Reductionism, Emergence, and Effective Field Theories

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Abstract

In recent years, a “change in attitude” in particle physics has led to our understanding current quantum field theories as effective field theories (EFTs). The present paper is concerned with the significance of this EFT approach, especially from the viewpoint of the debate on reductionism in science. In particular, it is a purpose of this paper to clarify how EFTs may provide an interesting case-study in current philosophical discussion on reduction, emergence and inter-level relationships in general.

Keywords: reductionism, emergence, fundamentality, inter-level relations, quantum field theory, renormalization

1 Introduction: A Recent “Change in Attitude” in Particle Physics

According to a view dominant in the 1970s and 1980s and still widely accepted, “fundamental physics” is the physics concerned with the search for the ultimate constituents of the universe and the laws governing their behaviour and interactions. Fundamentality, on this view, is the prerogative of the physics of smaller and smaller distances (or higher and higher energies), and accordingly particle physics and cosmology are currently identified as the fields where the quest for the “final theory” takes place.

Historically, the rise and establishment in the 1970s of the Standard Model (electroweak theory and quantum chromodynamics) marked a pivotal step in this search: a description of the physical world was obtained in terms of quarks and leptons as basic constituents of matter and their (nongravitational) interactions, interpreted in a unified way as controlled by the same principle (the gauge principle) and all described by a renormalizable quantum field theory. Among the many implications connected with the success of the Standard Model (tested

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down to distances of \(10^{-18}\) cm, in some cases), let us stress here two points. First, because of the apparently unified and fundamental character of the physical description it provided — a few basic entities and a unified treatment of their interactions — the Standard Model was commonly seen as representing a major success of reductionism and unification in natural science (Schweber, 1993, p. 35). Second, although the Standard Model was clearly not the whole story (since it left out gravity and also relied on a number of arbitrary parameters), its theoretical success and many empirical confirmations made it quite natural to expect fundamental physical theories to have the shape of a renormalizable quantum field theory (Weinberg, 1999, p. 242).

In more recent years, further developments in quantum field theory and in the application of renormalization group theory have brought a change in this way of regarding current fundamental physical theories. As a result of a “change in attitude” in particle physics (Weinberg, 1997, p. 41), the Standard Model is now understood as an effective field theory (EFT), that is, the low-energy limit of a deeper underlying theory which may not even be a field theory. Once one views current quantum field theories as effective theories, different positions about what is physically fundamental are possible. In recent years, the following two positions have emerged:

- The view that there is a fundamental theory — the so-called theory of everything (superstring theory, M-theory, ...) — at the bottom of both the Standard Model and general relativity (each understood as effective theories). This is the view prevailing among high energy physicists (S. Weinberg, E. Witten, D. Gross,...) and commonly labelled as “reductionist”.

- The view that physics obtains at most a never-ending tower of EFTs, with the corresponding picture of the physical world as layered into quasi-autonomous domains, each level having its own ontology and its own fundamental laws. The view, labelled as “antireductionist”, was formulated in such terms and especially defended by S. S. Schweber and T. Y. Cao in a series of recent works (for example: Cao and Schweber, 1993; Schweber, 1993; Cao, 1997, and 1999).

As regards fundamentality, two main questions are at stake here, namely: (a) whether there is a fundamental theory of everything (the “final theory”), and (b) what it means to say that a theory is “more fundamental” than another. Discussions of such issues usually take place in the context of the debate on reductionism in science: where the questions (a) and (b) are commonly addressed in connection with, respectively, (a’) the question of whether everything is reducible to a fundamental level (theory), and (b’) the question of the nature of inter-level relationships (inter-theory relationships) in a hierarchy of levels (theories).

The various implications of the EFT approach in particle physics, its philosophical significance and in particular its relevance to such themes as reductionism and fundamentality in science are now at the center of a developing
debate among physicists, historians and philosophers of physics (see for example Cao, 1999). A first aim of this paper is to clarify the terms of this debate, by exploring its background, the main concepts and issues involved and the key controversial points. The concern, here, is not so much with the details of the different personal positions, as with the general ideas that come into play. Accordingly, attention is paid more to the conceptual than to the ideological aspects (however effectively important ideologies are).

The first part of the paper is concerned with the historical background to the debate on EFTs, namely the discussion on reductionism and fundamentality in natural science as it developed in the scientific community from the middle 1960s to the early 1990s. As shown in Section 2, the majority of the basic issues addressed in relation to EFTs emerge in the context of this discussion: the present EFT debate can actually be seen as the most recent phase of such a discussion, its natural evolution in the light of new scientific developments and physicists’ “changes in attitude”. In the conceptual background to the whole subject there is obviously also the general philosophical debate on such notions as reduction, supervenience and emergence, and on related doctrines like reductionism, emergentism, and physicalism.

