The periodic table

The heart of the matter

One of science’s greatest creations is 150 years old this week. How it was created

is a perfect illustration of the process of scientific progress

科学界最伟大的作品之一是本周150岁。 它是如何创建的

是科学进步过程的完美例证

“La république n’a pas besoin de savants ni de chimistes.” With that curt dismissal a court in revolutionary France cut short the life of Antoine-Laurent de Lavoisier,argued by some to be the greatest chemist of all. Lavoisier’s sin was tax farming. He had been a member of the firm that collected the monarchy’s various imposts and then, having taken its cut, passed what remained on to the royal treasury. That he and many of his fellow farmers met their ends beneath a guillotine’s blade is no surprise. What had distinguished Lavoisier from his fellows, though, was what he chose to spend his income on. For much of it went to create the best-equipped chemistry laboratory in Europe.

共和国不需要科学家或化学家 由于这种简短的解雇，革命法国的一个法院缩短了Antoine-Laurent de Lavoisier的生命，一些人认为这是最伟大的化学家。 拉瓦锡的罪是税收农业。 他曾是该公司的成员，收集了君主制的各种财产，然后，在削减之后，将剩下的东西传给皇家财政部。 他和他的许多农民在断头台的刀刃下遇见了他们的目的并不奇怪。 然而，拉瓦锡和他的同伴之间的区别在于他选择花费他的收入。 其中大部分用于在欧洲建立装备最好的化学实验室。

Nothing comes of nothing. Where the story of the periodic table of the elements really starts is debatable. But Lavoisier’s laboratory is as good a place as any to begin,for it was Lavoisier who published the first putatively comprehensive list of chemical elements—substances incapable of being broken down by chemical reactions into other substances—and it was Lavoisier and his wife Marie-Anne who pioneered the technique of measuring quantitatively what went into and came out of a chemical reaction, as a way of getting to the heart of what such a reaction really is.Lavoisier’s list of elements, published in 1789, five years before his execution, had 33 entries. Of those, 23—a fifth of the total now recognised—have stood the test of time. Some, like gold, iron and sulphur,had been known since ancient days. Others, like manganese, molybdenum and tungsten, were recent discoveries. What the list did not have was a structure. It was,avant la lettre, a stamp collection. But the album was missing.

什么都没有。元素周期表的故事真正开始的地方是值得商榷的。拉瓦锡的宗旨实验室是一个很好的地方一样开始，因为它是拉瓦锡是谁发表的化学元素的物质第一推定的综合列表无法由白色化学反应到其他细分的物质，而且它是拉瓦锡和他的妻子玛丽 - 安妮开创了定量测量化学反应中产生和产生化学反应的技术，作为一种了解反应真正的核心的方法。有33个条目。其中，现在可识别的总数的23％ - 经受住了时间的考验。有些像金，铁和硫磺，自古以来就已为人所知。最近的发现是锰，钼和钨等其他产品。列表没有结构。在信件之前，它是一个集邮票。但这张专辑不见了。

Creating that album, filling it and understanding why it is the way it is took a century and a half. It is now, though, a familiar feature of every high-school science laboratory. Its rows and columns of rectangles, each containing a one- or two-letter abbreviation of the name of an element, together with its sequential atomic number,represent an order and underlying structure to the universe that would have astonshed Lavoisier. It is little exaggeration to say that almost everything in modern science is connected, usually at only one or two removes, to the periodic table.

创建该专辑，填写并了解它是一个半世纪的方式。 然而，现在它是每个高中科学实验室的熟悉特征。 它的行和列的矩形，每个包含一个或两个字母本文描述了元素的本质，它与序列的原子序数一起表示一个顺序和惊讶的拉瓦锡。 可以毫不夸张地说，现代科学中的所有东西都与周期表有关，通常是一两个被删除。

The Lavoisiers’ careful measurements had discovered something now thought commonplace—the law of conservation of matter. Chemistry transforms the nature of substances, but not their total mass. That fact established, another Frenchman,Louis-Joseph Proust, extended the idea with the law of definite proportions. Thislaw, published in 1794, the year of Antoine Lavoisier’s execution, states that the ratio by weight of the elements in a chemical compound is always the same. It does not depend on that compound’s method of preparation.

