# PARTICLE PHYSICS
## BRICK BY BRICK

To Mum and Dad, thanks for all
of your encouragement as a kid!

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# SCIENTIFIC MODELS

When asked 'what is science?' I draw a deep breath. There are many answers that could be given; a historical one, a philosophical one, a practical one. Instead my answer is that science, at its core, is the search and desire for the most accurate possible analogy of Nature. Scientists build these analogies not in words but in the language of mathematics. The analogies they build aim to become the truest mathematical models of the way the universe works and where everything in it came from. But, like the words of a poet, the language we use cannot perfectly capture the true beauty of Nature.

Poets and scientists differ, however, when evolving their work. Re-writing of a poem is likely to be subject to differing human opinion, re-writing scientific models of Nature is not. Science answers only to hard and repeatable evidence from experiment. If time and again a new scientific model does not hold up in the face of new experimental results, then it is discarded. To progress, a new or modified model of Nature is required. In this way science has evolved, developing ever-more accurate mathematical models of Nature.

Experimental data is constantly reminding scientists of the shortcomings of their current mathematical models. Although our scientific understanding of Nature is imperfect, we embrace and quantify this imperfection in the error envelope of the measurements. What has been shown historically is that new science usually lurks in the detailed understanding of these errors.

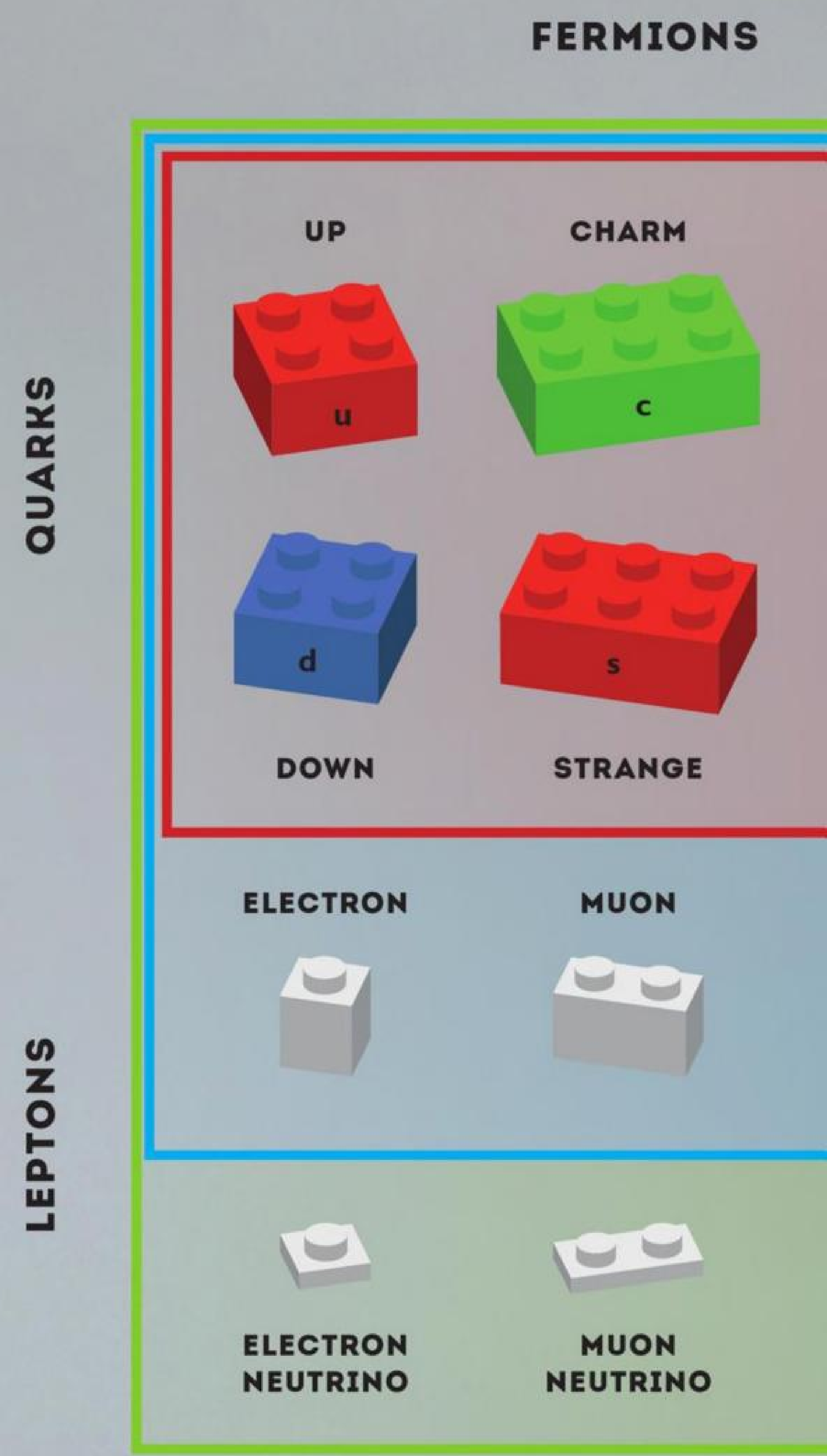
When explaining complex ideas, we often find ourselves using our own analogies and models. This is especially true when communicating science which is abstract to our everyday experience of the world. Plastic bricks are of course not particles. Each brick is made from trillions upon trillions of particles. Yet I feel that they can be used to provide a fun and engaging analogy to our understanding of that subatomic world. This plastic brick analogy, by the very definition of the word, is not a perfect description of Nature, but does take us close to a complete picture of the Universe at the smallest scale.

# THE STANDARD MODEL OF PARTICLE PHYSICS

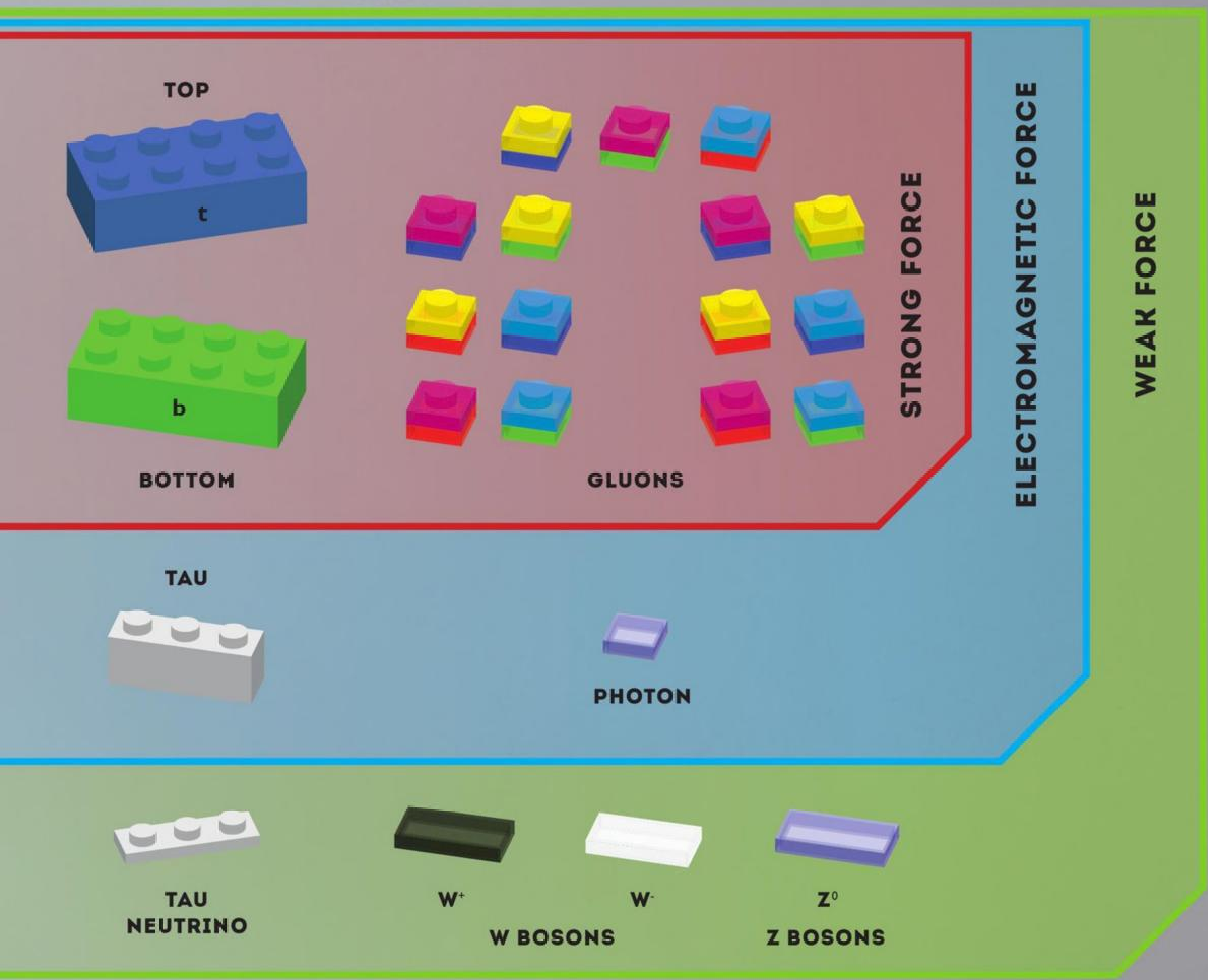
**The Standard Model is our current best model of the world at the smallest scales and was developed primarily throughout the 1960s and 70s. To this day there have only been minor adjustments made to it and every experiment which has put it to the test has shown it to be correct. Yet we know it cannot be a complete model of Nature. The Standard Model has no tested analogy for the dark matter which defines the size, shape and distribution of galaxies (see page 164). It also fails to explain the strange dark energy which is accelerating the expansion of our Universe. Most frustratingly for particle physicists is that the Standard Model is not able to tell us where all particles came from at the beginning of time itself (see chapter 8).**

