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30-SECOND CHEMISTRY

THE 50 MOST ELEMENTAL CONCEPTS IN CHEMISTRY, EACH EXPLAINED IN HALF A MINUTE

Editor **Nivaldo Tro**

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INTRODUCTION

Nivaldo Tro

The core idea of chemistry is that *the whole can be explained by its parts*. The properties of matter can be explained by the bits that compose it. Understand the bits, and you understand the whole. Philosophers call this idea reductionism. Reductionism has not always been popular in the history of thought, nor is it clear that it is universally true. But the stunning and ongoing success of chemistry in explaining the behaviour of matter – even living matter – suggests that, at a minimum, reductionism is a powerful and useful idea.

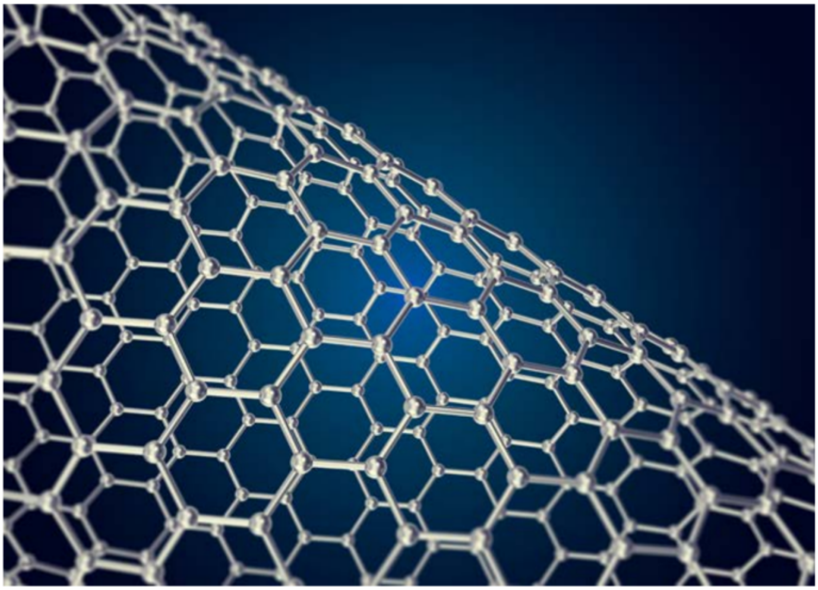
The 'bits' in chemistry are atoms, ions and molecules. Although the idea that matter has fundamental 'bits' is quite old – it was first suggested more than 2,000 years ago – its broad acceptance is quite recent, and occurred only about 200 years ago. Before that time, most thinkers thought that matter was continuous, that it had no smallest bits. The advent of the scientific revolution in the sixteenth century led thinkers to correlate their ideas about nature more carefully with empirical measurements. Since empirical measurements supported the particulate model, the continuous model was discarded.

Chemistry helps us understand that we - and all things around us - are made up of particles.

Once the particulate model was accepted in the 1800s, progress came relatively quickly. Scientists began figuring out the structure of the basic particles that compose matter, and by the early-to-mid twentieth century, chemists had good models that explained how atoms bond together to form molecules, and how the structures of atoms and molecules affect the properties of the substances they compose. In fact, throughout chemistry, the relationship between structure and properties is a key unifying theme.

A second unifying theme of chemistry is the progression from simple to complex. It turns out that, in nature, when you put together simple particles in slightly different ways, you can get vast complexity. Just as the 26 letters of our alphabet can be combined in different ways to compose many words, and just as you can combine those words in many ways to form an even larger number of complex ideas, so the 91 elements that compose matter can be combined to form many compounds, and those compounds can be combined to form an even larger number of complex substances, including all living things.

Graphene is a new, carbon-based material that is just one atom thick but is stronger than steel.