But curiously enough, despite the growing need in this context to pay more attention to what happens in basic science and especially in today’s physics (a point considered in Section 3), the literature does not seem to contain specific studies of the connections between the strictly philosophical debate and the “scientists’ debate” of the last years. It is therefore one main purpose of this paper to show that EFTs do provide a new and surely interesting case-study for the current philosophical discussion on reduction, emergence and inter-level relationships in general. The last two Sections are devoted to this task. Starting with the general idea of an EFT and its actual significance in particle physics (Section 4), some main controversial points of the debate on the EFT approach are considered in the final Section, where a conclusion is attempted as regards what EFTs can suggest and what they actually do not imply.

2 Funding and the Nature of Basic Science: A Debate among Scientists

In the early 1960s, for a number of reasons that are clearly illustrated in a recent article by Silvan Schweber (1997), the question of how to allocate finite government research funds started to become an urgent one in the United States. Accordingly, what criteria ought to be followed in making the funding choices among the different fields of science became the subject of a growing debate involving science administrators, economists, scientists and also philosophers. The problem was particularly felt with regard to basic research and especially high energy physics (HEP): why spend such a large amount of money, as required to support programs of experimental particle physics using accelerators, on a field far removed from our daily experience and therefore much less likely
to be of immediate technical and practical relevance than other branches of science? Funding, in this case, could not be justified on the grounds of important contributions to everyday technology and human welfare. Reasons for spending money on HEP had to be found “internally”, by looking at the nature, purposes and value of particle physics. Thus a discussion arose, especially among practicing scientists (mainly physicists); which can be taken as the starting point of the “scientists’ debate” on reductionism and fundamentality in natural science representing, as we shall see, the historical background to the present debate on EFT.

Let us make a selection and, following a rough periodization, single out two phases of this scientists’ debate that are of special relevance from the viewpoint of our paper, as follows. 1) A first phase, ranging from the mid-1960s to the rise of the Standard Model in the early 1970s, which was centered on the topic of large public support for the building of new particle accelerators and which began with the challenge posed by the physicist Alvin Weinberg (at the time director of the Oak Ridge National Laboratory) to the value of HEP and to the criteria for choice of which scientific research programs to pursue in general (A. Weinberg, 1963 and 1964). 2) A second phase, following the period of enthusiasm for the success of the Standard Model, which was dominated by the discussion of the Superconducting Super Collider (SSC) — a scientific project that started to be planned in 1982 and was definitively cancelled at the end of 1993.

1) Conceptually, a central topic in the 1963-1964 papers by Alvin Weinberg and the more or less direct responses to the problems they posed was the following question: what is the intrinsic value of basic research such as particle physics? The most common argument in support to HEP proposed at the time (but often also today) is the one identifying the intrinsic value of this field with its “fundamentality”. Particle physics is more fundamental than other areas of science (physics) in the sense that it contributes most to the advance of our fundamental understanding of the physical world, it is on the frontier of the exploration of nature to all its limits, it moves us closer to the ultimate laws of nature or ‘to the absolute logical structure of the universe’ (S. Weinberg, 1965, p. 73): this is the sort of statement to be found in the 1965 volume edited by Luke C. L. Yuan (at the time, the chairman of the Committee for the building of a new accelerator at Brookhaven), containing the views on the objectives of particle physics of a number of physicists such as Hans A. Bethe, Gary Feinberg, Julian Schwinger, Victor F. Weisskopf and Steven Weinberg. “Fundamentality”, “frontier research” and “unification” are the key concepts recurring in this line of defense of HEP. A further articulation was provided by Weisskopf’s distinction between two trends in the development of twentieth century science, namely: ‘intensive research’, including HEP and a good part of nuclear physics, that ‘goes for the fundamental laws’; and ‘extensive research’, such as solid state physics and plasma physics, that ‘goes for the explanation of

1Following the common usage, I shall use “HEP” and “particle physics” indifferently here.
2The unification issue and its relevance to the scientists’ debate on reductionism are thoroughly examined in Cat (1999).
phenomena in terms of known fundamental laws’ (Weisskopf, 1965, p. 24).