From there, it might have been a short step for Proust to arrive at the idea of compounds being made of particles of different weights, each weight representing a specific element. But he did not take it. That insight had to wait for John Dalton, a man who was the polar opposite of the aristocratic bon vivant Lavoisier.Dalton’s parents were so poor that he had been put to work at the age of ten. The man himself was an ascetic, colour-blind Quaker. And he was English.Dalton lived in Manchester, at a time when it was the world’s largest industrial city. He made a modest living tutoring, but spent most of his energy on scientific research, including into colour-blindness, a condition still sometimes referred to as Daltonism. That inquiry came to nothing.

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元素的名称的缩写，与信息通信技术连续原子序数一起，代表一年秩序和底层结构的宇宙，将有阿斯顿，法律，出版于1794年，安托万·拉瓦锡的执行年，重量的规定阙拉比化合物中的元素总是相同的。它不依赖于该化合物的制备方法。从那里开始，它可能是世界未来的一小步。但他没有接受它。有识之士不得不等待约翰道尔顿人，谁是贵族享乐主义Lavoisier.Dalton的父母很穷，他-能在十岁工作的对立面。这个男人本身就是一个苦行僧，色盲的贵格会。他是英国人。达尔顿住在曼彻斯特，那时它是世界上最大的工业城市。他做了一个适度的生活辅导，但他在科学研究方面的大部分精力，包括色盲，一直被称为道尔顿主义。这个调查一事无成。

But during the first decade of the 19th century he took Proust’s concept and showed not only that elements reacted in fixed proportions by weight, but also that those proportions were ratios of small whole numbers. The simplest way to explain this and indeed the way that Dalton lit upon—was to suppose each element to be composed of tiny, indivisible particles, all of the same weight. The Greek word for indivisible is “atomos”. Thus was the atom born.

但是在19世纪的第一个十年里，他采用普鲁斯特的概念，不仅表明元素按重量按固定比例反应，而且表明这些比例是小整数的比例。 解释这个问题的最简单方法，以及Dalton点燃的方式 - 假设每个元素都由微小的，不可分割的粒子组成，所有粒子都具有相同的重量。 不可分割的希腊词是“atomos”。 因此原子诞生了。

Dalton based his system of relative

atomic weights on hydrogen, the atoms of

which he found to be the lightest. And it

was quickly picked up by someone who,

though less famous than Lavoisier, per-

haps because of his grizzly end, was argu-

ably the greater man. Jacob Berzelius, a

Swede, furnished chemistry with its lan-

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The mighty atom

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Louis-Joseph Proust, extended the idea

with the law of definite proportions. This

guage. It was he who came up with the idea

of the abbreviations that now occupy the

periodic table’s rectangles. It was he who

combined those abbreviations with num-

bers, indicating the proportions involved,

to make formulae for chemical com-

pounds: H 2 O (water), H 2 SO 4 (sulphuric

acid), NaCl (table salt). And it was he who

used these formulae to describe reactions:

H 2 SO 4 + Zn ZnSO 4 + H 2 (sulphuric acid

plus zinc becomes zinc sulphate plus hy-

drogen). Though Dalton invented atomic

theory, it was Berzelius who embedded it at

the heart of the subject.

And Berzelius did more. He used Ales-

sandro Volta’s recently invented battery,

which created electricity from a chemical

reaction, to do the reverse. He employed

electricity to drive chemical reactions in

solutions (for example, releasing metallic

copper from a solution of copper sulphate),

a process called electrolysis.

Back in England, Humphry Davy, inven-

tor of the miner’s safety lamp, picked up

the idea of electrolysis and supercharged

it. He employed a more powerful version of

Volta’s battery to decompose molten mate-

rials, rather than solutions. In this way he

discovered sodium and potassium in 1807

and magnesium, calcium, strontium, bari-

um and boron in 1808. He also showed that

chlorine, previously thought to be a com-

pound of oxygen, was actually an element.

After Davy’s work new elements began

to flow in thick and fast. Iodine (1811). Cad-

mium and selenium (1817). Lithium (1821).

Silicon (1823). Aluminium and bromine

(1825). By then there were enough of them

for the next step on the journey to be taken.