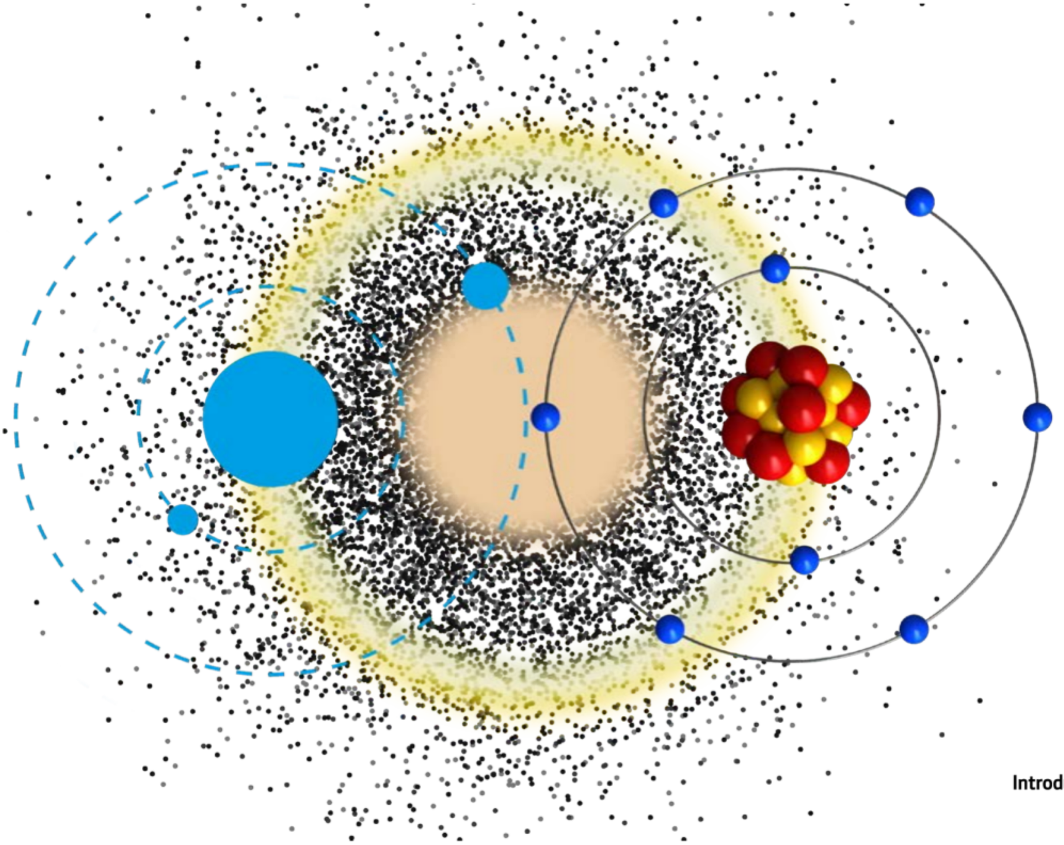
How far can chemistry go in its explanations? We still don't really know. We know that chemistry can explain how a gas behaves, but can it explain how a human brain behaves? The second half of the twentieth century saw the outgrowth of chemistry into biology with tremendous success. We now know details about the structures of the complex molecules at the core of life, and how those structures affect many attributes of living things. We have been able to custom-make molecules to fight disease, and even change the hereditary molecules (DNA) in living organisms to alter the characteristics of those living organisms. The twenty-first century has brought new challenges and new directions. On one frontier, scientists are using the ideas in chemistry to try to explain even more complex phenomena, such as human consciousness, for example. On another frontier, scientists are using chemistry to build ever smaller structures and machines, one atom at a time. Someday we may have molecular submarines, capable of navigating the bloodstream to fight invading cancer cells or viruses. On yet another frontier, scientists have created new materials such as graphene, a two-dimensional substance only one atom thick and stronger than steel. It seems that, at least for the foreseeable future, the power of the particulate model of matter to explain behaviour and produce new technology will continue.

A tour of this book

In this book, we present the 50 most important ideas in chemistry. Each entry is broken up into several parts: the **30-second chemistry** is the body of the explanation; the **3-second nucleus** is the idea expressed in a single sentence; the **3-minute valence** describes how the idea fits within a wider context, or can be applied to different circumstances. The book starts with **atoms**, their structures and their properties. It then goes on to show how atoms bond together to form **compounds**, and how we can understand bonding and the resulting **molecules**. From there we move on to the **states of matter** (gases, liquids and solids) and then on to **chemical reactions**. We then examine the **energetics** and describe the laws that govern the flow of energy. Finally, we survey four subfields of chemistry: **inorganic chemistry**, **organic chemistry**, **biochemistry** and **nuclear chemistry**. Our goal throughout is not to provide exhaustive or detailed accounts of chemistry, but rather to give you a flavour of the field – to show that behind all that happens around you and inside you, particles are doing a complex and beautiful dance that makes it all possible.

CHAPTER HEADER

The position of electrons within an atom is central to understanding how atoms bond together.



ATOMS, MOLECULES & COMPOUNDS

ATOMS, MOLECULES & COMPOUNDS
GLOSSARY

alkali metals The column of metals (group IA) on the far left of the periodic table that includes lithium, sodium, potassium, rubidium, cesium and francium.

atomic number The unique number assigned to each element that corresponds to the number of protons in the element's nucleus.

atomic theory The idea that all matter is composed of tiny particles called atoms.

classical physics Physics before the advent of quantum mechanics.

covalent bonding The joining of atoms by the sharing of one or more electrons.

electron A subatomic particle with a negative charge and a mass of 0.00055 amu (atomic mass unit).

element A fundamental substance that cannot be divided into simpler substances. There are 91 naturally occurring elements.

