THE GREAT COURSES®

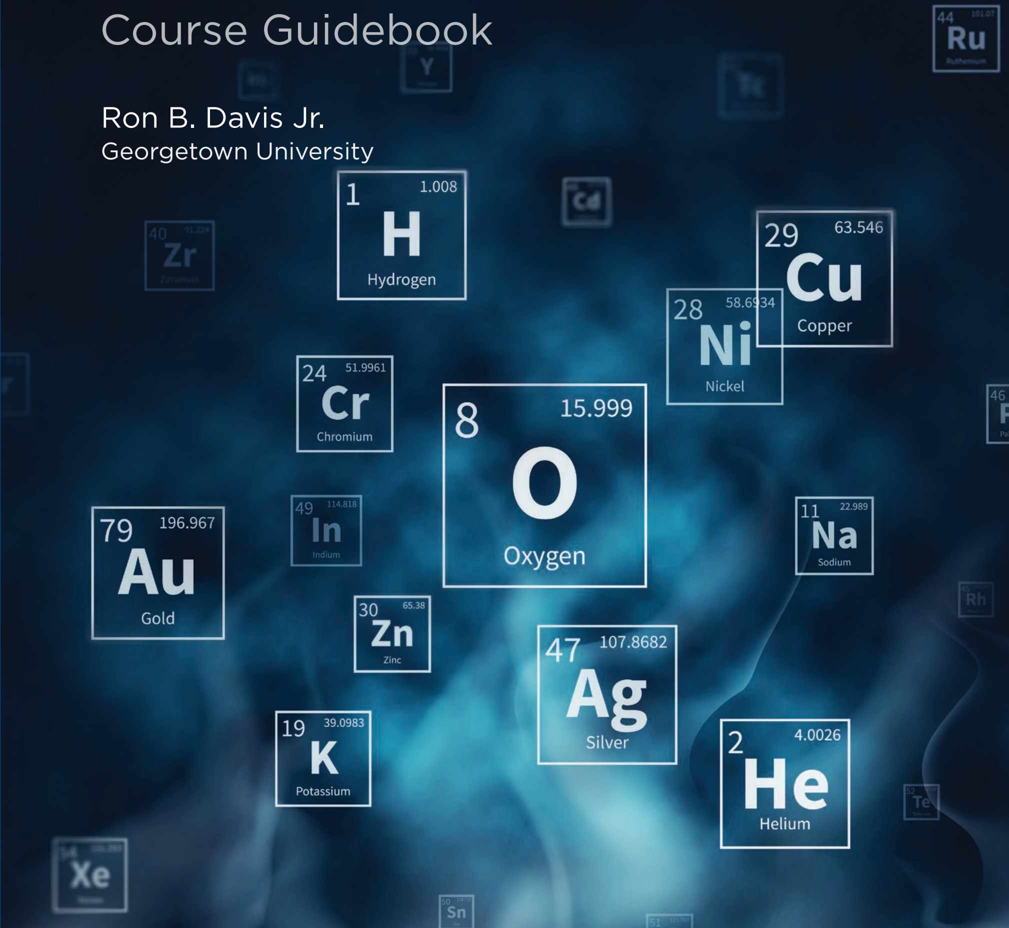
Topic
Science

Subtopic
Physics & Chemistry

Understanding the Periodic Table

Course Guidebook

Ron B. Davis Jr.
Georgetown University



THE GREAT COURSES®

LEADERSHIP

President & CEO	**PAUL SUIJK**
Chief Financial Officer	**BRUCE G. WILLIS**
Chief Marketing Officer	**CALE PRITCHETT**
SVP, Marketing	**JOSEPH PECKL**
VP, Customer Engagement	**KONSTANTINE GELFOND**
VP, Technology Services	**MARK LEONARD**
VP, Product Development	**JASON SMIGEL**
VP, General Counsel	**DEBRA STORMS**
VP, People	**AUDREY WILLIAMS**
Sr. Director, Creative & Production	**KEVIN BARNHILL**
Sr. Director, Content Development	**KEVIN MANZEL**
Director, Business Operations & Planning	**GAIL GLEESON**
Director, Editorial & Design Services	**FARHAD HOSSAIN**
Director, Content Research & Alternative Programming	**WILLIAM SCHMIDT**
Director, Creative	**OCTAVIA VANNALL**

PRODUCTION

Studio Operations Manager	**JIM M. ALLEN**
Video Production Director	**ROBERTO DE MORAES**
Technical Engineering Manager	**SAL RODRIGUEZ**
Quality Assurance Supervisor	**JAMIE MCCOMBER**
Sr. Post-Production Manager	**PETER DWYER**
Production Manager	**RIMA KHALEK**
Producer	**ALISHA REAY**
Content Developer	**JAY TATE**
Associate Producer	**ABBY INGHAM LULL**
Graphics Manager	**JAMES NIDEL**
Graphic Artists	**RON B. DAVIS JR.** **DANIEL RODRIGUEZ** **BRIAN SCHUMACHER**
Editing Manager	**OWEN YOUNG**
Sr. Editors	**STEVE BITTLE** **COURTNEY WESTPHAL**
Editor	**ANDREW VOLPE**
Assistant Editor	**CHARLES GRAHAM**
Audio Engineers	**GORDON HALL IV** **CHRIS HOOTH**
Camera Operators	**ERICA CORSO** **VALERIE WELCH**
Production Assistants	**RONNIE HASSAN** **LAKE MANNIKKO**

