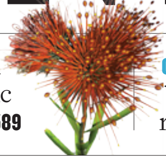
COMMENT

POLICY Climate scientists must try harder to be heard at the highest levels **p.583**

HISTORY A life of Erasmus Darwin, Charles's influential grandfather **p.586**

ART In conversation with an algorithmic species designer **p.589**

OBITUARY Bernard Lovell, who built Jodrell Bank telescope, remembered **p.592**



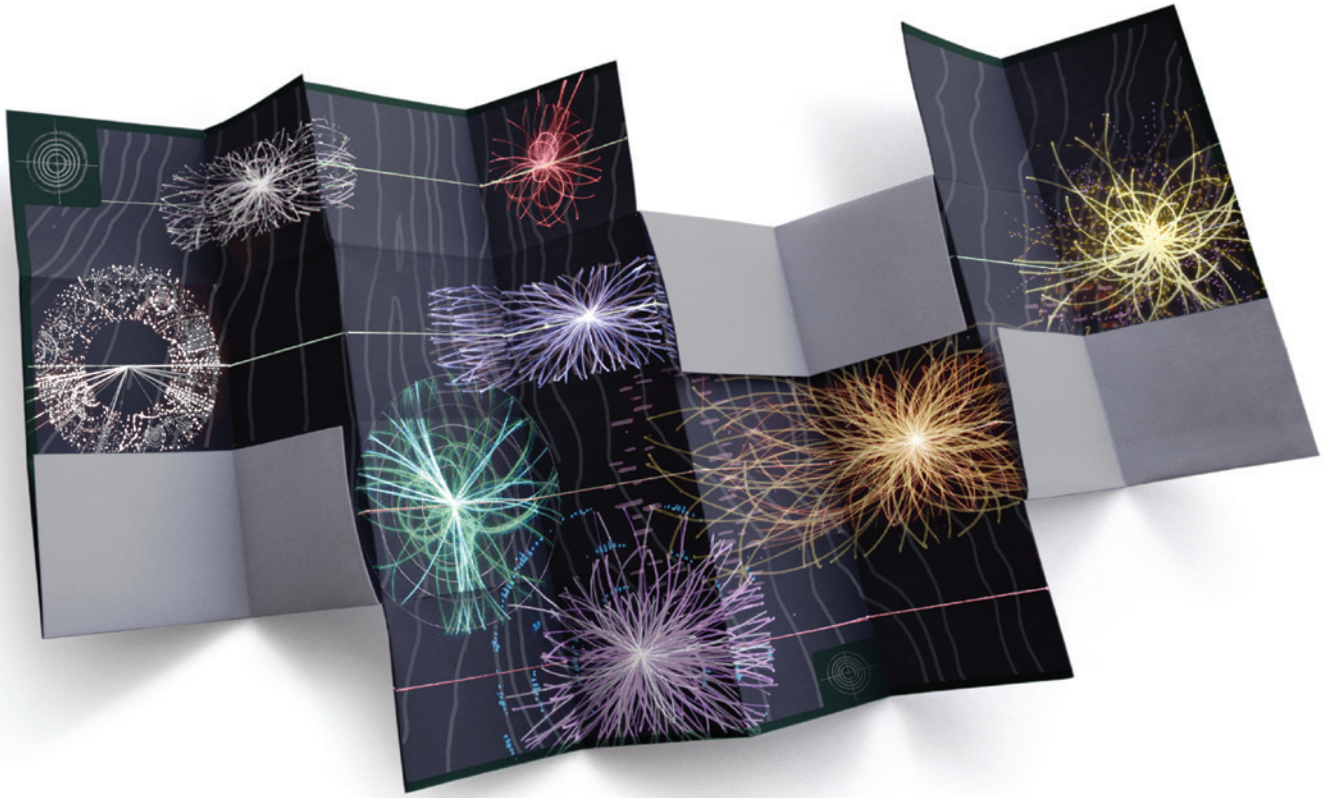


ILLUSTRATION BY BRENDAN MONROE

Beyond the Higgs

The Higgs boson is not the end of the story. There is more to map in the new world of extreme physics, says **Jon Butterworth**.

Finding the Higgs boson was on the 'to-do' list for particle physics for so long that I still haven't absorbed the fact that every lecture course, textbook and popular seminar in the field now needs revision.

The Higgs is predicted by the standard model of physics, and because it gives mass to all the fundamental particles, it is required for the model to work. The announcement last month of its discovery at CERN, Europe's particle-physics laboratory near Geneva, Switzerland, was a triumph for one mathematical approach to understanding the world. One could be forgiven for assuming that all particle physicists can now retire to their Geneva chalets or travel the world as pundits. Particle physics: done.

In fact, the discovery of the Higgs marks the dawn of a new era for researchers in extreme-energy physics. After all, we need to understand why the masses of fundamental particles have the values they do, and why some of the patterns in these fundamental particles are as they are.