The fundamentality argument in support of HEP as well as the intensive/extensive distinction were especially challenged by the leading solid state physicist Philip W. Anderson in a seminal article with the programmatic title More Is Different (1972). Anderson’s article, now considered a “classic”, was expressly written to defend the intrinsic value of other branches of physics, such as solid state physics (today: “condensed matter physics”) and in general what goes under the name of “low energy physics” (LEP), against a presumed intellectual (and therefore, financial) supremacy of HEP. Its main purpose was to oppose ‘what appears at first sight to be an obvious corollary of reductionism: that if everything obeys the same fundamental laws [the reductionist hypothesis], then the only scientists who are studying anything really fundamental are those who are working on those laws’ (p. 393). Anderson’s task was therefore to bring arguments to demonstrate how the work, say, of a solid state physicist could be as fundamental as the work of a particle physicist. In view of the relevance of his paper to the “scientists’ debate”, especially with regard to its successive developments, let us recall some basic notions on which his arguments rely:

a) The way down/way up distinction. Although commonly considered as an outstanding example of an antireductionist, Anderson does not oppose in his paper what he calls the reductionist hypothesis, ‘the ability to reduce everything to simple fundamental laws’ (p. 393) — ‘we must all start with reductionism, which I fully accept’ (p. 394) — but rather the constructionist hypothesis, that is ‘the ability to start from those [fundamental] laws and reconstruct the universe’ (p. 393).

b) The fact of emergence. The constructionist hypothesis is rejected because of the emergence of new properties: ‘at each new level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other’ (p. 393).

c) The hierarchical structure of science. Because of the fact of emergence, ‘one may array the sciences ... in a hierarchy’ according to the idea that the elementary entities of (less primitive) science X obey the laws of (more primitive) science Y, but this does not imply that science X is ‘just applied Y’ (p. 393). Condensed matter physics is not applied elementary particle physics, chemistry is not applied condensed matter physics, and so on. The entities of X are emergent in the sense that, although obedient to the laws of the more primitive level Y (according to the reductionist hypothesis), they are not conceptually consequent from that level (contrary to the constructionist hypothesis).}

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1How philosophically sound was Anderson’s way of arguing in his 1972 paper will not be our point here. For such a sort of analysis see for example Cat (1999, pp. 264-266).

4I am using here the terminology typically employed in the more recent phase of the scientists’ debate.

5Anderson’s paper especially stresses the relevance of broken symmetry to the fact of emergence. This important point is considered in another paper (Castellani, ‘Spontaneous Symmetry Breaking and Emergence’, in preparation).

6See the following statement by Anderson (1995, p. 2020): ‘This, then, is the fundamental philosophical insight of twentieth century science: everything we observe emerges from a more primitive substrate, in the precise meaning of the term “emergent”, which is to say obedient
d) *Decoupling between HEP and LEP.* What happens at the HEP level is not very relevant to what effectively happens at the LEP level: ‘the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science’ (Anderson, 1972, p. 393).

2) During the 1980s, the debate on funding and criteria for scientific choice took a new turn by focusing — as regards physics — on a ‘scientific project of unprecedented size and cost’ (Weinberg, 1993, p. 1): the building of a new particle accelerator known as the Superconducting Super Collider (SSC), with the objective of attaining the 1-TeV mass scale, that is, an energy domain where some answers could be found to questions left open by the Standard Model (first of all, the mechanism of electroweak symmetry breaking). Because of the cost of the project (estimated at about 4.4 billion dollars in 1987), well known scientists were asked to testify at congressional committee hearings on the significance of the SSC and therefore “forced” to take a definite position. Solid state physicists like James Krumhansl and Anderson opposed the project, for reasons similar to the argument defended in Anderson’s 1972 paper, while the majority of particle physicists strongly supported it. It is not our aim to enter into the details of the SSC debate here. Let us just mention — as best illustrations of a “reductionist pro-SSC” position, on the one side, and of an “antireductionist anti-SSC” position, on the other side — the arguments advanced by Steven Weinberg and the prominent biologist Ernst Mayr, respectively, in an exchange between the two scientists which appeared in the journal *Nature* in the years 1987-1988.

Weinberg’s 1987 defense of the SSC — and in general of spending on “big science” — is grounded on the usual (in the HEP supporters’ camp) argument that ‘particle physics is in some sense more fundamental than other areas of physics’ (1987, p. 434). In what way? Weinberg’s position relies on what he calls *objective reductionism*: a reductionism described in terms of ‘the convergence of arrows of scientific explanation’, ‘objective’ because it is ‘not a fact about scientific programmes, but a fact about nature’ (p. 436). Behind this view is the ‘intuitive idea that different scientific generalizations explain others [generalizations]’: so we have ‘a sense of direction in science’, ‘there are arrows of scientific explanation that ... seem to converge to a common source’ (p. 435). Particle physics, dealing with nature ‘on a level closer to the source of the arrows of explanation than other areas of physics’, is therefore more fundamental (p. 437).

As noted in the literature, a main controversial point in Weinberg’s argument is his intuitive idea of explanation — an explanation which can be also only “in principle” and is generally distinguished from deduction (in order to admit the
to the laws of the more primitive level, but not conceptually consequent from that level’.