The Standard Model describes the properties and interactions between a collection of particles which are, as far as we understand, fundamental. Each one cannot be subdivided into anything smaller, so they are the truest building blocks from which our Universe is made. It does not tell us what the particles are made from; it does not tell us their size; and it cannot predict the strength of the forces which shape our Universe. It is a mathematical model which is designed to fit the experimental data seen – and it does this fantastically well.

The possible lives of Standard Model particles are explained not as solid particles but as extended objects called fields which stretch out to infinity in space and time. At each point in space and time a particle has a non-zero probability of interacting with other particles. Yet when the particles interact, all of the possibilities crystallize into a single point in space and time with set behaviour. It is this single point that best fits the idea of a particle as a solid little ball. Without discussing the maths in detail it is difficult to explain the field-like nature of particles. Here instead we use bricks to represent these point-like particles when they interact, although the field-like aspects will lead us to some seemingly illogical outcomes.



## BOSONS





* *This particle has been hypothesised but never observed experimentally*

# THE HISTORY OF PARTICLE PHYSICS

## PREDICTIONS

### ELECTROMAGNETISM

**1803**
**JOHN DALTON**
Matter is made from different weight atoms
PAGE 14

### QUANTUM PHYSICS

**1905**
**ALBERT EINSTEIN**
Light is made of photons

**1928**
**PAUL DIRAC**
Dirac equations predict the antielectron and all other antiparticles
PAGE 88

**1930**
**WOLFGANG PAULI**
Neutrinos are needed to make sense of beta decay
PAGE 123

**1935**
**HIDEKI YUKAWA**
Mesons exchange the strong force in atomic nuclei
PAGE 92

## DISCOVERIES

### RADIOACTIVITY

**1897**
**J J THOMSON**
Discovery of the electron, the first subatomic particle

**1899**
**ERNEST RUTHERFORD**
Discovery of alpha and beta radiation
PAGE 86

**1911**
**EDWARD MARSDEN, HANS GEIGER AND ERNEST RUTHERFORD**
Discovery of the atomic nucleus
PAGE 86

**1919**
**ERNEST RUTHERFORD**
Discovery of the proton

**1932**
**JAMES CHADWICK**
Discovery of the neutron

### COSMIC RAYS

**1935**
**CARL D ANDERSON**
Discovery of the muon in cosmic rays
PAGE 89

**1947**
**CECIL POWELL, CÉSAR LATTES AND GIUSEPPE OCCHIALINI**
Discovery of the pion, Yukawa's meson
PAGE 92

**STANDARD MODEL**

**1964**
**MURRAY GELL-MANN AND GEORGE ZWEIG**
Prediction of quarks

**1967–1971**
**STEVEN WEINBERG, SHELDON GLASHOW AND ABDUS SALAM**
Electroweak force, W and Z boson predicted
PAGE 132

**1964**
**PETER HIGGS**
Prediction of the Higgs boson
PAGE 138

**1977**
**PIERRE FAYET**
Minimal Super-symmetric Standard Model proposed
PAGE 166

**BEYOND THE STANDARD MODEL**

**1980S AND 90S**
**MANY SCIENTISTS**
Development of string theories
PAGE 168

**1955**
**OWEN CHAMBERLAIN, EMILIO SEGRÈ, CLYDE WIEGAND, AND THOMAS YPSILANTIS**
Discovery of the antiproton
PAGE 98

**1964**
**VAL FITCH AND JAMES CRONIN**
Discovery of CP-violation in kaons
PAGE 156

**1974**
**BURTON RICHTER AND SAMUEL TING**
Discovery of the J/ Ψ, the first charmed particle
PAGE 106

**1995**
**DZERO AND CDF EXPERIMENTS**
Discovery of the top quark
PAGE 125

**1998**
**SUPER KAMIOKANDE**
Observation of neutrino oscillation
PAGE 147

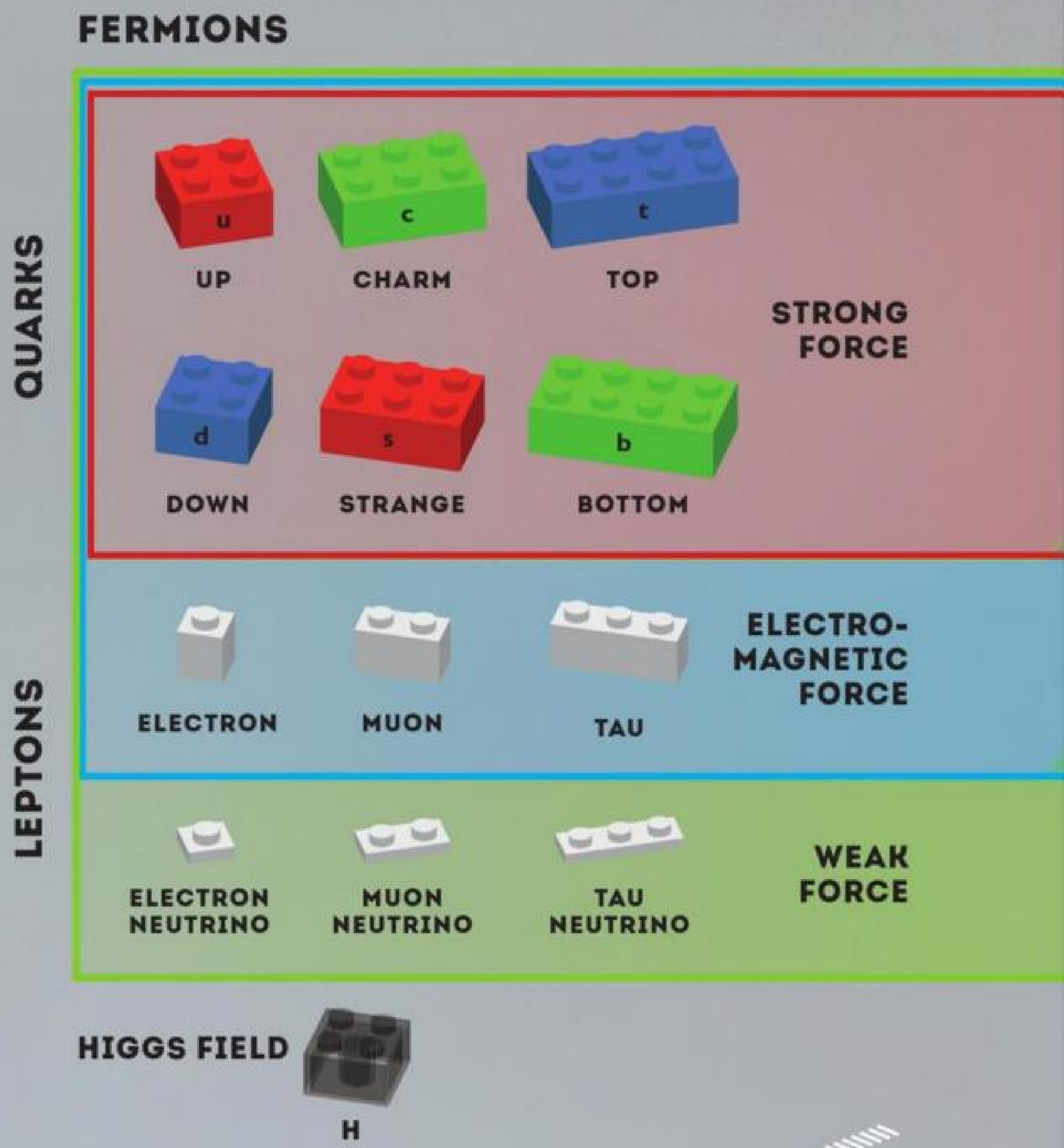
**2012**
**ATLAS AND CMS EXPERIMENTS**
Discovery of the Higgs boson
PAGE 138