In the early 1960s, several physicists concluded that, for the standard model to work, the Universe would need to be filled with a quantum field that gives mass to stuff. Peter Higgs said that if this field were there, it would have waves in it — Higgs bosons. Observing them is the only way to know whether the field really exists. It does.

Such vindication alone is strong encouragement to continue — to measure the Higgs boson and see whether it behaves as predicted, and whether it offers clues to other outstanding questions. We have a wild new frontier of physics to explore.

Particle physicists think in terms of energy scales. The strong nuclear force sets a scale at roughly the mass of the proton, equivalent ▶

▶ to about 1 gigaelectronvolt (GeV). The Large Hadron Collider (LHC) at CERN allows us to study physics up to and beyond the scale at which electroweak symmetry is broken, around 100 GeV. Above this energy, a symmetry exists between the weak nuclear force and electromagnetism that is not present at lower energies. The Higgs is what breaks this electroweak symmetry, and so its mass (around 125 GeV) is on a similar scale.

The Planck scale, on which gravity and quantum forces combine, is the only other fundamental energy scale that has been confirmed. It lies at about 10^{19} GeV, far beyond the reach of current or planned experiments. There must surely be new physics between 100 GeV and 10 billion billion GeV. The LHC will get us partway into this unknown region, but to go beyond that we will need all the clues we can find.

THE GREAT UNKNOWN

First, there are many questions to answer about the nature of the Higgs boson. One is why it is so light. If one assembles the standard model without fine-tuning some parameters, quantum effects mean that the Higgs boson's mass should grow and end up near the Planck scale. This is clearly wrong, and it hints at gaps in the theory.

Supersymmetry and extra space-time dimensions have been proposed as solutions to this problem. Supersymmetry introduces a set of particles that cancel out the quantum effects that would otherwise make the Higgs heavier. Extra dimensions could bring the Planck scale closer to 100 GeV. There is no direct evidence for either theory, but new particles or deviations from the standard model's predictions could turn up at the LHC any time, especially after the machine doubles its energy in 2014.

Reaching ever higher energies requires new developments in technology. The LHC is the biggest project ever in particle physics, yet the CERN budget has not grown in real terms. Research towards making higher-energy beams includes using high-current, low-energy beams to drive higher-energy, lower-current ones; accelerating electrons in the electromagnetic wake of a proton beam; and colliding muons (instead of protons and electrons) to avoid energy sharing between quarks and gluons and energy loss to synchrotron radiation. Not all of these approaches will work, but some might, which would open up new regimes of physics to explore.

Some discoveries can be made without reaching higher energies — the LHC's fast data rate allows for the observation of rare events. Several experiments at the LHC use this feature to address matter asymmetry. Our world is made of matter, not antimatter, yet most fundamental forces do not distinguish between the two. How was this imbalance generated? The LHC 'beauty' experiment, LHCb, is searching for tiny differences in the production of particles and antiparticles in decays involving *b* quarks.

Neutrino experiments might turn out to be our most significant inroad for decades to understanding the dominance of matter. Recent measurements at the RENO experiment in Seoul, South Korea, and the Daya Bay experiment in China suggest that matter–antimatter asymmetry might be especially high among neutrinos, which have a small mass and transform, or 'mix', readily among different types. Proposed experiments in the United States, Europe and Japan could follow up on this possibility.

Neutrinos are unique and mysterious in other ways. Many theorists think that the neutrino is a Majorana fermion — meaning it is its own antiparticle. If so, the neutrino's mass — unlike that of all other particles — does not come from the Higgs boson. Sensitive searches are now under way to find rare isotope decays that could tell us whether or not this is the case.

Other puzzles remain in the standard model, such as dark matter — invisible matter that affects the motions of stars and galaxies but does not seem to be made of any known particle. And we attribute the acceleration of the Universe's expansion to dark energy, but we do not know the physics behind it. A better understanding of how the strong interaction binds quarks and gluons into hadrons would be welcome. Current theory cannot predict how hadrons scatter at very high energies. Quarks and gluons seem to form a liquid at high energy densities, but this form of matter is poorly understood.

The standard model gives us a list of apparently fundamental particles, the only stuff in the Universe that is not made of other stuff. With the discovery of the Higgs, we now have a theory within which these particles can have mass, and this is a huge step forward.

Now we can relish the next steps, at the LHC and beyond. Perhaps researchers can build a linear collider to serve as a 'Higgs factory'. Perhaps another experiment will deliver a surprise that changes everything. Perhaps a breakthrough in the theory will explain the coincidences and patterns of the standard model.

The patterns seen in the periodic table before anyone knew about electrons and nuclei turned out to be a sign of the underlying structure of atoms. Maybe there is another layer of substructure that explains the patterns we see now in particle physics. ■

SEE NEWS FEATURE P. 572

Jon Butterworth *is professor of physics and head of the Department of Physics and Astronomy, University College London, London WC1E 6BT, UK.*
e-mail: j.butterworth@ucl.ac.uk