Heisenberg's Uncertainty Principle The quantum mechanical principle that certain quantities, such as position and momentum, cannot be simultaneously specified to arbitrary accuracy.

ionic bonding The joining of two atoms by the transfer of an electron from one to the other.

ionic compound A compound, usually composed of a metal and one or more non-metals, that contains atoms joined by ionic bonds.

isotope An atom that has the same number of protons as another atom, but a different number of neutrons.

mass number The sum of the number of protons and neutrons of an atom.

molecular compound A compound, usually composed of two or more non-metals, that contains atoms joined by covalent bonds.

neutron A subatomic particle with no charge and a mass of 1 amu.

noble gases The column of gases (group 8A) on the far right of the periodic table that includes helium, neon, argon, krypton, xenon and radon.

nuclear fusion The joining of two lighter nuclei to form a heavier one.

nuclear model A model for the atom in which most of the mass of the atom is contained in a small dense nucleus composed of protons and neutrons. Most of the volume of the atom is occupied by the electron cloud.

nucleosynthesis The process by which elements form within stars.

proton A subatomic particle with a positive charge and a mass of 1 amu.

quantum mechanics The realm of physics, developed in the early twentieth century, that deals with the very smallest particles that exist.

Schrödinger's Cat thought experiment A thought experiment involving the application of the uncertainty principle to a cat in a box with a radioactive substance that has a 50 per cent chance of decaying. If the atom decays, then the cat dies, so the cat is in a strange state of being both dead and undead, with a 50 per cent probability of each. Schrödinger used this experiment to show that quantum mechanical ideas are not applicable to large scale objects (such as cats).

valence electrons The highest energy electrons (and therefore the most important in bonding) in an atom.

velocity A measure of how fast (and in what direction) an object is moving.

MATTER IS MADE OF PARTICLES

the 30-second chemistry

The Ancient Greek philosophers believed that matter was infinitely divisible – that matter had no fundamental particles. Subsequent thinkers followed suit for more than 2,000 years. It was not until the eighteenth and nineteenth centuries that early chemists used careful measurements – primarily the relative weights of related samples of matter – to determine otherwise. And it wasn't until the early twentieth century that the question was definitely settled: the 1926 Nobel Prize for Physics was awarded to Jean Perrin for settling the matter. The Greeks were wrong – matter is particulate (it is made up of particles), and those particles are called atoms. And that turns out to be among the most important ideas in all of human thought. Why? Because the idea that matter is made of particles has enabled us to understand nature from the bottom up. What we found was remarkable: as far as we can tell, the particles that compose matter – their composition and structure – determine the properties of matter. Matter does what the particles that compose it do. Water boils at 100°C (212°F) because the three atoms that compose a water molecule bond together in a certain order, at a certain angle and at certain distances. Change any of these characteristics and water would be a different substance.

3-SECOND NUCLEUS

Matter is composed of particles. The nature of the particles – especially their structure – determines the properties of matter.

3-MINUTE VALENCE

Humans have wondered about the fundamental composition of matter for 2,500 years. The basic question is this: if you divide a sample of matter into smaller and smaller pieces, could you go on forever or would you eventually get to fundamental particles that are no longer divisible? For most of civilization, humans got the answer to this question wrong.