**AGE OF ACCELERATORS**

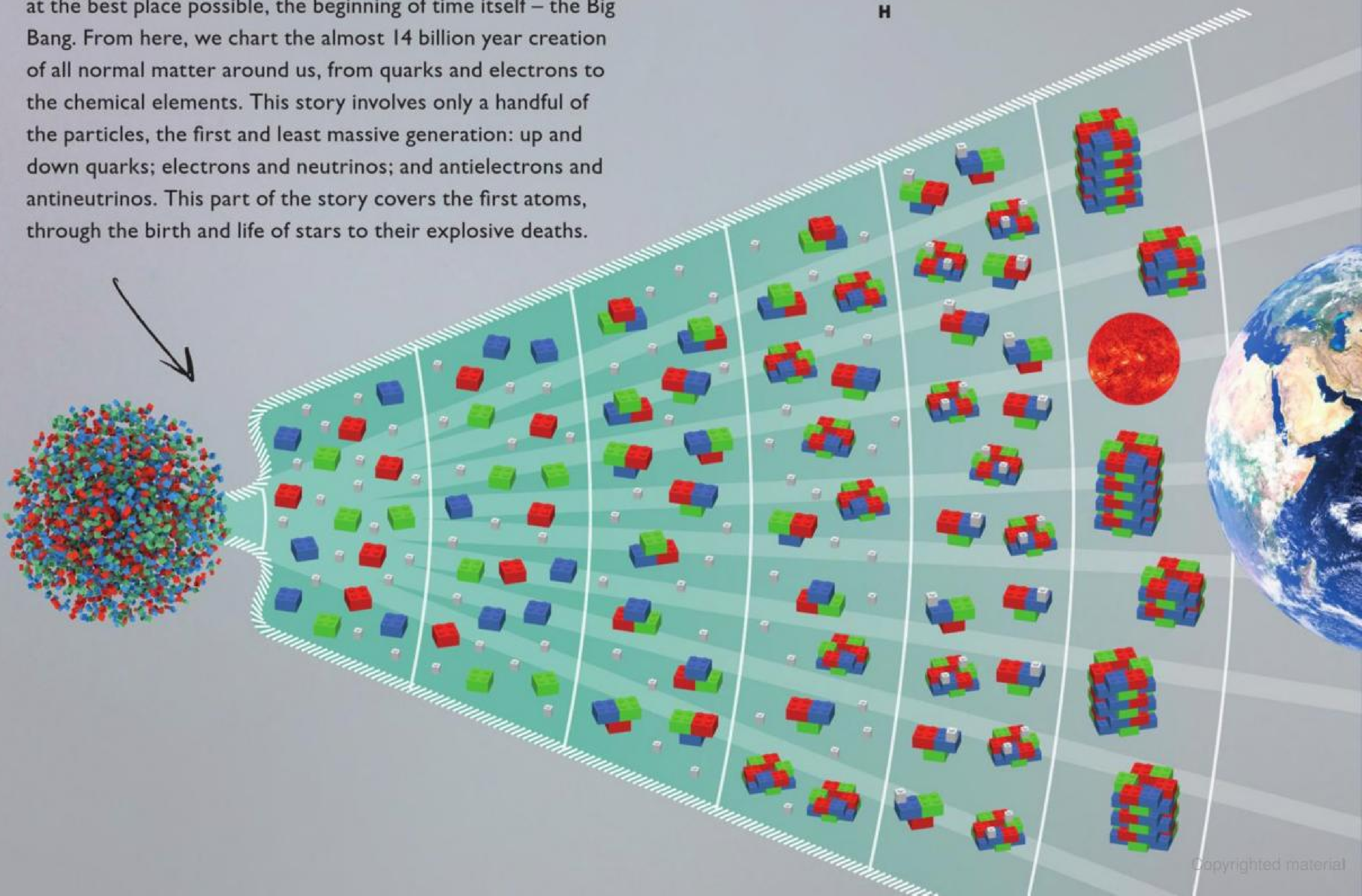
# THIS BOOK

**We begin this book, like any set of instructions, with a list of the parts – all of the most basic bricks from which our Universe is created. We also discuss important concepts which we will need later on in the book. There will be a lot of new words and necessary jargon here, so it will be a good point of reference as we continue.**

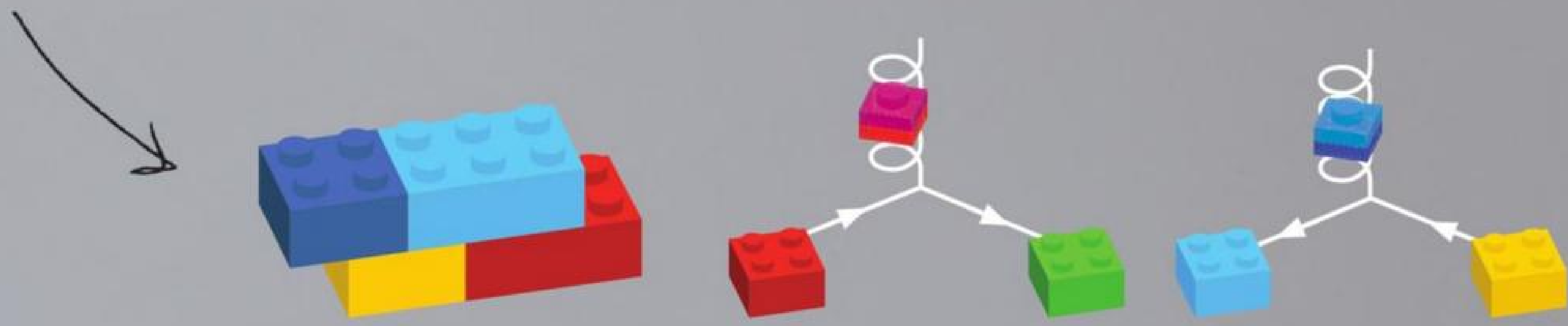
To remind you of the list of parts, they are helpfully printed on the pull-out flaps at the front of the book, and the inside flaps have a quick-look glossary of jargon.

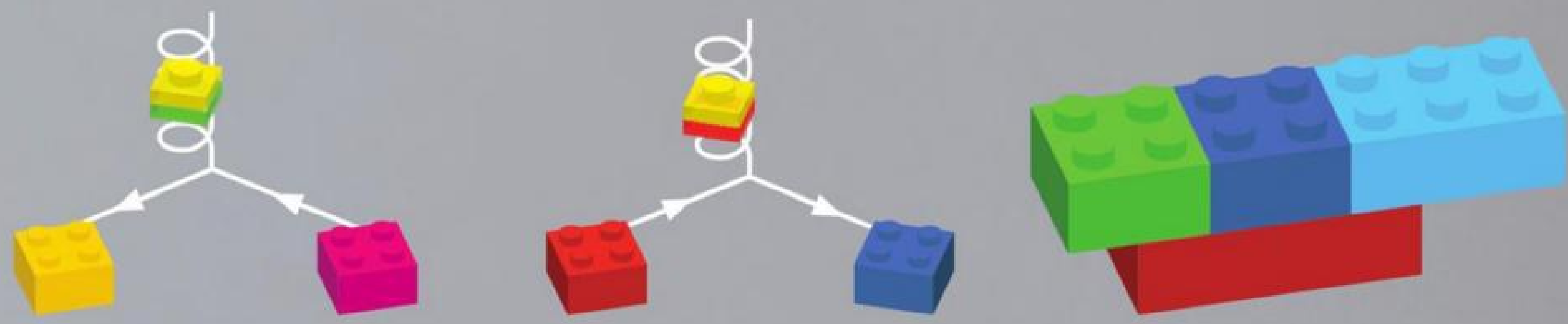



The rest of the book can then focus on the story and we begin at the best place possible, the beginning of time itself – the Big Bang. From here, we chart the almost 14 billion year creation of all normal matter around us, from quarks and electrons to the chemical elements. This story involves only a handful of the particles, the first and least massive generation: up and down quarks; electrons and neutrinos; and antielectrons and antineutrinos. This part of the story covers the first atoms, through the birth and life of stars to their explosive deaths.