It had been apparent from the time of

their discovery that sodium and potassium

were similar, as were calcium, strontium

and barium. Lithium, when discovered,

proved similar to sodium and potassium.

Likewise, bromine and iodine proved simi-

lar to chlorine. In 1829 Johann Dobereiner, a

German, noticed a curiosity about these

trios (members of groups now known, re-

spectively, as alkali metals, alkaline earths

and halogens), and also another triplet that

shared similar properties: sulphur, seleni-

um and tellurium. In each case, if the mem-

bers were arranged in order of atomic

weight, the middle element (sodium,

strontium, bromine, selenium) had a

weight that was the average of the lightest

and the heaviest of the three. Dobereiner

called this the law of triads. It was the first

hint of some underlying pattern.

The stamp collection continued to

grow. Thorium was discovered in 1829 (by

Berzelius, as it happened). Lanthanum fol-

lowed in 1838, erbium in 1843 and rutheni-

um in 1844. Then, in 1860, Robert Bunsen,

inventor of the burner that bears his name,

showed how new elements could be recog-

nised from brightly coloured lines in the

spectra obtained when materials contain-

ing them were heated in a flame. This ap-

proach was an instant success. Bunsen and

his colleague Gustav Kirchhoff added cae-

sium (1860) and rubidium (1861) to the list.

Others, copying them, added thallium

(1861) and indium (1863). Spectroscopic

analysis’s greatest triumph, though, was

helium (1868). This was recognised not

from a sample in the flame of a Bunsen

burner but in the spectrum of the sun.

As more and more elements turned up,

so the search for order intensified. In 1864

John Newlands, a Briton, almost got it. He

published what he called the law of oc-

taves. Arranging the known elements in or-

der of atomic weight, he believed he had

discerned that, like a musical scale, every

eighth element “rhymed” in the ways that

sodium rhymed with potassium, and chlo-

rine with bromine.

The trouble with Newlands’ scheme

was that an awful lot of the rhymes were

forced. A glance at a modern periodic table

shows why. For the tall, outer columns (and

discounting hydrogen, which is a law unto

itself) Newlands’ octaves work perfectly

for the lightest elements then known.

From the row beginning with potassium

(K, from the Latin kalium, meaning potash),

however, the tall outer columns are split

asunder by the intrusion of ten other, shor-

ter ones known as the transition metals. To

deal with that intrusion using data then

available required a mixture of luck and ge-

nius. And a few years after Newlands pub-

lished, a lucky genius wrestled with the

question in his study in St Petersburg.

Mendeleev

Albert Einstein, dapper in his youth, culti-

vated a waywardness of appearance in old

age that has contributed to the trope of the

mad professor. Dmitri Mendeleev (pic-

tured overleaf) looked like that from the

beginning—having his hair cut just once a

year by a shepherd, using wool shears. He

also behaved like a mad professor. He was

prone to dancing rages that put one biogra-

pher in mind of the protagonist of “Rum-

plestiltskin”, a children’s fairy tale. Also

like Rumplestiltskin he proved, metaphor-

ically at least, able to spin straw into gold.

For a time, Mendeleev had worked in

Germany with Bunsen and Kirchhoff, but

he had fallen out with them and returned

home. In 1869 he was professor of general

chemistry at the University of St Petersburg

and was writing a Russian-language text-

book on the subject. On February 14th of the

Julian calendar then in use in Russia (Feb-

ruary 26th by the Gregorian calendar em-

ployed in most of the rest of Europe), hav-

ing addressed halogens and alkali metals,

he was racking his brains for an organising

principle to act as a template for the rest.

The 14th was a Friday, and the problem ob-

sessed him more and more over the week-

end. But on Monday 17th, while waiting for

a sleigh to take him to the railway station

for a trip to an estate he had bought in the

countryside, he had a brainwave.

Mendeleev was an inveterate player of

patience. His brainwave was to recognise

that, just as games of patience require the

player to organise the pack as a grid of suits

in order of the value of the cards, so the ele-

ments might be arranged by their atomic

weights in “suits” that shared chemical and

physical properties. By making his own

pack, with each card representing one of

the 63 then-known elements, he was able

to embark on what was arguably the most

important game of patience ever played.