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3-SECOND BIOGRAPHIES

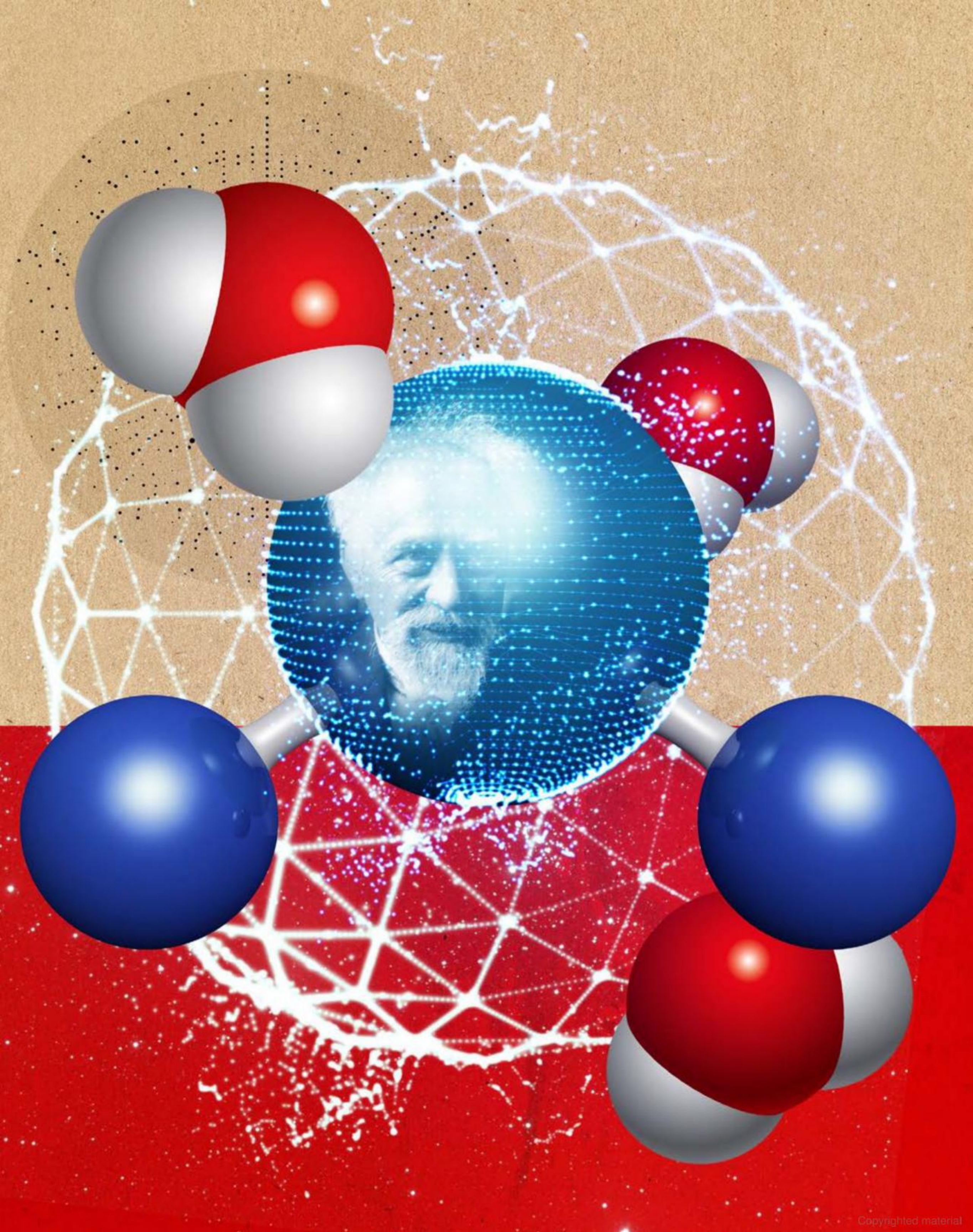
JOHN DALTON
1766–1844
English chemist who articulated the atomic theory of matter

JEAN PERRIN
1870–1942
French physicist who studied the motion of tiny particles suspended in liquid to experimentally settle the question of the particulate nature of matter

30-SECOND TEXT

Nivaldo Tro

Jean Perrin won the Nobel Prize essentially for proving the existence of atoms.



THE STRUCTURE OF THE ATOM

the 30-second chemistry

3-SECOND NUCLEUS

An atom consists of a tiny nucleus – containing protons and neutrons – with electrons in a diffuse cloud surrounding the nucleus.

3-MINUTE VALENCE

Matter is particulate – it is made of particles. But what are those particles like? What is their structure? The earliest models implied that the distribution of matter within an atom was fairly uniform, but later experiments suggested otherwise. The atom itself is mostly empty space with nearly all of the mass contained in a small space called the nucleus.

In 1897, J. J. Thomson discovered a new type of particle – the electron – that was much smaller than the atom itself. Thomson demonstrated that electrons were negatively charged, that they were present in all different kinds of matter and that their mass was 1/2,000th the mass of the lightest atom. Thomson's discovery implied that the atom itself was composed of even smaller particles. Based on his discovery, Thomson developed a model for the atom called the 'plum-pudding model'. In this model, even the lightest atoms were composed of thousands of electrons held in a sphere of positive charge. In 1909, Ernest Rutherford (pictured) set out to confirm Thomson's model, but he proved it wrong instead. Rutherford accelerated particles (8,000 times more massive than electrons) at a thin sheet of gold atoms. Most of these particles were not deflected by the gold atoms, but a few bounced back. Rutherford claimed that his results were 'about as credible as if you fired a 15-inch [38-cm] shell at a piece of tissue paper and it came back and hit you.' Rutherford developed a new model for the atom – the nuclear model – in which the mass of the atom is concentrated in a small space called the nucleus. Most of the volume of the atom is empty space.