7To reach the required energy for the creation of a Higgs particle was surely a central motivation for the SSC, but not the only one. This point is especially stressed in Weinberg (1993, pp. 210-215). Greater details on the various purposes of the SSC project can be found in Glashow and Lederman (1985).
Weinberg’s position actually does not easily fit into traditional philosophical schemes, and even Mayr, in his 1988 article on the limits of reductionism, encounters some difficulties in classifying it from the viewpoint of his own 1982 distinction among three kinds of reductionism: namely, a constitutive reductionism, which is just the analytic method of studying an object by reducing it into its most basic constitutents; a theory reductionism, postulating that ‘theories and laws formulated in one field of science can be shown to be special cases of theories and laws formulated in some other branch of science’ (1982, p. 62); and an explanatory reductionism, which is ‘the view that the mere knowledge of its ultimate components would be sufficient to explain a complex system’ (1988, p. 475). According to Mayr, Weinberg is defending something similar to theory reductionism; while Weinberg, on his part, prefers to stress the objective (not semantic) character of his own view.

The really “bad” reductionism, for Mayr, is explanatory reductionism. Mayr defines his antireductionist position essentially in opposition to this kind of reductionism, which he rejects on the basis of the fact of emergence (just as in Anderson’s 1972 paper the constructionist hypothesis was rejected on the grounds of emergence): ‘new and previously unpredictable characters emerge at higher levels of complexity ... hence complex systems must be studied at every level, because each level has properties not shown at lower levels’ (1982, p. 64). For this reason Mayr is then led to doubt that HEP research (the SSC project, in the specific case) ‘would contribute not only to our understanding of the subatomic world, but also to that of the middle world’ (1988, p. 475).

As we see, the fact of emergence, a kind of autonomy of levels of organization and hence a sort of “decoupling” are central themes in the antireductionist camp of the ‘scientists’ debate’. But also a reductionist like Weinberg accepts the fact of emergence and agrees in rejecting what Mayr calls explanatory reductionism. So on what does the disagreement really rest in this debate? From what we have seen so far, on the consequences (we could say: ideological consequences) that are drawn from the same facts — for example, the fact of emergence: i.e. the consequences about what is more fundamental in science and what is the scope of basic research. This is exactly the same situation that we shall find when considering the controversy over the philosophical implications of EFT. As we shall see in Section 5, from the same facts — the EFT approach in particle physics and its “extreme version” — quite different conclusions have been drawn as regards reductionism and fundamentality in physics.

In subsequent works (1993, 1995a, 1998) Weinberg, challenged on this point, tries to be more precise about what he means by explanation and objective reductionism, later dubbed by him “grand reductionism” (“the view that scientific principles can all be in principle traced down to a small body of simple universal laws” [1998, p. 79]) and opposed to what he calls “petty reductionism” (“the view that the mere knowledge of the constituents of a complex system would be sufficient to understand the system” [ibid.]). We prefer not to enter here into the question as to whether Weinberg actually succeeded in making his position philosophically sound. In any case, he is surely very clear on what he thinks about reductionism and fundamentality in natural science.
3 Levels and their Relationships: Some Desiderata in the Philosophical Debate

Mayr’s three types of reductionism resemble categories typically employed in the philosophical debate on reduction and reductionism, where distinctions between some kinds of reduction (reductionism) — ontological reduction, epistemological or semantic reduction, explanatory reduction or reductive explanation, methodological reduction, ... — are ordinarily discussed. Most concepts recurring in the scientists’ debate, such as emergence, hierarchy of levels (levels of organization/levels of description), analysis versus synthesis and the part/whole relation are in fact current philosophical subject matters. But the field of application is markedly different: much of the recent philosophical discussion on such matters is mainly concerned with the relation of mental to physical phenomena. Among philosophers, however, it is now becoming a desideratum ‘to stop thinking of these issues exclusively in terms of mental properties, and to look for examples in more basic science’, as has been said with regard to the question of emergent properties (Humphreys, 1997, p. 15).

Both the scientists’ debate of Section 2 and the general philosophical debate on reduction, supervenience and emergence are in some sense centered on the following question: assuming a level structure of “units” of some kind, how are the levels related? The question, of course, first of all depends on what level structure is assumed. Some philosophers prefer not to speak of levels altogether; Sahotra Sarkar (1998), for example, suggests using the term “realm” instead of the more common “level”, in order to avoid assuming a hierarchical relationship between different levels (fn. 22, p. 193). Given that we are not so much concerned, in this paper, with “intra-level” or “domain-preserving” relationships as rather with “inter-level” relationships (to use current terminology), let us speak freely of levels. Moreover, since the whole debate we are considering is basically referred to the physical world and its description, let us follow the common usage among natural scientists and understand “levels” in terms of a given scale — a length scale, for example, or an energy scale. A level (and its hierarchical position) will accordingly be intended as defined in correspondence to a given value range of the scale: in terms of energy, for example, a level \( L_i \) will be considered “coarser” than another level \( L_j \) if corresponding to a lower range of energy values.