He claimed subsequently that the an-

swer had come to him in a dream. Perhaps.

But after having worked for four days on

the problem without much rest, the

boundary between sleep and wakefulness

must have been pretty blurred. Whatever

the details, the result was a grid of cards

that arranged the elements in a pattern (see

picture). He published it two weeks later.

His grid was not perfect. Indeed, it was

full of holes. But those holes (some of

them, anyway) turned out to be keystones.

Though there was no reason, in the 1860s,

to believe that all the elements had been

discovered, Newlands had behaved as

though they had been. Mendeleev had

enough confidence to leave gaps in order to

make the pattern work. At the time, some

took this as a sign of weakness. In fact, it

was a sign of strength—the more so be-

cause, for several of the gaps, he described

in detail the properties of the elements he

predicted would fill them, and these pre-

dictions were, by and large, fulfilled.

Similarly, there are places in Mendel-

eev’s original table where it works only by

cheating—that is, by swapping two adja-

cent elements between the places to which

their atomic weights assign them. Here,

Mendeleev argued that the accepted

weights were incorrect, and needed re-

measuring. Sometimes, he turned out to be

correct about this, too. But not always. A

few such pairs, cobalt and nickel for exam-

ple (which actually share a slot in the pub-

lished table), remained stubbornly out of

kilter, providing evidence that atomic

weight was really a proxy for some deeper

structural principle

Crucially, Mendeleev was not con-

strained, as Newlands had been, by precon-

ceptions about how things ought to be. At

points where the octave rule did not work,

he let the grid burst out of its corset. This

can be seen at both the top and the bottom

of the published table.

The upper-right-hand extension con-

tains the transition metals. Here, subse-

quent discoveries have proved Mendeleev

more or less correct in his insights. The

lower-left-hand one is more problematic.

Its contents are a grab bag, though it does

contain all of the then-known members of

the set of elements called lanthanides. Ar-

guably, Mendeleev was lucky that by 1869

only three lanthanides had been discov-

ered. In a modern table there are 15 and, to-

gether with the actinides below them, they

form an awkward interpolation that is of-

ten relegated to the bottom as an asterisked

footnote. Whether Mendeleev’s game of

chemical patience would have been helped

or hindered by having more lanthanides in

the pack is an intriguing question.

There was also an invisible gap, the fill-

ing of which was one of the table’s greatest

triumphs. Helium, which Mendeleev ig-

nored because its atomic weight could not

be established, turned out to be the lightest

member of a whole, new row (or column, in

a modern table). These are the noble gases,

undiscovered previously because they are

chemically inert. The others are neon, ar-

gon, krypton, xenon and radon.

Like Davy’s discoveries, the noble gases

came all of a tumble. All but radon were the

work of William Ramsay, a Briton. With va-

rious collaborators, Ramsay isolated argon

in 1894, helium in 1895 and neon, krypton

and xenon in 1898. Instead of chemistry, he

used physical processes. All except helium

were products of the newly developed

technology of cryogenics, which he used to

liquefy air and then separate it into its

components, according to their boiling

points. Helium, he found by heating a min-

eral called cleveite.

The transmutation of the elements

The 1890s also saw the first inklings that at-

oms themselves might not, despite the

meaning of their name, be truly indivis-

ible. The initial evidence that atoms could

spin off parts of themselves, and must

therefore have smaller components, came

in 1896. That was when Henri Becquerel,

who was investigating the nature of phos-

phorescence, wrapped some uranium salts

in photographic paper and found that the

paper got fogged. Thus did Becquerel dis-

cover radioactivity.

The following year, J.J. Thomson

worked out that “cathode rays” emitted

into a vacuum by a negative electrode were

electrically charged particles that weighed

far less than any atom. Then, in 1899, Ernest

Rutherford, a former student of Thom-

son’s, showed that Becquerel’s radiation

had two components, which he dubbed “al-

pha” (heavy, positively charged particles)

and “beta” (light, negatively charged ones).

Becquerel himself, in 1900, showed that

beta particles were the same as Thomson’s

cathode rays. Seven years later, Rutherford

demonstrated that alpha particles were he-

lium ions (thus incidentally explaining

why cleveite, which is an ore of uranium, is

also a source of helium). The stage was now

set for some of the most important experi-

ments in history: Rutherford’s attempts to

find out what atoms looked like.