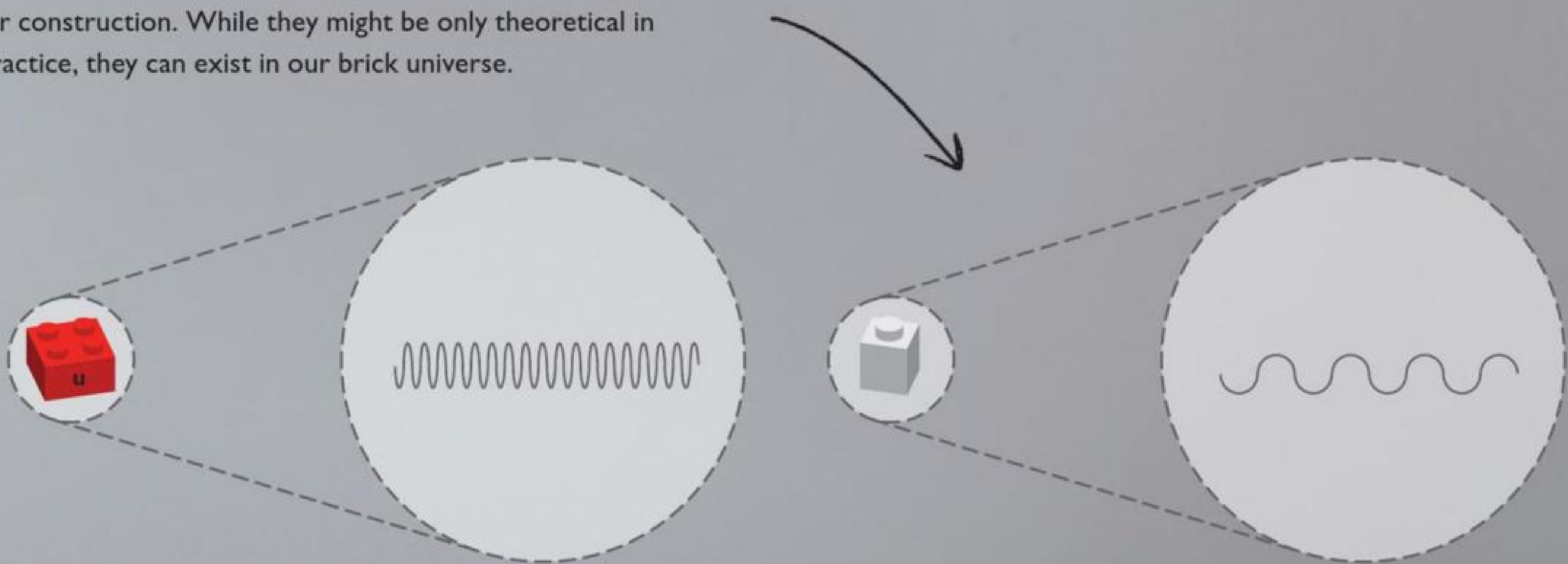


The second section of the book discusses the forces of Nature in detail while charting the human story of our ever-growing understanding of particle physics. This story takes us back in time as experiments create conditions ever closer to those not experienced since the Big Bang. There have been thousands of people who have dedicated their lives to advancing human knowledge in this field. While I would like to acknowledge every one I am afraid that it will be just the headline names that get mentioned here. Once we have explored the forces in greater detail you can then use the list of extended construction rules to build an entire zoo of exotic particles of your very own.





Finally we discuss the future of particle physics – the gaps in our knowledge and some of the theories which hope to fill them. New particles are being introduced as well as new rules for construction. While they might be only theoretical in practice, they can exist in our brick universe.

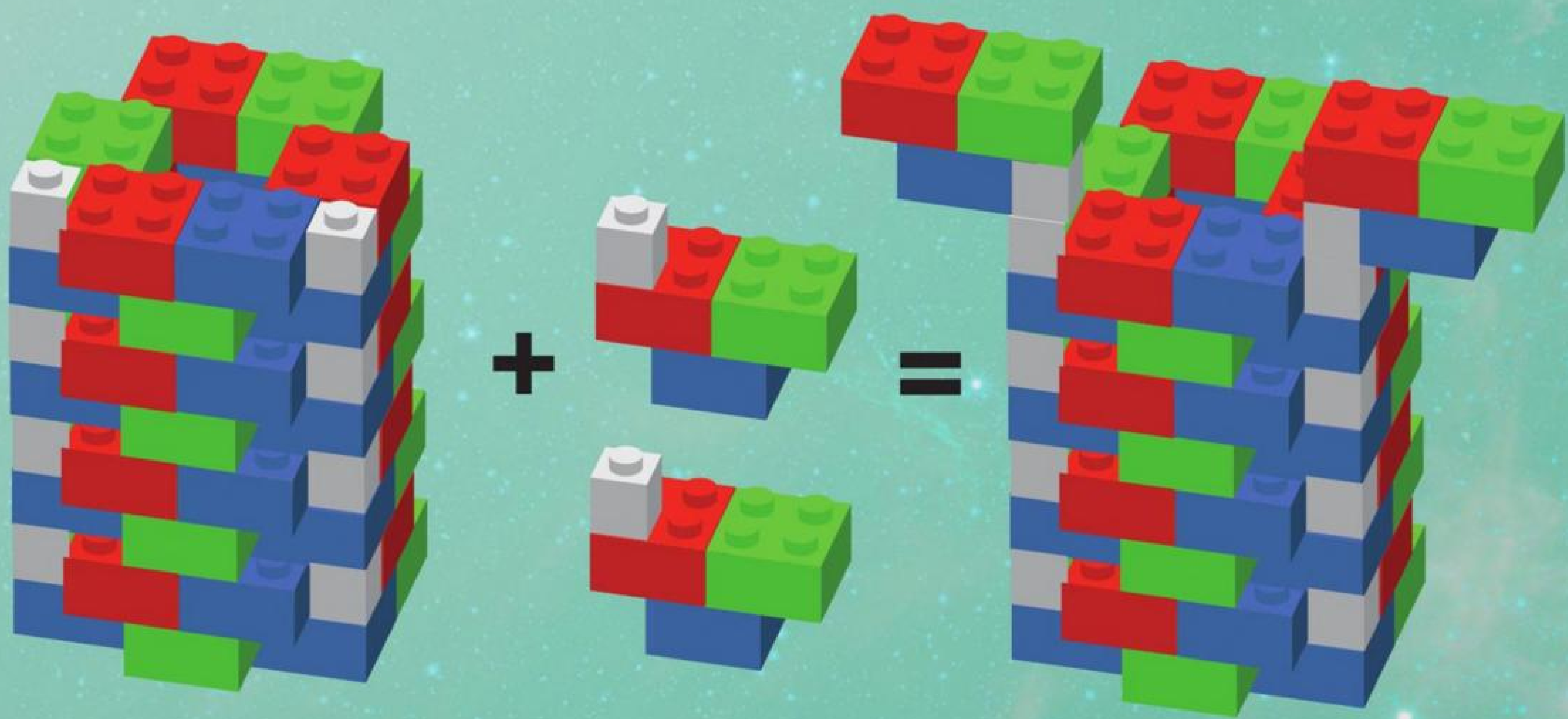


***All of the matter around us is built from chemical elements, each made from a unique type of atom***

# ATOMS

The Greek philosopher Democritus, who lived from 460 to 370 BC, imagined all matter could be divided up into smaller and smaller pieces until eventually there would be a particle which could no longer be divided. This smallest unit of matter he named the atom, from the ancient Greek *atomos* which translates as indivisible. Democritus's atomic idea of matter survived through to the 18th century, a time when chemistry came out of the shadow of alchemy and into the science mainstream. Evidence was building that pure chemical elements reacted together to form new compound chemicals in whole ratios of their mass, for example oxygen and hydrogen reacted in a ratio of 8:1 to form water (note this ratio refers to the total atomic weights not the number of atoms). Englishman John Dalton suggested that this was evidence that chemicals were built from smaller pieces, atoms, and that each chemical element was made from different types of atom. Dalton's new atomic theory proved successful until the end of the 18th century when strange radiation showed that atoms were not as their name suggested - they were divisible to yet smaller parts.