Given a hierarchical structure of two or more levels \( L_i \)'s, where level \( L_{i+1} \) is coarser than level \( L_i \), the main question is then: how are the units in two successive levels \( L_i \) and \( L_{i+1} \) related? Is the relation of the units in level \( L_{i+1} \) to the units in level \( L_i \) better described in terms of “reduction to”, or “supervenience on”, or “emergence from”? Again, some preliminaries need to be settled; first of all, what are the appropriate units in the level structure: theories, concepts,
entities, properties, ...? As has been pointed out, much of the philosophical discussion has been “clouded” by a lack of agreement on this point (Klee, 1984, p. 45). A way of restricting the unit choice is to start with distinctions such as those between ontological and epistemological aspects, and formal and non-formal (substantial) issues. Let us cut the discussion short, here, and just take one example: namely, the recent analysis offered by Jeremy Butterfield for reduction, supervenience and emergence as (formal) relations holding between theories (Butterfield and Isham, 1999, pp. 114-126).

Intending theories as sets of sentences closed under deduction (the syntactic conception), Butterfield’s analysis first aims to show that, by approaching reduction in terms of “definitional extension” (the notion making precise the intuitive idea of one theory $T_1$ being reduced to another theory $T_2$), ‘there may well be no single “best” concept of reduction’ (p. 120). On the one side, definitional extension is sometimes too weak for reduction, whence the controversy over how to supplement it (starting with Ernst Nagel’s well known proposal, motivated by the idea that $T_2$ should explain $T_1$, where explanation is conceived in deductive-nomological terms). On the other side, definitional extension is sometimes too strong (an objection going back to Paul Feyerabend), prompting one to appeal to such concepts as approximation, limiting relations and analogies between theories. Supervenience, a notion ‘apparently weaker than definitional extension but also quite precise’ and therefore by many considered a good candidate for capturing the idea of emergence, is then shown not to live up to its promise of sharply distinguishing reduction and emergence. Turning finally to emergence itself, what results is a heterogeneous picture of this notion. Butterfield’s conclusion is then the following: rather than seeking for a general formal definition of emergence (for which there does not seem to be much prospect, as in the case of reduction), ‘we need to bear in mind the variety of ways that theories can be related: in particular, with one theory being in some sense a limit of the other, or an approximation to it’ (p. 115).

The preceding analysis is a very good example of how the need to search for concrete examples and to be ‘concerned with detailed mechanisms rather than broad generalizations’ (Sarkar, 1998, p. 17) is becoming commonly felt in the philosophical discussion on reduction, emergence, and inter-level relationships in general. It is exactly in this spirit that we shall turn now to consider the EFT approach and its significance from the viewpoint of the above discussion. A main aim of this paper is to show that EFTs do provide a new and stimulating concrete case-study for this discussion.

10To be precise, Klee’s observation is especially referred to the philosophical discussion on emergence.

11We do not need to enter into such details here. A sort of overview, although not complete, of these distinctions in the philosophical literature is offered in Sarkar (1998, Chapters 2 and 3).

12According to Butterfield, this choice is not decisive: the arguments he presents would hold also under other choices, and in particular on the semantic conception of theories as classes of models.
4 EFT: The General Idea and its “Extreme Version”

As a way of introducing EFT, let us start with the general idea of an “effective theory” and then see how this idea applies in the framework of quantum field theory (QFT).

An effective theory (ET) is a theory which “effectively” captures what is physically relevant in a given domain. More precisely, following a characterization by the particle physicist Howard Georgi, an ET is an appropriate description of the important (relevant) physics in a given region of the parameter space of the physical world (1997, p. 88).

The idea is a very natural one: physics usually changes as one changes the scale considered (what is physically relevant differs from one region of the parameter space to another) at very different ranges of energy scales (or length scales), we can have remarkably different physics. Which is to say, when referring to one physical system, that the system in “coarse grain” can appear very different from that in “fine grain”. Now, in general, it is possible to describe a limited range of physical phenomena, or equivalently the relevant physics in a limited region of the parameter space, without having to describe everything at once. This is the point of using an ET: to obtain a most appropriate and convenient description of the relevant physics in a limited domain. Such a description, only applicable within a well defined domain of validity, is thus intrinsically approximate.