EDITORIAL & DESIGN

Sr. Managing Editor	**BLAKELY SWAIN**
Graphic Designer	**RHOCHELLE MUNSAYAC**
Sr. Editorial Associate	**JENNIFER ROSENBERG**
Editorial Assistant	**WILLIAM DOMANSKI**

RON B. DAVIS JR.

GEORGETOWN UNIVERSITY

Ron B. Davis Jr. is an Associate Teaching Professor of Chemistry at Georgetown University, where he has been teaching since 2008. He earned his PhD in Chemistry from The Pennsylvania State University, where his research focused on the fundamental forces governing the behavior of complex biomolecules, such as proteins. After several years as a pharmaceutical research and development chemist, he returned to academia to teach chemistry at the undergraduate level.

Ron's research has been published in such scholarly journals as *Proteins* and *Biochemistry* and has been presented at the Annual Symposium of The Protein Society. He also maintains an educational YouTube channel and provides interviews and content to various media outlets, including HISTORY and the Discovery Channel.

At Penn State, Ron was the recipient of a Dalalian Fellowship and the Dan Waugh Teaching Award. He is also a member of the Division of Chemical Education of the American Chemical Society.

🌐 › ChemSurvival.com

▶ › youtube.com/chemsurvival

› @Chem_Survival

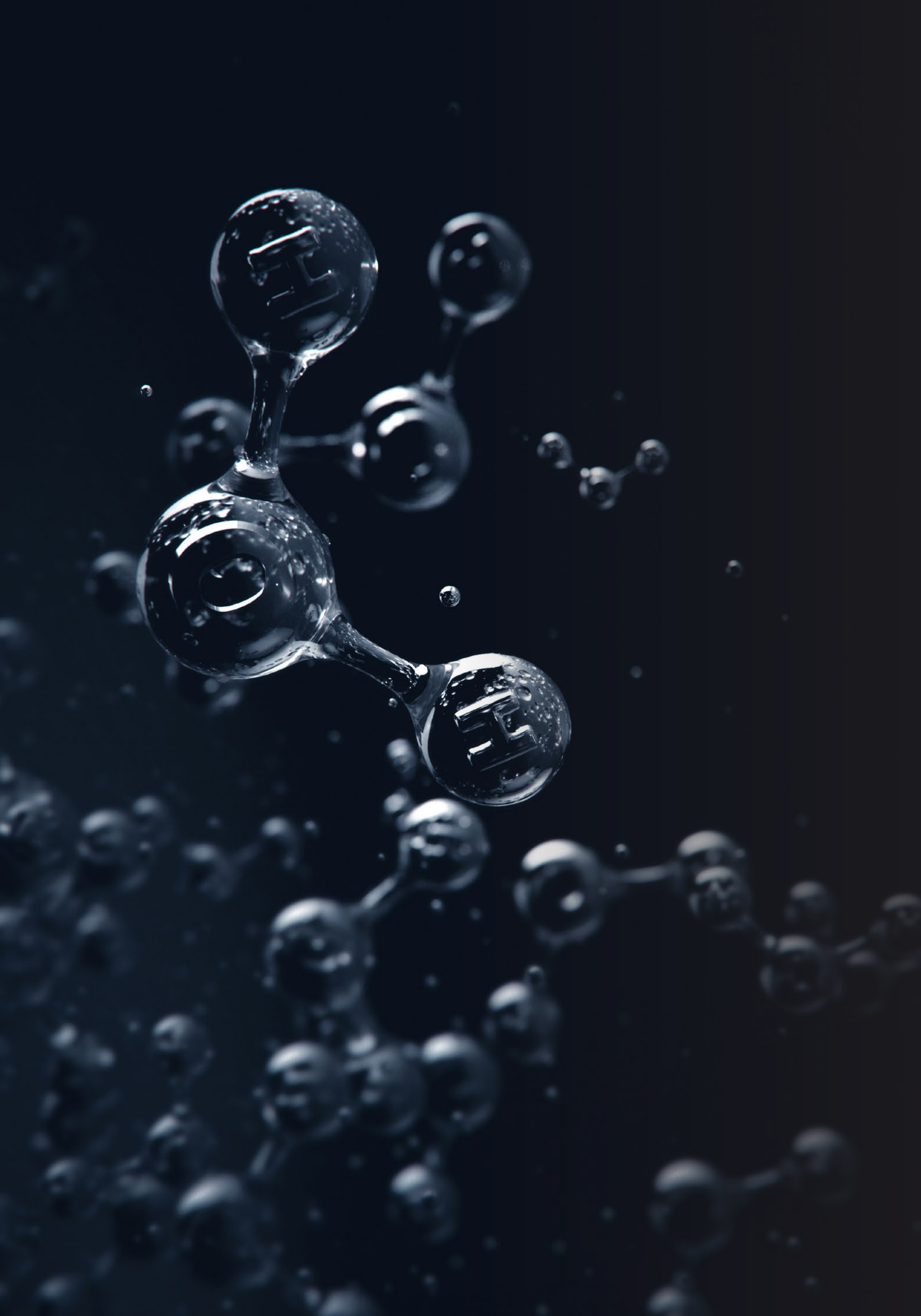
f › ChemSurvival Enterprises

TABLE OF CONTENTS

INTRODUCTION

ELEMENTS

SUPPLEMENTARY MATERIAL


H
O
H

UNDERSTANDING THE PERIODIC TABLE

In a broad sense, the periodic table of the elements is the product of more than 2,000 years of thought, investigation, and discourse. It serves both as an endlessly fascinating collection of names, symbols, and physical data and as a tool for making predictions about nature's most fundamental materials—the elements.

This course begins with an overview of the modern periodic table, discussing its remarkable tendency to bring elements with common properties into nearby locations on the table. You will be introduced to some of the most fundamental features of the table as you explore how elements have gotten their names and symbols and what their positions on the table say about their properties.

Next, you will be introduced to how the table has captured our understanding of exactly what an element is and how we have learned to organize elements in increasingly meaningful ways:

- from the first modern conception of elements in the 18th century;
- to the breakthrough work on arrangements of the elements in the 19th century, culminating with Dmitri Mendeleev's now-famous table and predictions of new elements;
- to the ways that the 20th-century table embodies our understanding of the distinct atomic structure that makes up each element.

You will come to understand how humankind's ongoing discovery of new elements and evolving understanding of atomic structure has required constant reevaluation of how the periodic table is arranged.

Then, you will discover how the periodic table helps explain the processes by which elements become distributed throughout the universe and the abundance and rarity of certain elements on the surface of Earth versus deep inside the planet (lecture 5). You'll also consider the ultimate fate of unstable atoms over geologic and even cosmologic timescales (lecture 6).