One previous guess had been that they

were vortices in the luminiferous aether

through which light and radio waves were

thought to propagate. That hypothesis,

however, died with the aether itself, when

the latter’s existence was disproved experi-

mentally in the 1890s. Rutherford’s experi-

ments, conducted between 1908 and 1910,

probed matter by firing alpha particles at

gold foil. Most sailed through, to be record-

ed by a scintillation screen beyond the foil.

But a few were deflected from their

courses, to be recorded by other screens,

including one behind the source. This

screen’s recording of alpha particles re-

turning whence they had come was de-

scribed by Rutherford as being “almost as

incredible as if you fired a 15-inch shell at a

piece of tissue paper and it came back and

hit you”. His explanation, now abundantly

proved true, was that the atoms in the foil

had tiny, positively charged nuclei, which

were reflecting the positively charged al-

pha particles, and that these nuclei were

surrounded by electrons.

Regardless of an atom’s exact nature,

losing alpha and beta particles necessarily

changes it. Such radioactive decay proved a

source of yet more members of the periodic

table. Polonium and radium—decay pro-

ducts of uranium—were found in 1898 by

Pierre and Marie Curie. Actinium, the light-

est actinide, followed in 1899. Radon was

recognised in 1900. Protactinium in 1913.

Models of the atom also became more

sophisticated. In 1913, Rutherford and a

Danish colleague, Niels Bohr, suggested

electrons orbit the nucleus as planets orbit

the sun, with electrical attraction playing

the role of gravity. In the same year Henry

Moseley, another of Rutherford’s con-

frères, found a mathematical relationship

between an element’s x-ray spectrum

when bombarded with electrons and its

atomic number in the table. In pairs like

cobalt and nickel, where the table had been

fudged, Moseley confirmed the fudges to

be correct. He tidied up the lanthanides,

predicting missing elements as Mendeleev

had done. He also predicted two new tran-

sition metals, with atomic numbers 72 and

75, which duly turned up in 1923 (hafnium)

and 1925 (rhenium).

Moseley’s x-ray spectra demonstrated

that an element’s atomic number does not

depend directly on its atomic weight. Ruth-

erford soon showed that the atomic num-

ber is actually the number in a nucleus of a

positively charged particle that came to be

known as a proton. Even though protons

weigh almost 2,000 times as much as elec-

trons, the two have equal (though oppo-

site) charges. An atom, which has equal

numbers of both, is therefore electrically

neutral. Protons are not, though, heavy

enough to account for measured atomic

weights. That requires a second, electrical-

ly neutral particle, the neutron. This was

discovered in 1932. Neutrons are also the

reason that an element can have atoms of

different atomic weights, known as iso-

topes. These isotopes have different num-

bers of neutrons.

The Bohr-Rutherford model of the atom

had a problem, though. Electrostatic forces

should pull the electrons into the nucleus

rather than keeping them in orbit. Here,

the new science of quantum mechanics

came to the rescue. Quantum theory re-

quires objects to be both particles and

waves. The wavelike aspect of electrons

means that when they circle an atomic nu-

cleus they settle into self-reinforcing

three-dimensional standing waves, called

orbitals. The stability of these standing

waves stops the electrons being drawn into

the nucleus. And here, at last, is the expla-

nation for why the periodic table is the way

that it is.

Spdfg

For reasons deep in the heart of quantum

mechanics, each orbital can have either

one or two electrons in it, but not more.

The orbitals themselves come in different

types (see diagram) and these are arranged

in shells around a nucleus. The first shell

has one type “s” orbital, for a maximum of

two electrons. The second, a type s and

three type p, for a maximum of eight. The

third has one s, three p and five d, for a

maximum of 18. The fourth, one s, three p,

five d and seven f, for a maximum of 32. Et

cetera. The names are derived from the

spectral lines seen by Bunsen and his fol-

lowers. The colours of these lines represent

energy released as light by electrons mov-

ing between orbitals.

It is the shells that define the table’s

rows. In the first row, which consists of hy-

drogen (one electron) and helium (two),

the first shell is filled up. In the second row,

from lithium to neon, the second shell is

filled. The third row, from sodium to argon,

fills the s and p orbitals of the third shell.