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3-SECOND BIOGRAPHIES

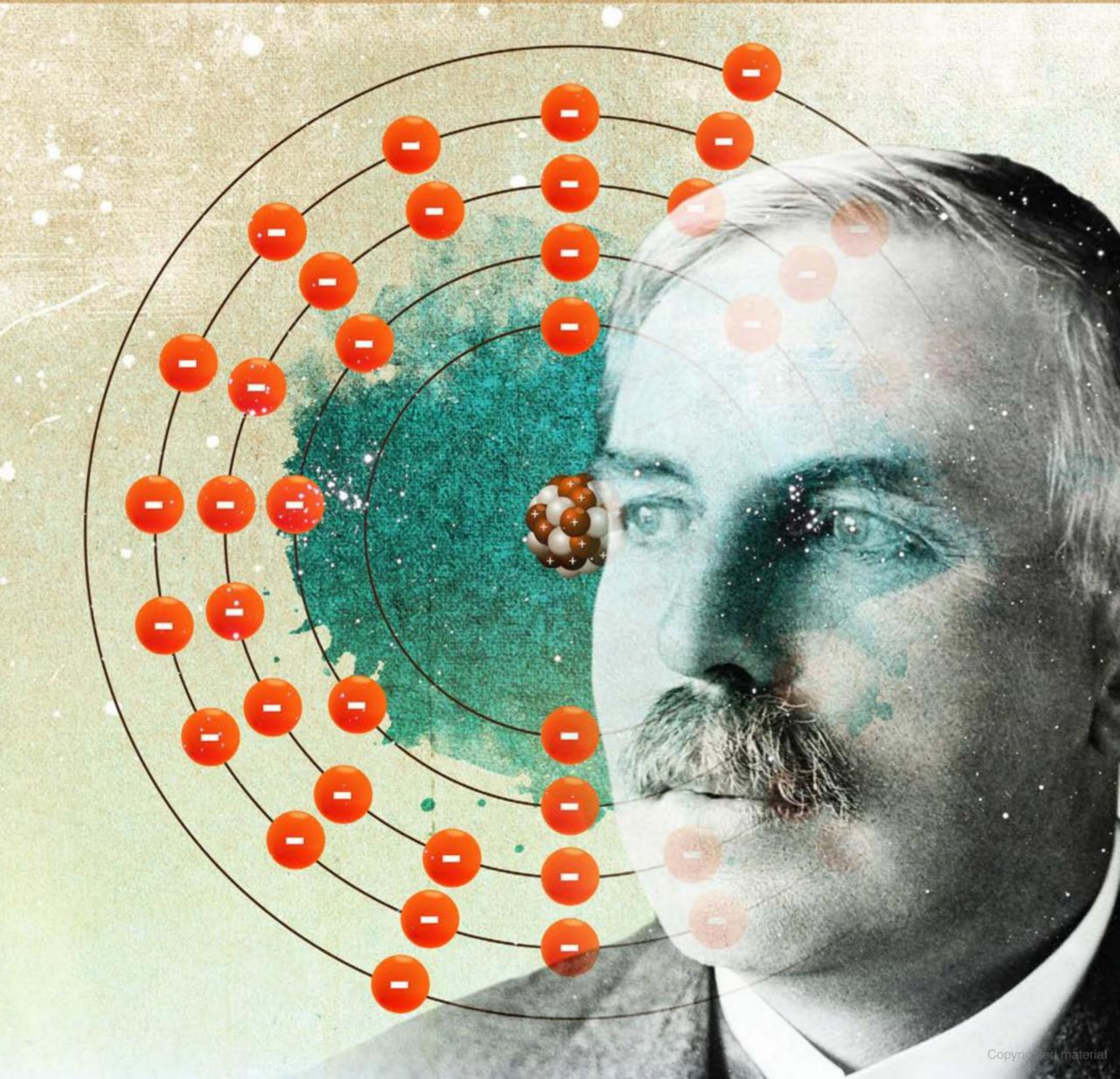
J. J. THOMSON
1856–1940
English physicist who discovered the electron

ERNEST RUTHERFORD
1871–1937
New Zealand physicist whose famous Gold Foil Experiment established the nuclear model for the atom

30-SECOND TEXT

Nivaldo Tro

The nuclear atom, with the nucleus enlarged to be visible. If drawn to scale, the nucleus would be a tiny dot, too small to see.



INSIDE THE ATOM

the 30-second chemistry

The number of protons in the nucleus of an atom is called the atomic number (Z) and it determines the identity of the atom and its corresponding element. For example, helium (Z=2) has two protons in its nucleus and sodium (Z=11) has eleven protons in its nucleus. The number of known elements ranges from Z=1 to Z=118 – as shown in the periodic table on the facing page. Each element has a name, a symbol and a unique atomic number. The number of neutrons in the nucleus of an atom can vary within atoms of the same element. For example, most helium atoms have two neutrons, but some have three. Atoms with the same number of protons but a different number of neutrons are called isotopes. Since most of the mass of an atom is due to its protons and neutrons, the sum of the numbers of these two particles is called the mass number (A). Scientists specify isotopes with the following notation: $^{A}_{Z}X$, where X is the chemical symbol, Z is the atomic number and A is the mass number. For example, the helium isotope with 2 neutrons is specified by $^{4}_{2}He$.

