

Given all this, it would seem that no reasonable person could deny that some notion of reductionism has contributed to major advances in many areas of science. However, as pointed out by Mayr (2004), in doing so one should take care not to confuse reductionism with analysis, which is the method of breaking down, of dissecting a complicated (or complex) system into its parts. This approach, which we call 'methodological reductionism', is almost inevitable, but by no means does it imply that starting from the study of individual components of a given object, i.e. starting from a useful description of those parts, can the behaviour of the system, seen as a whole, be justified.

Perhaps it is no coincidence that the reductions of theories discussed by philosophers, with just a few exceptions, are interesting from a historical point of

[1] In reality, even mathematics is not completely formalised, and that is not always considered a negative fact. For example, Thom joked about the fact that the term 'rigour' reminds him of the 'rigor mortis'.

view, allow a rigorous logical analysis but are not very stimulating for scientists active in research, and are difficult to apply to the situations of current scientific interest. Among the few exceptions we find those considered in two interesting books, Batterman (2002) and Bokulich (2008), and in the collection of articles (Humphreys and Bedau 2006). A statement by the editors of this last source is particularly noteworthy: *we believe that progress in understanding emergence will be helped by a familiarity with work in areas outside psychology and the philosophy of mind. By understanding how emergent phenomena occur and are represented in physics and artificial life, for example…*

Einstein said that to understand how theoretical physicists work it is not necessary to care too much about what they say (especially on official occasions) but rather to look at what they do. In a similar way, to get an idea of how reduction of theories really works, it seems better to go beyond the statements of the various scientists, distinguished as they may be, and beyond the general formulations of epistemologists. Indeed, even Einstein was not immune from inconsistent thoughts, for example, he claimed that: *The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction.* But his major scientific achievements, beginning with those published in the *annus mirabilis*, did not at all follow a reductionist approach. Only after reaching the age of 40 did he embark on a project of unification, which was however doomed to failure. The same path was followed by Hilbert, who after having made so many major contributions to the most diverse sectors of mathematics and physics, entered into a fruitless programme of the complete formalisation of mathematics.

It is worth mentioning that declarations of principle sometimes arise from legitimate reasons in defence of academic interests. It is no secret that the passionate defence of reductionism pursued by Weinberg was largely motivated by lobbying in the U.S. Congress in support of the SSC project, the giant Superconducting Supercollider intended to study the physics of elementary particles. Similarly, Anderson's manifesto, *More is Different* (Anderson 1972), constitutes an attempt of condensed matter physicists, which we appreciate, to fight at a cultural level the overwhelming power of elementary particle physicists. After the papers by Weinberg and Anderson, with their opposite views on the role of the Big Science at the beginning of the 1990s, reductionism has been widely reconsidered and debated by physicists, see e.g. Schweber (1993); Anderson (1995).

The second purpose of our book is to look at a few cases taken from contemporary physics and to clearly present their relevance to the debate on reductionism, hence emergence.

Indeed, we do not find it particularly interesting to argue in favour or against the reductionist point of view, which in its most extreme formulation may even be a ghost, since virtually no one has really supported it and even fewer have practised it. We find it much more interesting to study in detail some specific cases without hesitating to enter into technical matters. The point that seems important to us is to understand the reasons for which a very detailed understanding of many complex phenomena is possible without having to resort to any Theory of Everything: adopting this perspective, we would like to understand the real connection between the different levels of description of reality. In the same vein, we also argue that emergent phenomena are by no means inexplicable. Indeed, they can be understood through the analysis of the connections between different levels of description or theories.

Therefore, one main focus of this book is to investigate the fact that the structure of various sciences (or more often theories) $X_1, X_2, \ldots, X_n, \ldots$ is not hierarchical and inclusive—which would mean that $X_1$ is contained in $X_2$, $X_2$ contained in $X_3$ and so on—but that, on the contrary, there is only a partial overlap between 'neighboring' sciences. By contrast, 'distant' sciences are almost completely disconnected: $X_1$ partially overlaps with $X_2$, but has almost no intersection with $X_3$; $X_2$ partially overlaps with $X_3$ but has almost no connection with $X_4$ and so on.

The really crucial point that we want to make here is that the interesting things occur at the borders, where two different levels of description meet: this often leads to novel concepts that cannot be categorised into what epistemologists call *bridge laws*, but rather can be considered as emergent properties. Indeed, the transition from one theory to another does not happen in a regular or simple way, in general, but through a procedure technically known as a *singular limit*.

This type of structure, which perhaps leaves the fundamentalists of ultimate truth unsatisfied, is in our opinion the motivation for which science exists and speaks sensibly about the natural phenomena occurring at a given level of observation (e.g. through the laws of hydrodynamics) without having to refer to a detailed comprehension of the underlying levels of observation (e.g. of the microscopic dynamics).

The central aspect resides in the fact that the transition from a more fundamental theory to a more phenomenological one almost never consists in a mere process of approximation, but rather in the emergence of new properties and concepts which are not present in the more fundamental level of description.

In our view the relevance of these facts is not always well understood and appreciated. Berry (1994) and Primas (1998) are among the few who have strongly and explicitly acknowledged the need for a singular limit in some of the most interesting reductions of theories. This does not amount to a mere technicality but is the crucial point from which concepts that cannot be contained in the more detailed theory emerge.