In this chapter we delve inside the atom to the particles from which every atom is made.

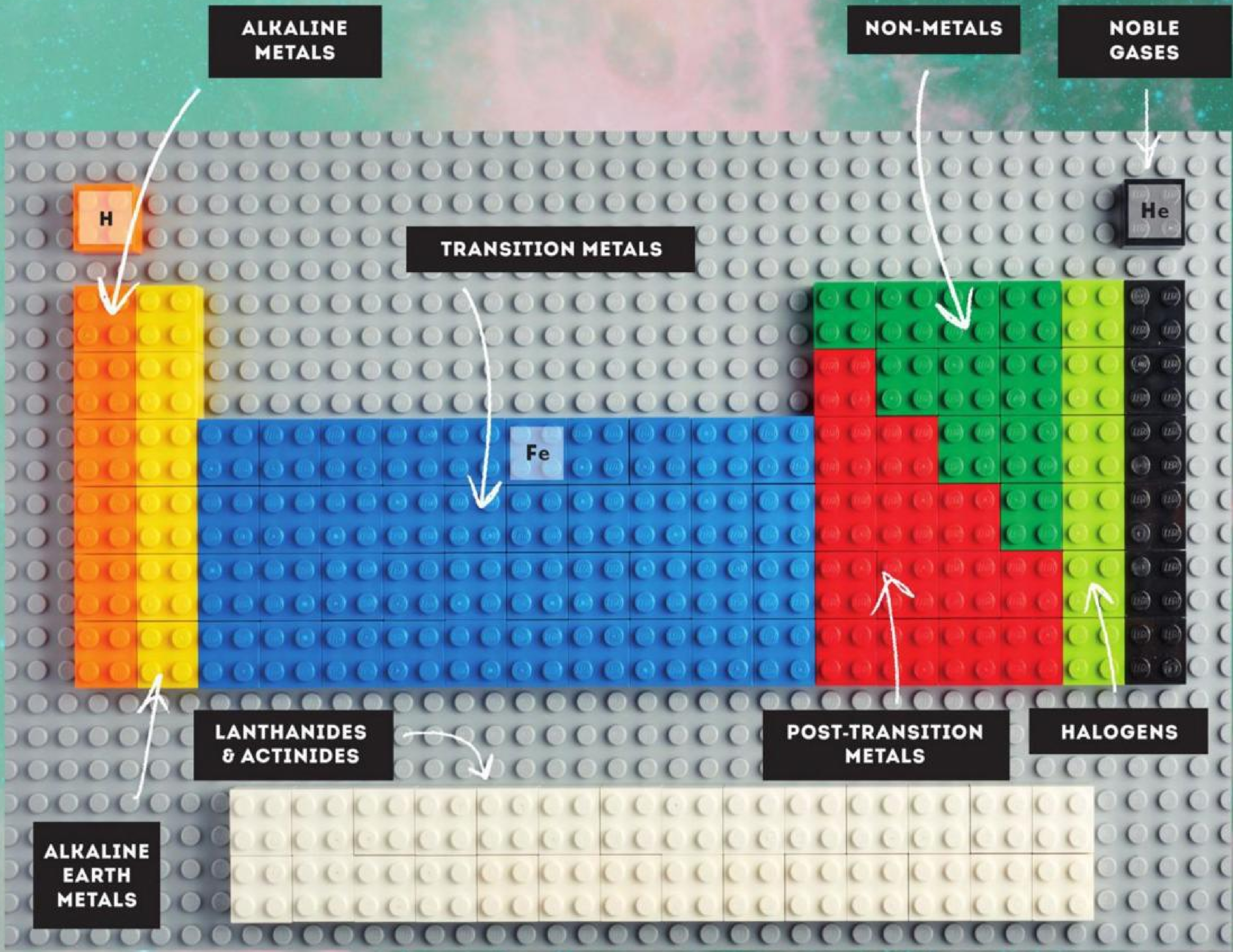


OXYGEN + 2 HYDROGEN = WATER

## THE PERIODIC TABLE

Toward the end of the 19th century over 100 elements had been discovered, each made from a unique type of atom. Periodically changing patterns, like increasing octaves in music, were used by Dmitri Mendeleev to place these elements into the periodic table. Similarities in behaviour of elements in the same group of the periodic table suggested that they shared some common structure. But if the atoms are, as the Greek word atomos means, uncuttable then how can there be anything smaller? It was not long before things less massive than the lightest atom hydrogen were discovered. These unexpected new 'atoms' seemed to be the reason for the phenomenon of electricity. The discovery of new radiation emitted from atoms confused the subject further and it soon became clear that science was not all wrapped up.

The first row of hydrogen (H) and helium (He) are the elements found in large quantities in the early Universe (pages 42–3) while all elements up to iron (Fe) are made in stars (pages 58–9) and other elements are made in the explosive deaths throes of stars (pages 60–1).

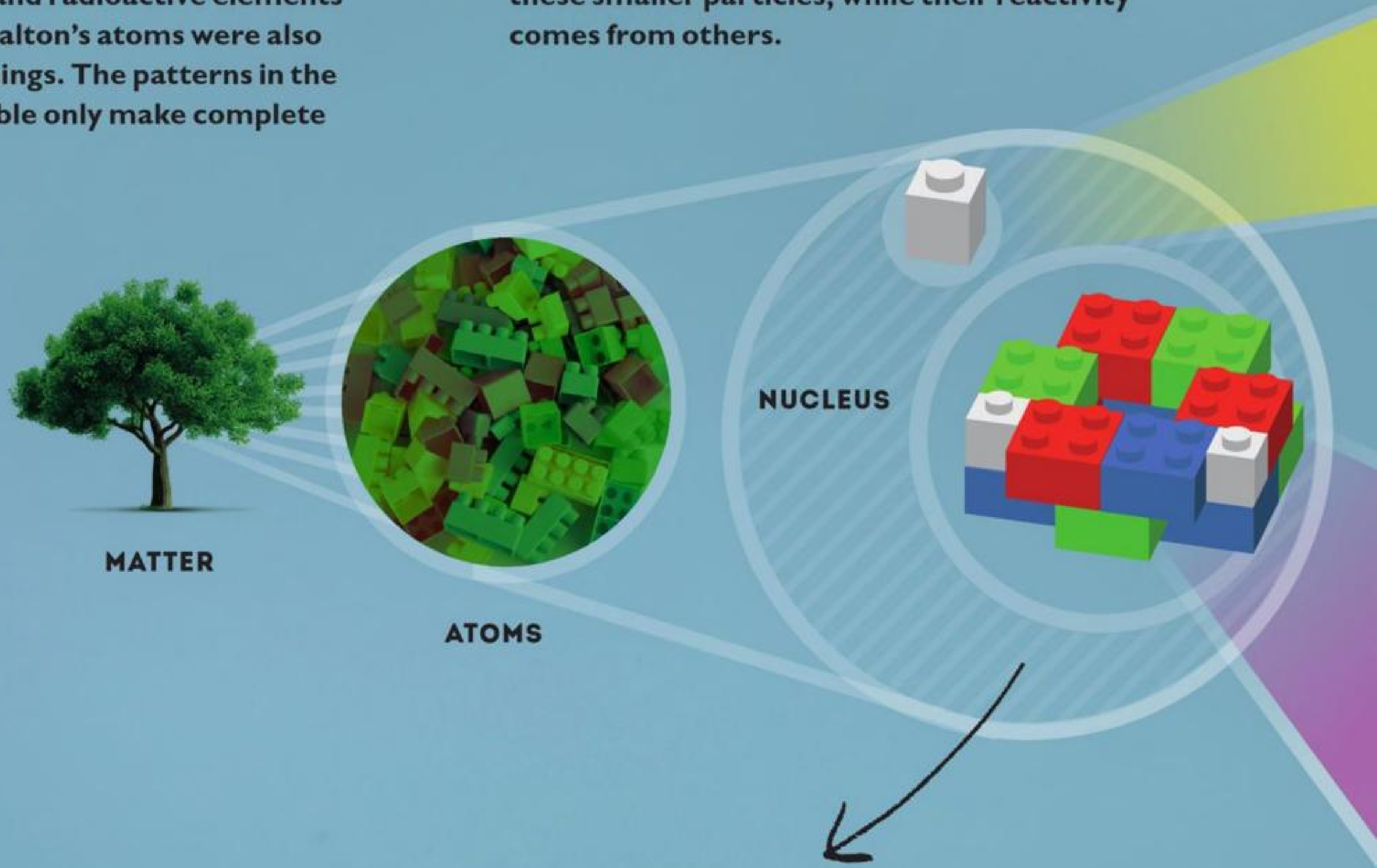


*The wide variety of atoms in Nature are all composed from just three smaller, subatomic things*