Subatomic Particles

	Mass (amu)	Charge (relative)
Proton	1.0	+1
Neutron	1.0	0
Electron	0.00055	-1

3-SECOND NUCLEUS

An atom is composed of protons, neutrons and electrons. The number of electrons in a neutral atom always equals the number of protons in its nucleus.

3-MINUTE VALENCE

All atoms are composed of the same three subatomic particles: protons, neutrons and electrons (see table below). So what makes one atom different from another? The numbers of those particles. Incredible as it may seem, both sodium (a reactive metal that explodes in water) and helium (an inert gas that reacts with nothing) are made of the same subatomic particles, just different numbers of them.

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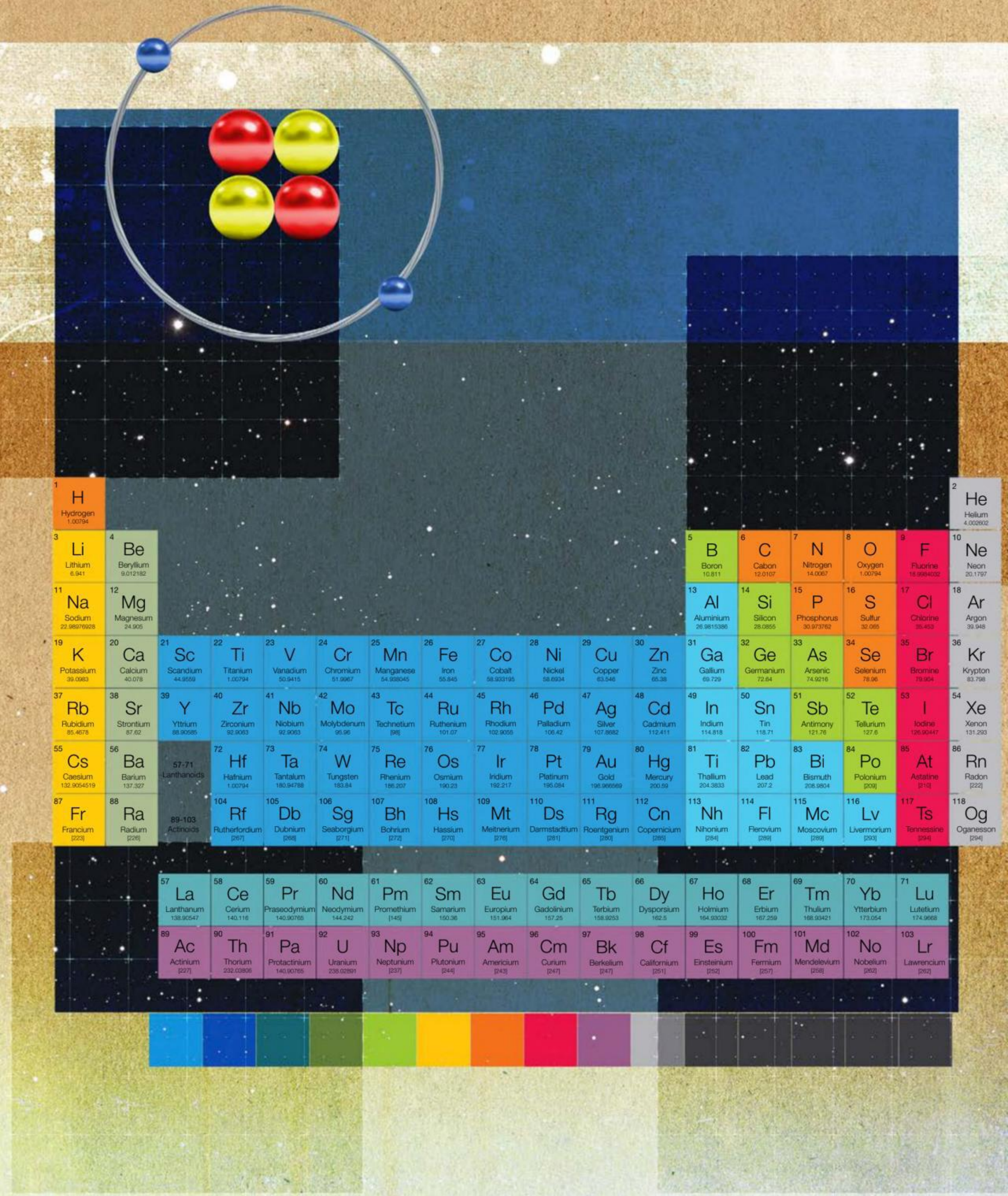
3-SECOND BIOGRAPHY

JAMES CHADWICK
1891–1974
English physicist who discovered the neutron

30-SECOND TEXT

Nivaldo Tro

The periodic table lists the 118 known elements (91 naturally occurring and 27 synthetic) according to their atomic number (top left in each element box).