This book cannot and does not aim to be a text on the philosophy or history of science. Our main intention is to discuss, with specific examples, the importance of the singular limits and the emergence of new concepts in the process of theory reduction. Therefore, this book is primarily dedicated to all researchers in physics and in neighbouring sciences, chemistry and mathematics in particular, who want to reflect critically on their work. We hope, however, that the book is of interest to those philosophers of science who like to consider the most recent results obtained in the natural sciences and their consequences for more general studies.

Our selection of arguments follows a natural criterion: it is dictated by our personal research interests and competence, as developed in our recent scientific activity.

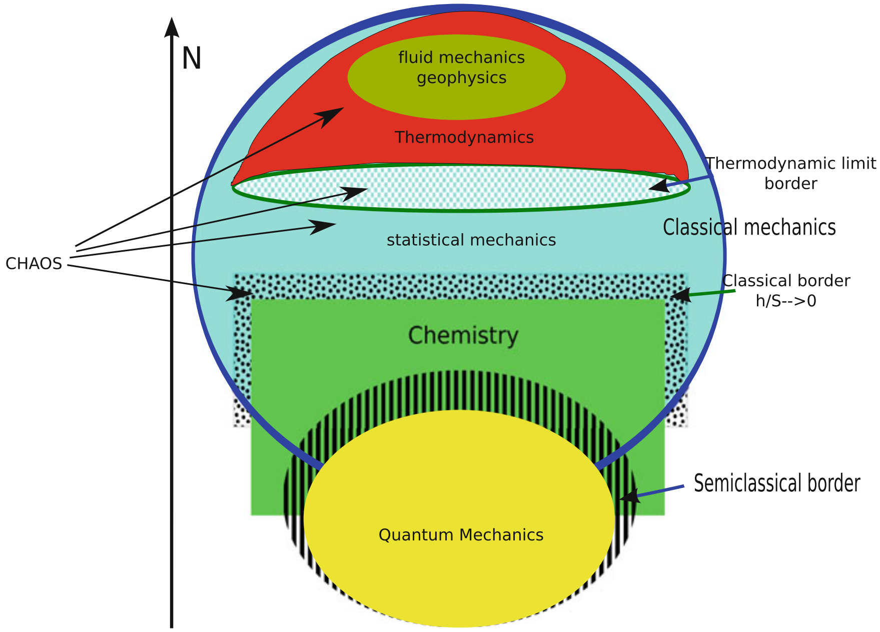


**Fig. 1** Inter-theoretic relations treated in this book. The levels of reality correspond roughly to increasing the number of elements involved ($N$ in the picture)

The structure of the book is as follows: we begin with a Dialogue that we would like to think of as being in the style of Galileo, which informally introduces the technical issues discussed in the rest of the book.

Chapter 2 introduces the problem of reductionism from a historical and philosophic view and does not claim to be either complete or original. Furthermore, the possible original implications for the field of epistemology of our analysis of physical theories are beyond the scope of the present book. Nevertheless it has been included so that the book is self-contained, and to the benefit of readers lacking a solid background in the philosophy of science. For the same reasons, we have kept a general description outlining the precise framework of our thesis.

Each of the central chapters (Chaps. 3–6) treats a specific subject: *Statistical Mechanics and Universality*; *Irreversibility and macroscopic behaviour*; *Chaos*; and *Quantum Mechanics and Chemistry*. The main purpose of these chapters is to demonstrate the importance of singular limits in all attempts at inter-theoretic reductions. These chapters also stress that these reductions do not conform to the standard textbook views of philosophy of science, based on the identification of microscopic theory, macroscopic theory and bridge laws. A sketch of this structure is shown in Fig. 1. These self-contained chapters can be read independently of one another.

Chapter 7 includes a partial analysis of more recent developments. In particular, we present some random thoughts about the unity of science in a non-reductionist point of view, as well as discussing some propositions of unifying theories concerning, e.g. fractals, dissipative structures, computational algorithms, which have become popular over the last few decades. In our opinion, those theories are often more or less concealed or disguised descriptions of different forms of reductionism, which deserve to have a critical eye cast over them at the very least, because of their popularity.

Perhaps the reader wonders about the roles of the characters Simplicio, Sagredo and Salviati, in the dialogue. Salviati expresses opinions that the authors share and, as in Galileo's dialogue, Sagredo is a non-impartial referee. Simplicio, at variance with the character of the Galilean dialogue, is not totally naive, he represents points of view that are commonly advocated by a number of contemporary scientists. Since active researchers are not all interested in the foundations of their disciplines, it is not unusual to find inconsistencies in their views.

We conclude these introductory notes with some clarifications.

In the first place, we observe that our purpose is that of making a simple point concerning theory reduction in physics, by examining several examples of current interest. We do not attempt to exhaustively address all foundational issues related to all branches of physics, including those concerning the various interpretations of quantum mechanics. We could have made the same point discussing other examples, such as those of statistical/entropic forces, of Casimir forces, of cold atoms, of the coherence or decoherence phenomena in modern macroscopic experiments, of Verlinde's theory of gravity as fluctuation induced, etc. Our selection is motivated by our familiarity with the chosen examples.

Throughout the book we quote authors who are well known in our fields of research, but who may not be known to a wide readership. Nevertheless, we preferred not to add bibliographic notes for them, for sake of simplicity and of readability.

Finally, historical references are made, including anecdotical ones. Surely, they do not meet the exacting standards of professional historians. However, we make no pretence of producing a historical opus. These references have always been used as conceptual examples. In any case we have detailed our bibliographic references.

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