For reasons we shall briefly see next, this general ET idea proves particularly useful and interesting in the framework of QFT, where it can be made very precise. Actually, the development of the EFT idea has been of special consequence to particle physics, leading to the “change of attitude” mentioned in Section 1 which is at the basis of the so-called modern view of QFT: i.e., the view that ‘the most appropriate description of particle interactions in the language of QFT depends on the energy at which the interactions are studied’ (Georgi, 1989, p. 446). On this view, current QFTs are understood as EFTs.

13 Historically, it is rather the other way round. According to Weinberg (1995b, p. 523), an earliest example of an EFT in physics is the theory of low-energy photon-photon interactions derived in the 1930s by H. Euler and others. Effective Lagrangians for soft pions were used since 1967, but it is actually only in the late 1970s (on the grounds, first of all, of important work by Weinberg in 1979) that it was realized that ‘effective field theories could be regarded as full-fledged dynamical theories, useful beyond the tree approximation’ (Weinberg, 1997, p. 42).

14 For the scope of our discussion, it will be sufficient to employ the term “theory” in the usual physicists’ sense of a set of fundamental equations (or simply some Lagrangian) for describing some entities, their behaviour and interactions.

15 As we shall see, on the renormalization group approach the effect of changing the scale can be absorbed in a change of the parameters of the theory.

16 In particle physics, as is known, energy and length scales are inversely related. The usual unit system is \( h = c = 1 \), whence the dimensional relations \([\text{length}] = [\text{time}] = [\text{energy}]^{-1} = [\text{mass}]^{-1}\). The mass \( M \) of a particle is therefore equal to its rest energy \( Mc^2 \) and to its inverse Compton wavelength \( Mc/h \).
each EFT explicitly referring only to those particles (fields) that are actually of importance at the range of energies considered. By changing the energy scale the EFT description accordingly changes, ‘to reflect the changes in the relative importance of different particles and forces’ (ibid.).

As stated above, the key point is the separation of the physics at the chosen energy scale from the physics at much higher energies; but how does this separation or “decoupling” exactly obtain? In the QFT framework, the decoupling of physical phenomena, as well as the changing of the (effective) physical description as the scale changes, occur according to specific and precise rules. This is due essentially to some important peculiarities of the local quantum field description and, in particular, to the concept of the renormalization group (RG) and its deep impact on particle physics. The emergence of the EFT idea (and approach) is in fact intertwined with the development of renormalization theory (RT); from the so-called old RT, introduced in the 1940s to deal with the divergence problems arising in quantum electrodynamics, to the recent new understanding of renormalization which is grounded on the RG concept. Without entering in detail, let us shortly see how EFT comes out in this context.

In its original meaning, renormalization was nothing other than a means of removing the infinities occurring in perturbative calculations in a QFT. To do this, the conventional strategy adopted in the “old RT” was more or less the following: first separate the divergent parts (high energy processes) from the finite parts (low energy processes) in some way, usually by introducing a cutoff \( \Lambda \) (threshold energy for the validity of the theory); then absorb the divergences in some appropriate redefinition (“renormalization”) of the parameters (such as masses and coupling constants) of the theory; finally, to take into account the neglected high energy effects (in a cutoff-independent theory), remove the cutoff by letting \( \Lambda \to \infty \) — with the consequently arising problems as regards the actual meaning of the cutoff (on this last point, see especially Cao and Schweber, 1993, pp. 52-55).

A first step towards a new understanding of RT was the introduction of the RG concept in the QFT framework during the 1950s, on the grounds of renormalization invariance: i.e., an arbitrariness in the choice of the parametrization of the theory to renormalize (and the consequent introduction of RG as the group of transformations relating the different parametrizations). That RT was not just a technical device for removing infinities became a clear and accepted idea only after the revival and extension of the application of the RG methods by Kenneth Wilson in the early 1970s. By applying his previous results on RG in field theories on a lattice to the study of critical phenomena (generalizing the 1966 Kadanoff theory of scaling near the critical point for an Ising ferromag-
Wilson in fact laid the basis for what is now the current conception of renormalization: namely, the conception that renormalization is essentially ‘an expression of the variation of the structure of physical interactions with changes in the scale of the phenomena being probed’ (Gross, 1985, p. 153). The RG enters the picture by regulating (through the so-called RG equations) the way in which this variation occurs. Let us just focus on some fundamental steps.