1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Cabon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 1.00794	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.98976928	12 Mg Magnesum 24.905											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.9559	22 Ti Titanium 1.00794	23 V Vanadium 50.9415	24 Cr Chromium 51.9967	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.729	32 Ge Germanium 72.64	33 As Arsenic 74.9216	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 92.9063	41 Nb Niobium 92.9063	42 Mo Molybdenum 95.96	43 Tc Technetium [98]	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.293
55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57-71 Lanthanoids	72 Hf Hafnium 1.00794	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Ti Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.9804	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon [222]
87 Fr Francium [223]	88 Ra Radium [226]	89-103 Actinoids	104 Rf Rutherfordium [267]	105 Db Dubnium [268]	106 Sg Seaborgium [271]	107 Bh Bohrium [272]	108 Hs Hassium [270]	109 Mt Meitnerium [276]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [284]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]
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		89 Ac Actinium [227]	90 Th Thorium 232.03806	91 Pa Protactinium 140.90765	92 U Uranium 238.02891	93 Np Neptunium [237]	94 Pu Plutonium [244]	95 Am Americium [243]	96 Cm Curium [247]	97 Bk Berkelium [247]	98 Cf Californium [251]	99 Es Einsteinium [252]	100 Fm Fermium [257]	101 Md Mendelevium [258]	102 No Nobelium [262]	103 Lr Lawrencium [262]	

WHERE DID ATOMS COME FROM?

the 30-second chemistry

According to the big bang model, our universe began as a hot, dense collection of matter and energy that rapidly expanded and cooled. During the first 20 minutes of that expansion, hydrogen and helium (the two most abundant elements in the universe) formed from the soup of subatomic particles. Then nucleosynthesis stopped as the universe continued to expand and cool. Eventually, after about 500 million years, the first stars formed. Stars are the nurseries in which all other elements are made. As stars burn – through a process called nuclear fusion – they fuse together the nuclei of smaller atoms to form larger atoms. Young stars fuse hydrogen atoms to form helium. This fusion gives off tremendous amounts of heat and light and can power a star for billions of years. As a star ages, and if it is large enough, fusion can continue to form larger atoms such as carbon and oxygen – all the way up to iron. The formation of elements beyond iron requires the input of energy, and only happens in the supernova stage of a star's life. A supernova is essentially a large exploding star. The energy emitted by a supernova can power the nucleosynthesis of elements up to uranium, the heaviest naturally occurring element.

3-SECOND NUCLEUS

Atoms form through nucleosynthesis, which began in the first few minutes after the big bang and happens to this day within the core of stars and supernovae.

3-MINUTE VALENCE

Our planet naturally contains about 91 different elements. Where did the atoms that compose these elements come from? How did atoms form? They formed through a process called nucleosynthesis, which began about 13.7 billion years ago at the very birth of our universe.

RELATED TOPICS

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3-SECOND BIOGRAPHIES

ARTHUR EDDINGTON
1882–1944
English astronomer and physicist who first suggested that stars are powered by fusion

FRED HOYLE
1915–2001
English astronomer who formulated the theory of nucleosynthesis within stars