# INTO THE ATOM

The work of John Dalton showed us that the world around us is not made from just one type of atom, as the Ancient Greeks thought. The study of electricity and radioactive elements soon showed that Dalton's atoms were also made from other things. The patterns in the modern periodic table only make complete sense once we understand that atoms are constructed from smaller building blocks. Atoms owe their atomic weights to some of these smaller particles, while their reactivity comes from others.

**LOOKING INTO AN ATOM**




### ATOMIC NUCLEUS

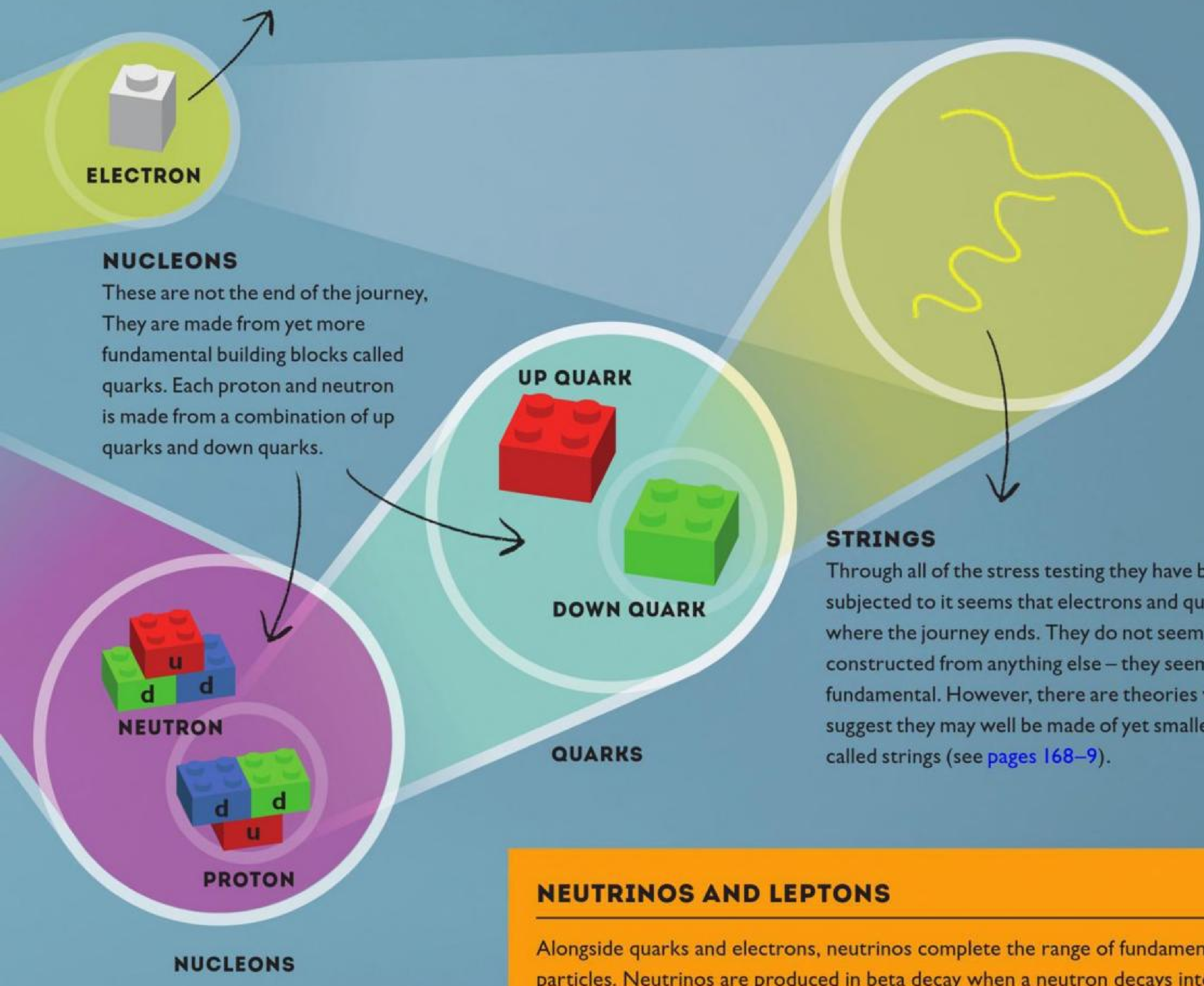
This lies at the centre of every atom and is made from the nucleons – protons and neutrons. The nucleus is the source of the radioactivity seen coming from some chemical elements.

### WHAT'S IN A NAME?

Protons get their name from the Greek for first. Neutrons are so called as they are electrically neutral. Electrons are named such as they are the atom of electricity.

### ELECTRONS

These lie in clouds surrounding a central nucleus. Electrons participate in and dictate the chemical reactions of an element. It is the number of electrons within an atom which determines the periodic nature of chemical reactions.




### NUCLEONS

These are not the end of the journey, They are made from yet more fundamental building blocks called quarks. Each proton and neutron is made from a combination of up quarks and down quarks.

### STRINGS

Through all of the stress testing they have been subjected to it seems that electrons and quarks are where the journey ends. They do not seem to be constructed from anything else – they seem truly fundamental. However, there are theories which suggest they may well be made of yet smaller things called strings (see pages 168–9).

### NEUTRINOS AND LEPTONS

Alongside quarks and electrons, neutrinos complete the range of fundamental particles. Neutrinos are produced in beta decay when a neutron decays into a proton and an electron, which is always accompanied by a neutrino. The electron and neutrino form a group which are called leptons. Being lighter than the protons and neutrons known at the time, they take their name from the Greek *leptós* which means small, thin or delicate.

***There are twelve antimatter particles which are mirror opposites of the matter particles***

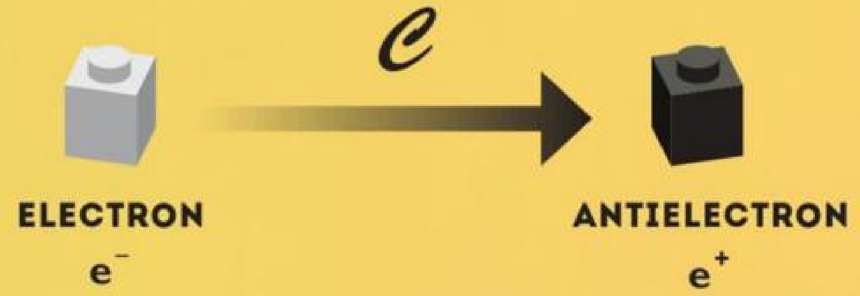
# WHAT'S THE ANTIMATTER?

**It has also been predicted and observed that the twelve fermion matter particles each have a mirror opposite, a particle where everything about their behaviour is reversed. These are the fundamental particles of antimatter.**

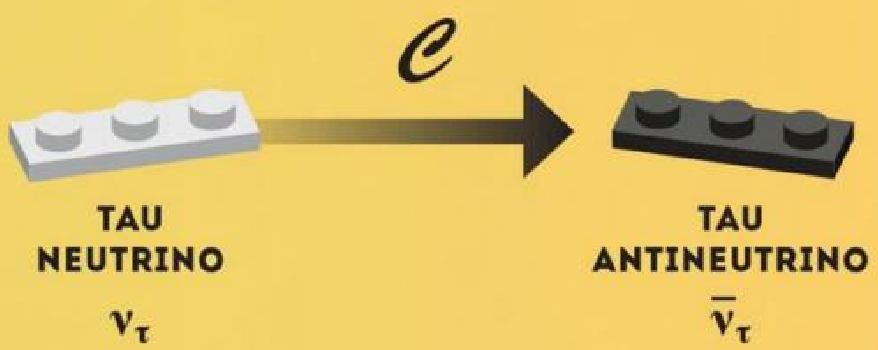
Where an electron would be said to have a negative electric charge its antimatter version the antielectron (also called the positron) has a positive electric charge. Flipping the properties of the particles like this is done in a special mirror known as charge inversion (C) which changes a particle to an antiparticle by flipping its charge. Particles and antiparticles interact with each other in totally opposite ways.