The fourth, from potassium to krypton,

fills the s and p orbitals of the fourth shell

and the d of the third shell (which has ten

electrons altogether, for the ten columns of

transition metals).

Compounds are created either by un-

paired electrons from different atoms

forming joint orbitals called covalent

bonds, or by the complete transfer of un-

paired electrons between atoms, to create

paired orbitals in the recipients. When this

happens, the resulting positive and nega-

tive ions are held together by electrostatic

forces—a process called ionic bonding. The

repetitive order in which the shells are

filled in each row means that elements in

each column of the table have the same

combination of unpaired electrons, and

thus similar properties. For example, the

noble gases are inert because they have no

unpaired electrons. Further analysis

showed, moreover, that the difference be-

tween metals and non-metals depends on

how easy an atom’s outer electrons are to

detach (if easily detached, they can flow as

an electric current, reflect light in the way

that makes metals shiny, and confer ductil-

ity on the solid form of the element). And

that, essentially, is chemistry solved.

It is not quite, however, the end of the

story. In the 1930s physicists discovered

that radioactivity could, in essence, be re-

versed by bombarding atoms with sub-

atomic particles to increase their atomic

numbers. This way, new elements can be

produced. Technetium, created in 1937, was

the first such. Two years later francium, the

last to be discovered in nature, was isolated

as a decay product of actinium. From that

moment the extension of the periodic table

became work for physicists, not chemists.

Technetium is strange. Despite its low

atomic number (43) it has no stable iso-

topes, and is thus found only transiently in

nature. This is a quirk of the physics of pro-

tons and neutrons that it shares with pro-

methium (61). But at the heavy end of the ta-

ble, beyond lead (82), radioactivity is

compulsory for all. And beyond uranium

(92) it is so compulsory that “transuranics”

were once thought not to occur in nature.

This part of the periodic table was the

playground of Glenn Seaborg, an American

physicist. In 1940 Seaborg was part of a

group at the University of California,

Berkeley, that made neptunium (93). When

the group’s head left later that year, Seaborg

took over. On his watch americium (95), cu-

rium (96), berkelium (97), californium (98),

einsteinium (99), fermium (100), mendele-

vium (101) and nobelium (102) were all

created. But his first discovery, plutonium

(94, in 1941), was the most important. On

July 16th 1945, the first atom bomb, a pluto-

nium-implosion device, was tested at Ala-

mogordo, New Mexico. On August 9th of

that year another of the same design de-

stroyed Nagasaki, in Japan.

Americium has its uses, too. Since it

was a synthetic product, it was patentable,

and Seaborg did, indeed, patent it. It was

(and is) employed in smoke detectors, and

he drew a tidy income from that fact for

many years. Beyond 95, though, the practi-

cal point of extending the table became less

and less obvious as elements became less

and less stable.

Efforts to make new elements slowed

down after 1955, though there was a pick up

again in the mid 1990s. Neither chemistry

nor the wider world, however, reverberated

with excitement at the creation of darm-

stadtium (110), roentgenium (111), coperni-

cum (112) and nihonium (113) in the way that

they had with the discovery of potassium,

or helium, or radium or plutonium. What

started as stamp collecting has returned to

its roots—except in one regard. This is that,

thanks to Mendeleev’s brilliance, element-

hunters now have an album in which to

stick their discoveries.

The heaviest element of all, oganesson

(118), was created in 2002, though named

only in 2016. Oganesson completes the ta-

ble’s seventh row. Chemically, it should be

a noble gas. But, with only a few atoms of it

to play with at a time, and with those atoms

having lifetimes measured in millisec-

onds, it seems improbable anyone will ever

know for sure.

Despite physicists’ best efforts, then,

the eighth row has not been reached. But as

Mendeleev himself said, “To conceive, un-

derstand and grasp the whole symmetry of

the scientific edifice, including its unfin-

ished portions, is equivalent to tasting that

enjoyment only conveyed by the highest

forms of beauty and truth.” For those who

share this view, and see in the periodic ta-

ble a supreme example of nature’s poetry,

the row-completing, album-filling addi-

tion of oganesson may seem as good a place

as any to stop. 7