A first conceptual point is the realistic interpretation of the cutoff, that is to ‘take seriously the idea of a physical cutoff at a very large energy scale $\Lambda$’ (Polchinski, 1984, p. 269). A second point is ‘the idea of smoothly lowering the cutoff’ (p. 270). On the RG approach, the effect of changing the scale or rescaling ($\Lambda_o \rightarrow \Lambda(s) = s\Lambda_o$) can in fact be absorbed in a change of the parameters, so that, for one parameter $g$, a trajectory $g = g(s)$ is defined as $\Lambda(s)$ varies. The RG equations so describe the flow of the parameters in a parameter space as one changes the scale. The important thing is that, typically, as one scales down to lower energies the solutions of the RG equations approach a finite dimensional sub-manifold in the space of possible Lagrangians: thus generally defining an effective low energy theory, which is formulated in terms of a finite number of parameters and is largely independent of the high energy starting situation (to be more precise: independent up to high energy effects that are suppressed by powers of $E/\Lambda$, where $E$ is the low energy at which the effective theory is appropriate).

Practically, in terms of a situation with particles having very different masses, what results is the following: if the energy $E$ at which we are working (the experimental energy) is much less than the mass $M$ of a particle (the “heavy” particle), we can act as if the particle was not there. The mass $M$ plays the role of the cutoff and the physics at the energy $E \ll M$ is describable by an EFT which is approximately renormalizable. The nonrenormalizable interactions are due to the heavy particle that has been ignored and their effects are small, being represented by terms that are suppressed by powers of $E/M$. When, on the contrary, the experimental energy $E$ approaches the cutoff $M$, the heavy particle cannot be ignored any more (the effects of the nonrenormalizable interactions are no longer small). A new theory (“new physics”) is required, which can be a renormalizable QFT, another EFT or something completely different.

Taking this view to its “extreme version” (Georgi, 1989, p. 455), we arrive at the following interesting scenario: in a situation with different elementary particles $p_i$, each particle Compton wavelength $\lambda_i$ ($\lambda_i = 1/M_i$, where $M_i$ is the mass of the particle $p_i$) can be taken to be associated with a boundary between two EFTs. For distances larger than $\lambda_i$ (or for energies lower than $M_i$), the particle $p_i$ is omitted from the physical description, which is obtained in terms of an effective theory with cutoff $\Lambda = M_i$; for distances shorter than $\lambda_i$ (energies higher than $M_i$), the particle $p_i$ is included and the physics is described by another theory, which can be an EFT with a higher energy cutoff (in case there is another particle with a larger mass).

In principle, we thus obtain a level structure of effective theories, each level corresponding to a given energy scale. In addition, these levels are related in a precise way, through the so-called matching conditions regulating the connec-
tions between the parameters in the two theories on either side of the boundary. Namely, the parameters must be so related that the two theories provide the same physical description just below the boundary.

Given this layered structure of EFTs, we can distinguish between two ways of looking at it:

a) The way down from the EFT appropriate at the available energy at which we start to the theories successively appropriate as we go down to higher energies.

b) The way up: from the finer-grained theories at higher energies to the coarser-grained theories at lower energies.

Low energy theories are approximations to the corresponding high energy ones: the “way up” accordingly marks the direction in which theories emerge one from each other, if we accept the ‘general idea of one theory $T_1$ being emergent from another $T_2$ if, in a certain part of $T_2$’s domain of application, the results of $T_2$ are well approximated by those of $T_1$’ (Butterfield and Isham, 2000, p. 57).

5 Conclusion: What the EFT Approach Suggests and What It Does not Imply

Summing up:

- Current QFTs, once the best candidates for being fundamental theories, are now commonly seen as EFTs, i.e. low energy approximations to other (more fundamental) theories.

- EFT is the most appropriate and convenient way of describing (in the framework of QFT) the relevant physics in a limited energy domain. It is therefore an intrinsically approximate and context-dependent description.

- The EFT approach is grounded on the RG concept: the variation of the (effective) physical description with the changing scale is described by the RG equations.

- The EFT approach in its extreme version provides a level structure (“tower”) of EFTs, each theory connected with the preceding one (going “up” in the tower) by means of the RG equations and the matching conditions at the boundary; the boundary for an EFT is set at the cutoff given by the mass $M_i$ of the next heaviest particle $p_i$ excluded in the EFT’s physical description.

- The way up in the level structure of EFTs marks the direction in which the theories emerge one from each other.

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20The terminology — “going up” towards lower energies (larger distances)/“going down” towards higher energies (smaller distances) — is chosen in order to show the connection with the way down/way up distinction in the hierarchical conception of natural sciences discussed in Section 2.
In the light of these points, let us now turn to the conclusive point of this paper: whether and how the EFT approach is of some philosophical relevance, especially with regard to reductionism and related issues. We shall distinguish between: a) a positive part — what the EFT approach can suggest; and b) a negative part — what the EFT approach does not imply.

a) EFTs undoubtedly offer a concrete example in the context of basic science for analysing the way in which theories (on different levels) can be related. More precisely, the EFT approach provides a level structure of theories, where the way in which a theory emerges from another (in the sense mentioned at the end of Section 4) is in principle describable by using the RG methods and the matching conditions at the boundary. The basic question concerning the inter-level relationships — given a level structure, how are the units in different levels related? — can here be addressed in a concrete and definite manner: we have formal and substantial tools for determining how successive effective theories are related one to each other. Moreover, what is particularly advantageous from the viewpoint of the philosophical discussion, the conceptual framework remains always the same. All the theories are formulated in the same QFT language, thus allowing us to avoid the typical translation problems arising when discussing “heterogeneous” intertheoretical relationships.