In these diagrams, the arrow and $\mathcal{C}$ indicates a charge inversion.

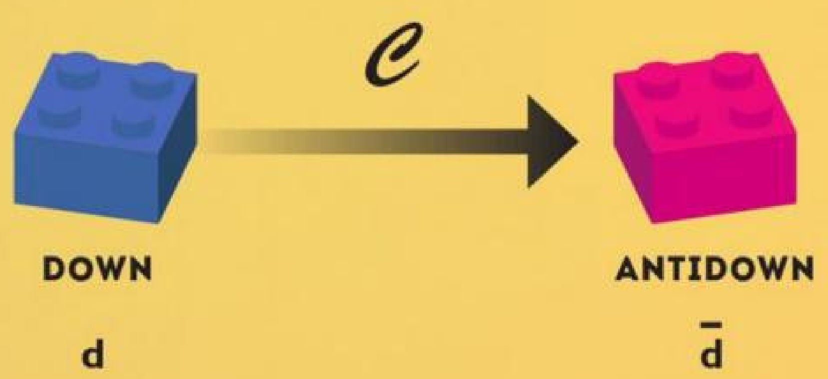
An electron can be changed to an antielectron using a charge inversion.




A tau neutrino changes to a tau antineutrino using a charge inversion.




A down quark changes to an antidown quark by charge inversion.




We use a line, called a bar, above the particle symbol to show it is the antiparticle.

| ANTIFERMIONS | | GENERATION 1 | GENERATION 2 | GENERATION 3 | |
|---|---|---|---|---|---|
| | ANTIQUARKS | $\bar{u}$ ANTIUP | $\bar{c}$ ANTICHARM | $\bar{t}$ ANTITOP | **Up-type antiquarks** Charge +2/3 |
| | ANTIQUARKS | $\bar{d}$ ANTIDOWN | $\bar{s}$ ANTISTRANGE | $\bar{b}$ ANTIBOTTOM | **Down-type antiquarks** Charge -1/3 |
| | ANTILEPTONS | $e^+$ ELECTRON | $\mu^+$ MUON | $\tau^-$ TAU | **Charged antileptons** Charge + 1 |
| | ANTILEPTONS | $\bar{\nu}_e$ ELECTRON ANTINEUTRINO | $\bar{\nu}_\mu$ MUON ANTINEUTRINO | $\bar{\nu}_\tau$ TAU ANTINEUTRINO | **Antineutrinos** Charge 0 |

Just as with matter particles there are twelve anti-matter particles. Their name is the same as the matter particles just with *anti* stuck on the front.

Today antimatter is created in high-energy locations such as particle accelerators (see pages 98–9), and the particles colliding with our atmosphere (see pages 94–5). Antimatter would have existed naturally in abundance in the hot early Universe but it has long since been obliterated. When matter and antimatter meet one another they annihilate each other to form pure energy – usually in the form of light.

*The forces dictate how particles interact and combine to form atoms, elements and chemicals*

# FORCES

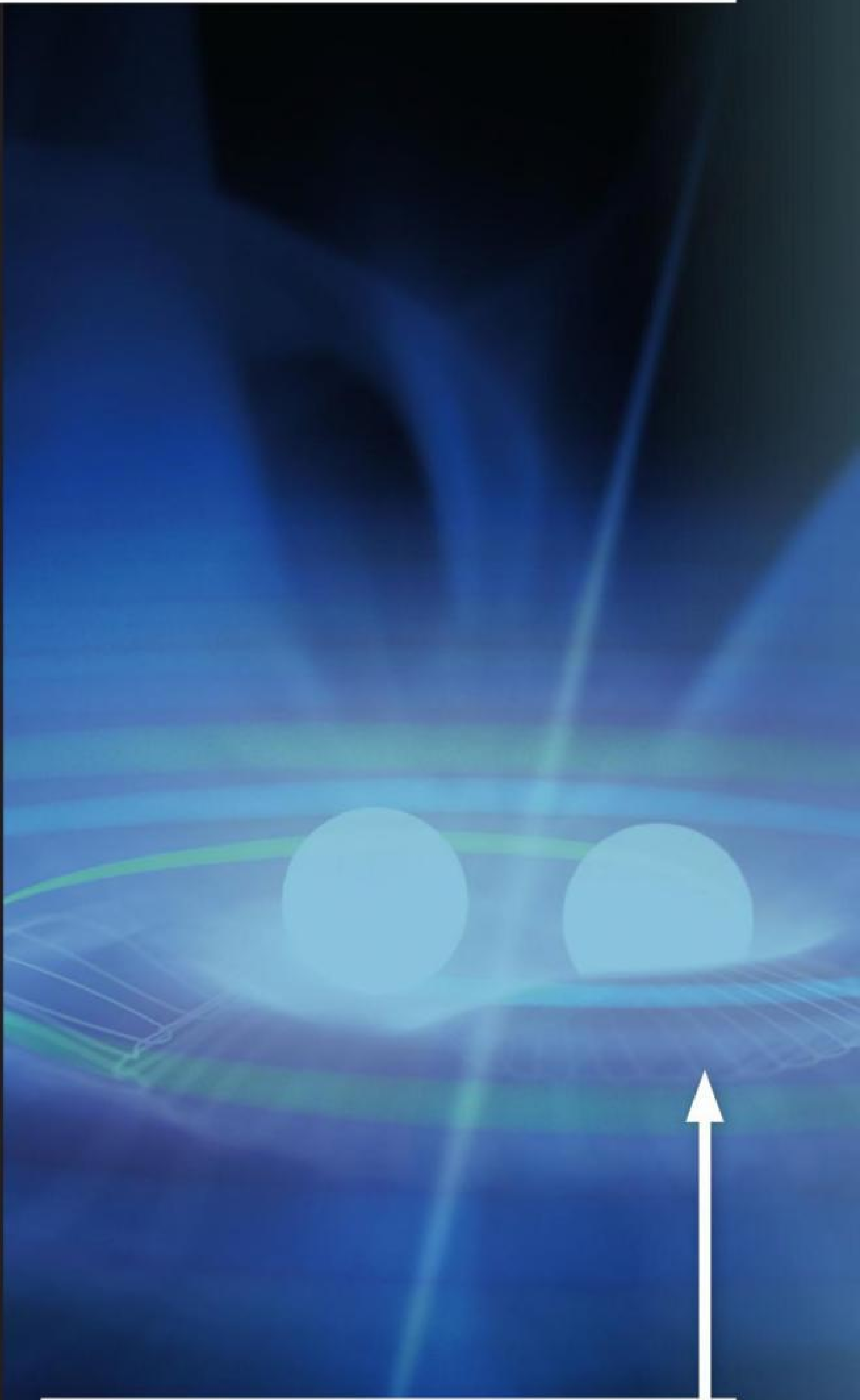
**Now we have a set of building blocks we need some building instructions and these are dictated by the forces of Nature. Rather than step-by-step explicit instructions, these forces impose guidelines and restrictions as to how fundamental particles interact and combine with one another. Nature seems dictated by the influence of four fundamental forces. Two you may be familiar with as they have an infinite range of influence – the forces of gravity and electromagnetism. The other two will be less familiar as they are confined to the nucleus of an atom – the weak and strong nuclear forces. The influence of each force is exchanged between fermion particles by a separate class of particles called bosons, named after the Bengali theoretical physicist Satyendra Nath Bose.**