30-SECOND TEXT

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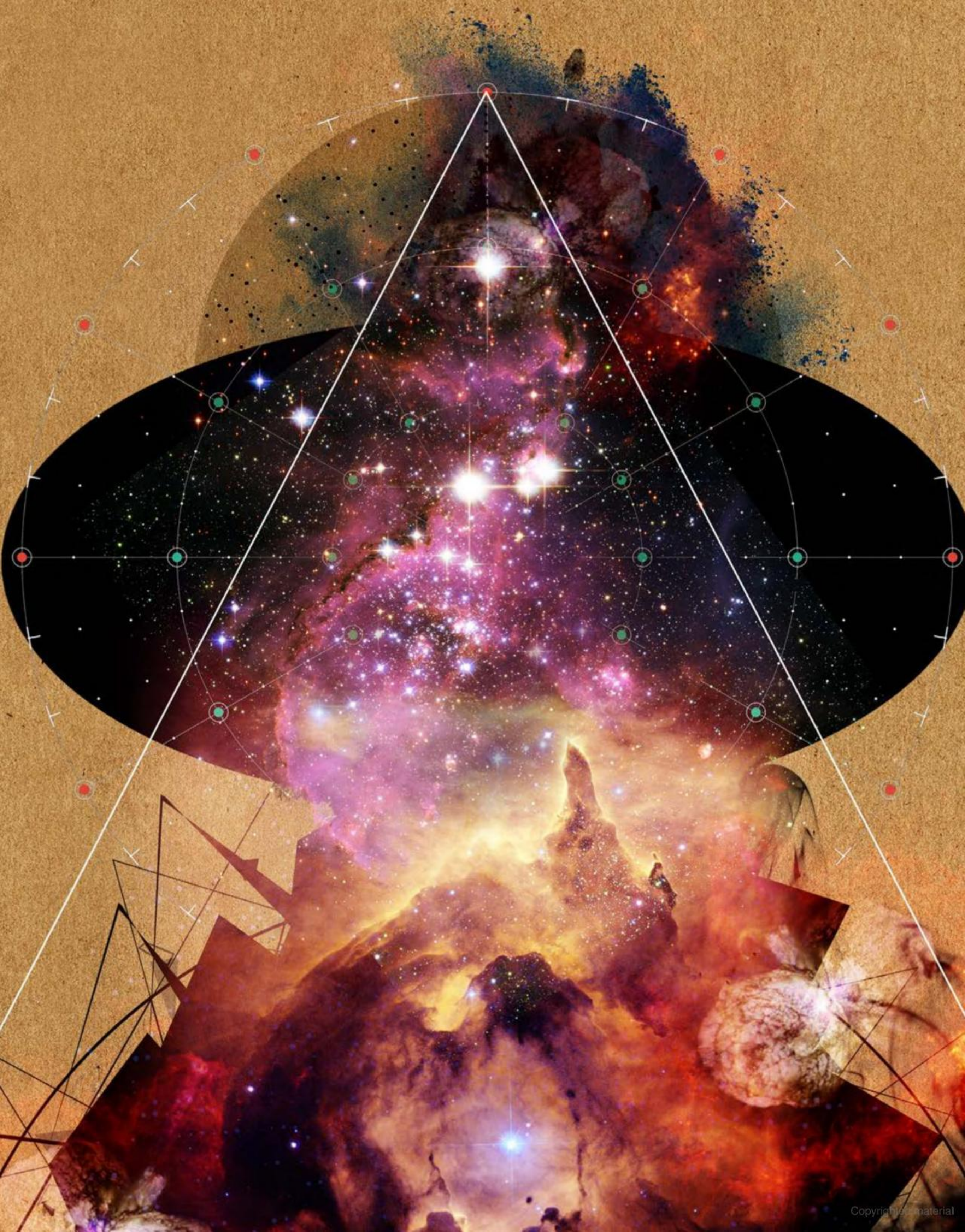
In stars, smaller atoms fuse together to form larger atoms. All atoms beyond helium were born in the core of stars and supernovae.



THE DUAL NATURE OF THE ELECTRON

the 30-second chemistry

An electron travelling through space behaves very differently from a baseball flying towards the outfield. A baseball has a definite trajectory – a deterministic path that it follows. A good outfielder can predict where a baseball will land. This prediction requires the outfielder simultaneously to know two properties of the flying baseball: its position (where it is) and its velocity (how fast it is going). If the outfielder only knew one of these two properties, he or she could not predict the baseball's path. An electron behaves differently because it has a dual nature: a wave nature (associated with its velocity) and a particle nature (associated with its position). The key to understanding electron behaviour is Heisenberg's Uncertainty Principle, which states that 'an electron never exists as both a wave and a particle simultaneously'. It is either one or the other, but not both. Although Heisenberg's principle solved a great paradox (how something can be both a wave and a particle), it implied the death of determinism. If you can't observe the wave nature and particle nature of the electron simultaneously, then you can't simultaneously know its velocity and its position, which means you can't predict its future path.

3-SECOND NUCLEUS
For electrons and other small particles, the trajectories of classical physics are replaced with the probability distributions of quantum mechanics.

3-MINUTE VALENCE
Are the smallest particles that exist, such as electrons, just like those that we can see with our eyes only smaller? Does an electron orbiting an atom behave like a planet orbiting the Sun? No. Electrons behave differently. Electrons, and other small particles, have a wave-particle duality that makes it impossible to predict exact trajectories for them. Instead, we describe their behaviour in terms of probability.

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3-SECOND BIOGRAPHIES
ERWIN SCHRÖDINGER
1887–1961
Austrian physicist central to the development of quantum mechanics and known for the thought experiment 'Schrödinger's Cat'

WERNER HEISENBERG
1901–76
German physicist who articulated the 'Uncertainty Principle'

30-SECOND TEXT
Nivaldo Tro

In an atom, electrons do not orbit the nucleus like planets orbit the Sun. Instead, they exist in clouds of probability.