31 Coda: Where are we heading?

The LHC, in its first years of running, has been a remarkable success. The discovery of the Higgs boson in an extremely complex environment is an extraordinary achievement, both experimentally and also in the application of our understanding of many facets of the Standard Model. This particle appears, at the $10\%-20\%$ level, in several channels, to be the Higgs field of the simplest version of the Standard Model. Over the next few years these measurements will improve and additional channels will be studied. In Chapter 4 of this text we studied the Standard Model as an effective-field theory. In that discussion our treatment of the Higgs sector was somewhat tentative; we entertained the possibility that the Standard Model might fail at scales of order 1 TeV. It is quite possible, however, that over the next few years we will establish that the Standard Model, *including only a single Higgs doublet*, provides a complete description of nature up to a scale of a few TeV. This would represent an extraordinary achievement.

Yet we have many unanswered questions. As this book goes to press the LHC is beginning to run at close to its design energy of 14 TeV. It is quite possible that, as we explore this new energy frontier, we will see one or more major discoveries – a candidate for dark matter, evidence for supersymmetry, additional Higgs fields, a new $U(1)$ gauge boson Z' or something totally unanticipated. Experiments at the *cosmic frontier* searching for dark matter, CMB polarization or non-Gaussianity and other phenomena are coming on line and/or improving their reach, and major discoveries might be made over the next few years. Alternatively we have seen that the LHC has already excluded many possibilities for new physics. It is conceivable that the answers to many questions do not lie at energies which will be accessible in the next few years.

To conclude this book, an assessment of some of the ideas for Beyond the Standard Model physics, and their prospects, is appropriate.

31.1 The hierarchy or naturalness problem

The hierarchy problem is strongly suggestive of new physics at TeV energy scales. Supersymmetry, broken at around one TeV, is a possible solution which we have explored extensively in this book. But the mass of the Higgs and LHC exclusions strongly suggest that, if supersymmetry is present at all, it is broken at scales of order tens of TeV or even higher. This raises significant experimental challenges. Even a collider with center of mass energy in the 100 TeV range does not have a 10 TeV reach, much less 30 TeV or more. At a theoretical level there is the question, what might account for such a scale? We have

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discussed some possible explanations for varying degrees of tuning but certainly have not established a compelling criterion; basically once one has admitted tuning, it is hard to decide how much is too much.

Strongly interacting Higgs and other (non-supersymmetric) dynamical explanations of the hierarchy problem have to confront different challenges. For technicolor and its variants, there are the long-standing questions of flavor-changing neutral currents and precision electroweak physics; now there is the additional puzzle of why there should be a particle behaving like an elementary Higgs field. This latter question is confronted more directly in "little Higgs theories" (and their variants), where the Higgs emerges as a pseudogoldstone boson of other interactions. Here perhaps the biggest challenge is the complex set of constraints on these theories, not least of which is simply: how do the required non-Abelian global symmetries emerge? Many ideas are being explored and, at the same time, the possibility of composite Higgs particles provide another target for experimental searches.

31.2 Dark matter, the baryon asymmetry and dark energy

Dark matter remains the subject of extensive search efforts. Apart from the hierarchy problem, the "wimp miracle" is another pointer to possible new physics at the electroweak scale. Much of the parameter space for supersymmetric wimps has been ruled out by direct and indirect detection searches, but some remains, and there are tantalizing hints for dark matter with more interesting properties. At the same time we have seen that axions provide a plausible candidate for the dark matter. The ADMX experiment is, as of the time of writing, probing an interesting part of the axion parameter space. There are ideas under consideration to search for far lighter axions. It is quite possible that in the next few years we will see a discovery; alternatively, there will be important exclusions.