## GRAVITY

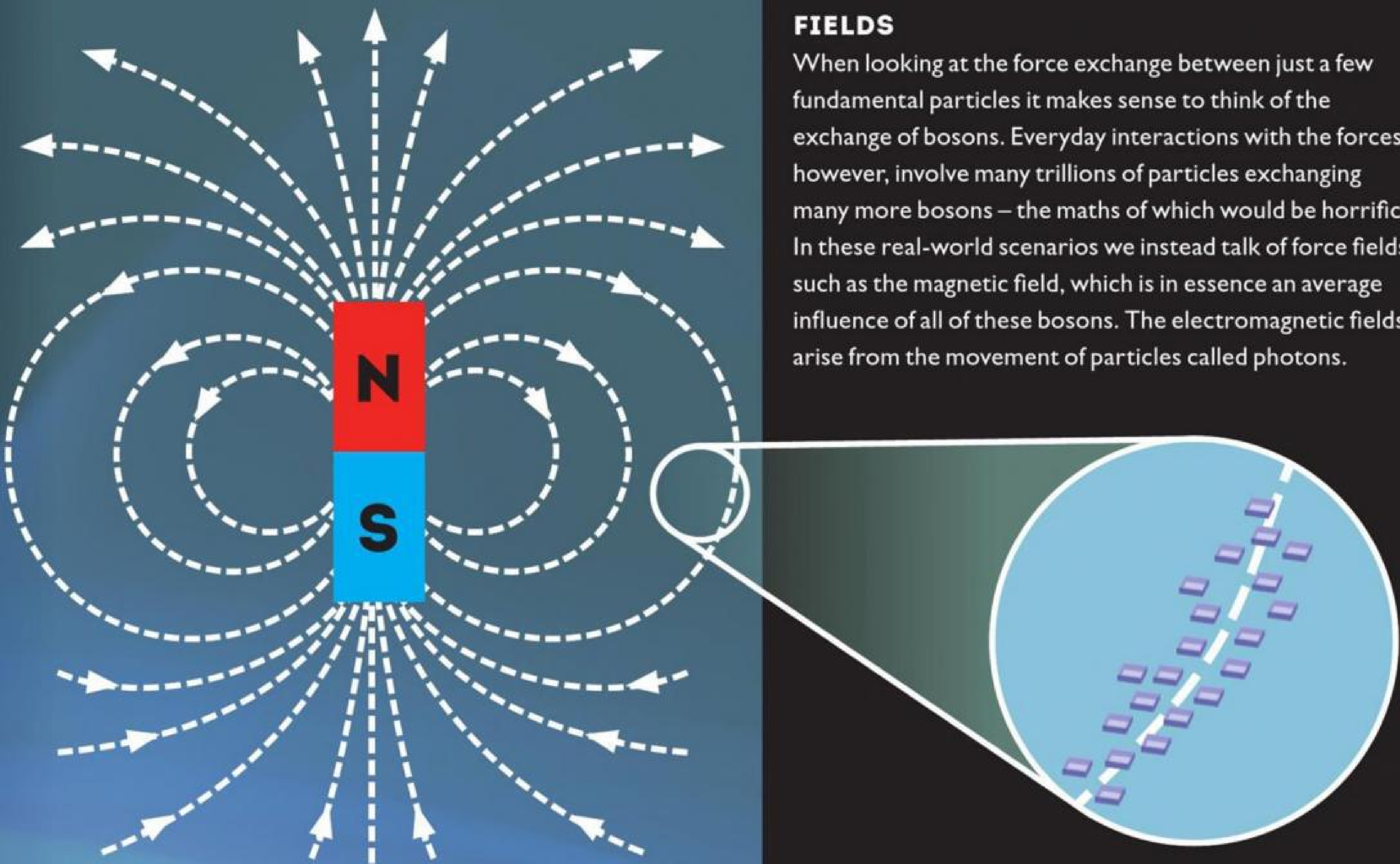
While gravity will be the most familiar force as it is firmly fixing you to the surface of this planet, it is the weakest fundamental force. This weakness and the tiny masses of particles mean that gravity does not really affect the lives of particles as it does our own. Gravity is ignored when considering the interaction of particles.

## GRAVITONS

The graviton is the boson particle predicted to exchange the, always attractive, gravitational force between objects with mass. Gravitons are not part of the Standard Model and remain theoretical, having not been observed experimentally. The recent discovery of gravity waves however, provides indirect evidence of gravitons – where there is a force field there are usually bosons.

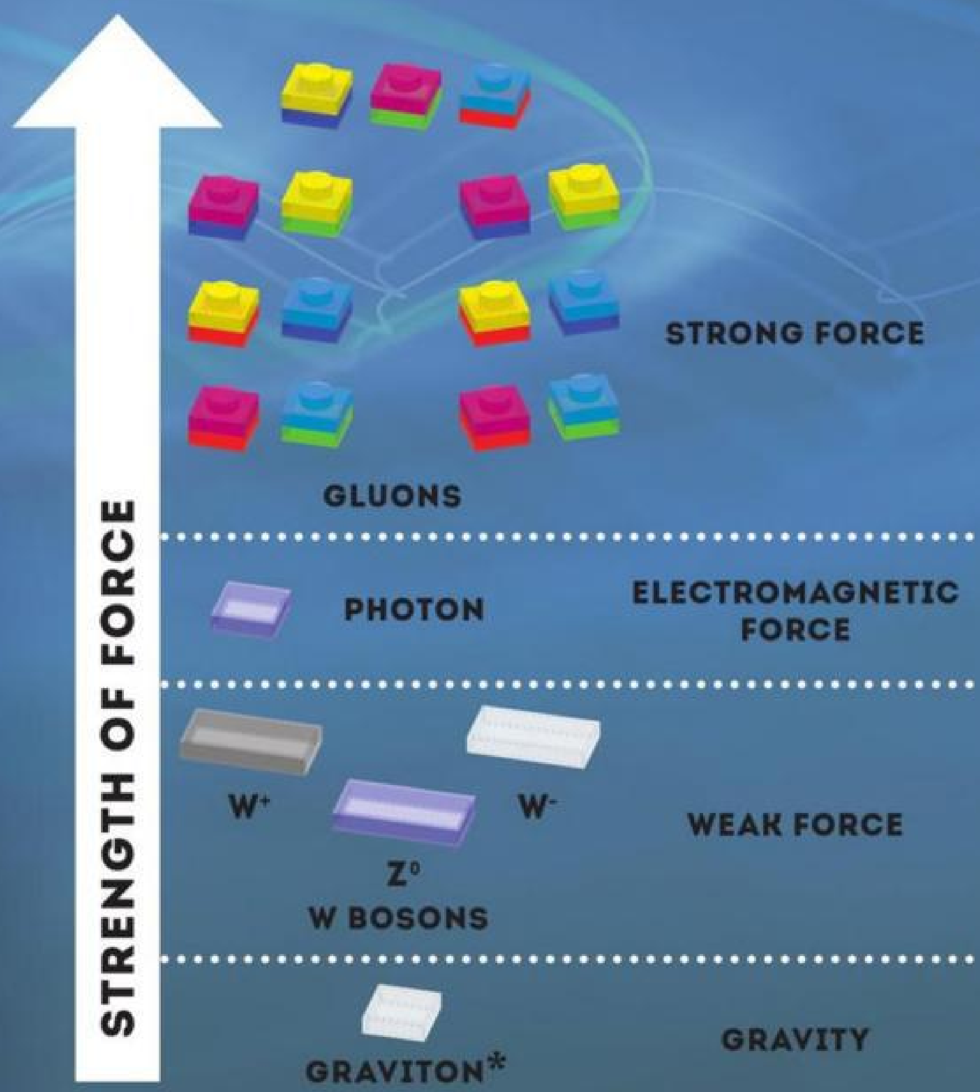


Gravity waves might, like all other forces, be made from the concerted behaviour of boson exchange particles: gravitons.




## FIELDS

When looking at the force exchange between just a few fundamental particles it makes sense to think of the exchange of bosons. Everyday interactions with the forces, however, involve many trillions of particles exchanging many more bosons – the maths of which would be horrific. In these real-world scenarios we instead talk of force fields, such as the magnetic field, which is in essence an average influence of all of these bosons. The electromagnetic fields arise from the movement of particles called photons.




## BOSONS

The influence of each force is exchanged between quarks and leptons by a separate set of particles called bosons.

With the exception of gluons (the exchange particles of the strong force (see page 27)), bosons do not connect together like fermions to build more complex matter. Instead they are just messengers which exchange information and energy between particles.

On the left we can see the four forces in order of strength along with associated bosons.

** This particle has been hypothesised but never observed experimentally*