The tower picture grounded on the extreme version of EFT might appear to be mere speculation. It results, however, from generalizing a concrete situation: in other words, it is not “pure” speculation. Today’s physics (particle physics, first of all, but also other fields such as condensed matter physics) does in fact provide a number of concrete examples of known theories which are effective low energy versions of other known theories — for example, the chiral effective theory $SU(2)_R \times SU(2)_L$ approximating quantum chromodynamics (QCD) at low energies, or the Landau theory of Fermi liquids, which is the effective field theory of the low-energy excitations in a conductor.

b) As mentioned in Section 1, a discussion has recently arisen among physicists, historians and philosophers of physics about what the EFT approach entails with regard to reductionism and fundamentality in natural science. In particular, on the basis of EFT and its extreme version, definite conclusions have been drawn about whether a fundamental (final) theory exists, whether the notion of fundamentality in science makes sense and, finally, whether reductionism (or antireductionism) holds. The best example in this sense is provided by Cao and Schweber, who surely go further than anybody else in analysing the implications of EFT and in deriving specific philosophical theses from it. We already mentioned the kind of antireductionist position they defend. Their position is more precisely specified in the following terms: the EFT approach endorses ‘a pluralism in theoretical ontology, an antifoundationalism in epistemology and an antireductionism in methodology’ (Cao and Schweber, 1993, p. 69). Central facts to which Cao and Schweber make reference for their theses are: first, the remarkable stability of an effective low energy theory (largely decoupled from

\footnote{An introductive lecture on the effective low energy theory of QCD is, for example, Gasser (1997). For a specific presentation of the Landau theory of Fermi liquids as an EFT see Polchinski (1992).}
the corresponding high energy theory); second, the necessity for an empirical input in determining the effective low energy theory (more precisely: in determining the coupling constants in the cut-off Lagrangian) in the case where the high energy theory is not known.

A specific discussion of the theses defended by Cao and Schweber is not our aim here. We are interested rather in the following point: how far are claims of the above sort legitimate? Let us attempt an answer by considering, in the light of what we have seen in Section 4, what the present EFT approach in particle physics does not imply as regards the reductionism and fundamentality issues. Schematically:

- The fact that current QFTs are now seen as EFTs does not imply any specific thesis about the existence of a final theory. The high energy theory could be another EFT, a local QFT or something completely different (in this sense the picture of a tower of EFTs is in some ways misleading).

- The EFT approach does not imply that the idea of a theory being more fundamental than another is meaningless. The fact that an effective low energy theory ‘is equally fundamental to the original high energy formulation insofar as our only concern is low energy physics’ (Gross, 1999, p. 59) does not entail that the high energy theory could not be seen as more fundamental from a different perspective.

- The EFT approach does not imply antireductionism, if antireductionism is grounded on the fact of emergence, as in the case of Anderson (1972) or Mayr (1988). The EFT schema, by allowing definite connections between the theory levels, provides an argument against the basic antireductionist claim of the scientists’ debate. A reconstruction (the way up) is not excluded, even though it may have to be only in principle. In this sense, EFT does not represent a vindication of Anderson’s 1972 views, as has been claimed (Schweber, 1993, p. 36).

In short: keeping ideology away, EFT does not provide general answers to the basic questions of the “scientists’ debate”. The present EFT approach in particle physics is actually a practical and convenient way of proceeding in describing natural phenomena, grounded on a very natural idea — the idea that the physical description depends on the scale — which in the context of the modern view of QFT proves to be very useful and fruitful. Moreover, the known EFTs surely offer new and interesting concrete cases for the philosophical discussion on inter-level relationships.

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22 A short critical discussion is provided in Huggett and Weingard (1995, pp. 187-189).
23 See for example the argument by Cao (1997, p. 347), according to which the endless character of the tower of EFTs is entailed by the local operator formulation of QFT.
24 Not having the complete renormalizable theory at infinitely short distances, we need empirical inputs. But if such a theory was available, ‘we could work our way up to the effective theory at any larger distance in a totally systematic way’ (Georgi, 1989, p. 455). In general, as already said, if the high energy theory is not known, we need an empirical input in determining the low energy effective theory.
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