The origin of the baryon asymmetry is an interesting question about which we don't have sharp clues or evidence. Electroweak baryogenesis in the Standard Model itself has long since been ruled out. Within supersymmetric theories there remain corners of the parameter space where it might yet be allowed but, given the present tunings involved in most supersymmetric theories, this seems a bit of a long shot. Affleck–Dine baryogenesis, discussed in Chapter 19, could still be operative even if supersymmetry is broken at some high energy scale but, without the discovery of supersymmetric particles, it is unclear how one might accumulate evidence for this mechanism. Leptogenesis as a possibility receives support from the discovery of the neutrino mass. But, if right-handed neutrinos are at scales of order $10^{14}-10^{16}$ GeV, the reheating temperature after inflation needs to be of this order, which seems unlikely. Put differently, a determination of the scale of inflation, and the development of a theory of reheating, would significantly constrain models of leptogenesis (and neutrinos mass).

For dark energy, the principle experimental question appears to be whether the dark energy is indeed a cosmological constant, or whether $w = -1$ (see Eq. (18.15)) in its equation of state. This is already established at the 10% level; upcoming experiments, such as the Dark Energy Survey, will reduce the errors further.

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31.3 Inflationary cosmology

Here perhaps the largest question to which we may obtain experimental access over the next few years is the energy scale of inflation. If this scale is in the range $10^{15}-10^{16}$ GeV, it is likely to be established by observation of the tensor polarization of the CMB, known as *B mode* polarization. This would be remarkable, first, in that it would represent our earliest observation of the universe, a time of order 10^{-25} seconds after the big bang. Second, it would be a guide to thinking about other energy scales in physics. Is this scale, perhaps, related to a scale of unification or string theory, for example? It would certainly be a guide to modeling inflation.

31.4 String theory and other approaches to foundational questions

String theory, thought of literally as a quantum theory of strings, is remarkable in many ways. It is a consistent theory of quantum gravity. It incorporates gauge interactions like those of the Standard Model. It can exhibit other striking features of the Standard Model, such as repetitive generations. String theory also includes many elements which have appeared in our speculations about Beyond the Standard Model physics, including:

1. axions: axions appear with approximate Peccei–Quinn symmetries which are potentially good enough to solve the strong CP problem;
2. low-energy supersymmetry;
3. new strong interactions;
4. multiple generations of quarks and leptons;
5. unification of the known forces;
6. possibly large extra dimensions, warped spaces and the like;
7. discrete symmetries of sorts interesting for model building but, as would be expected of theories of quantum gravity, no global continuous symmetries.

At the same time string theories appear robust as quantum theories of gravity. But, as currently understood, it is hard to see how weakly coupled strings could provide a complete description of nature.

There are several issues, as we have seen. Principal among these are understanding the fixing of moduli and supersymmetry breaking. These problems are intimately connected. For string theories (compactifications) without supersymmetry, even at one loop there is a potential for the moduli; this tends to zero for large radius and small couplings, the regions where the calculations are reliable. Supersymmetric models either respect supersymmetry exactly (due to the presence of more than four supersymmetries or due to discrete symmetries) or they break supersymmetry non-perturbatively and are subject to the same difficulties.

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So we face the problem that superstring theories, in the realms in which we understand them, almost certainly cannot describe nature. Instead, we can retreat a bit and take from string theory the lesson that sensible theories of quantum gravity exist and can account for many features of the low-energy world (gauge theories, chiral fermions). But there is almost certainly some other structure needed to describe the world around us. Whether string theory is a part of this larger structure, or whether such a structure describing nature is a distinct entity, we do not know. The landscape hypothesis is tied to the former view. Efforts to escape it would seem tied to the latter. Clues for exploring these questions include the web of dualities and questions such as the presence or absence of quantum tunneling between different vacua.

The success of the Standard Models of particle physics and of cosmology mean that we can formulate very precise questions about how nature might be structured. But these questions are challenging. The author, for one, hopes for discoveries over the next decade which provide direction to our speculations. It is to be hoped that this book has laid out a range of theoretical tools of value to those who seek an understanding of the universe at a deeper level.

Suggested reading

An enumeration of the conceptual problems of the landscape and an approach to thinking about a reformulation of quantum general relativity appears in Banks (2014).