Next, the course will turn to the naturally occurring elements that make up our world, beginning with the simplest elements, hydrogen and helium (lecture 7), from the top row of the periodic table, the starting point for building up all other elements.

The table's unusual shape is based on four distinct blocks of elements that bring elements with similar atomic structure together. The course starts on the left side of the table, called the *s* block, which includes sodium and potassium (lecture 8) as well as magnesium and calcium (lecture 9)—elements that play key roles in nutrition, rock-forming minerals, and many modern technologies.

Then, the course addresses the right side of the table, known as the *p* block, which is home to the most diverse block of elements (lectures 10–16), ranging from metals to nonmetals. You will learn how the properties of inert noble gases (lecture 11), highly reactive halogens like chlorine (lecture 12), life-giving oxygen and nitrogen (lecture 13), and complex carbon-based molecules (lecture 14) can all be explained by features of their atomic structure that place them into this one block of the table. The course will investigate the unique diagonal of elements known as the metalloids (lecture 15), whose intermediate properties make them indispensable materials in many modern technologies. The course will also investigate so-called weak metals of the *p* block (lecture 16), such as tin and lead, paying special attention to how their proximity to metalloids and nonmetals on the table influences their properties.

Next, the course turns to the large expanse in the middle of the table, the *d* block, which is home to many familiar metallic elements (lectures 17–20). You will learn how variations in the atomic structure of elements within this block explain a host of useful properties, such as color, magnetism, hardness, melting points, corrosion resistance, and ability to catalyze chemical reactions.

The longest block of all is commonly depicted as a detached strip of elements beneath the main body of the table. The top row of this *f*-block region of the table contains most of the naturally occurring rare-earth elements (lecture 21), a group of metals whose usefulness in technological applications came to light only after the challenges of detecting and separating elements so similar to one another were overcome.

The course concludes with the now-completed bottom row of the table, where you'll find radioactive elements 87 through 118 (lectures 22–24), many of which were not discovered until the dawn of the nuclear age. You will learn how the race to create new superheavy elements using cutting-edge technology was guided by the periodic table itself and gave rise to an international competition known as the transfermium wars.

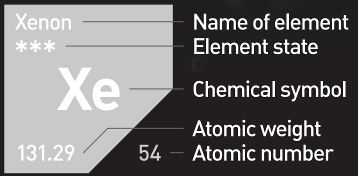
Atomic structure drives the organization of the periodic table, allowing the positions and relationships of the elements within the table to help us understand and predict the properties of each element. This is why the periodic table offers endless insights into all matter in our world—from nature to sophisticated technology.

ORGANIZATION OF THE COURSE

LECTURE #	SUBJECTS
1–6	overviews of atomic structure, development of the table, and patterns among the elements
7	the first row of the table: hydrogen and helium
8–9	left-side metals: sodium and magnesium groups, or vertical groups 1 and 2, aka the *s* block
10–16	right-side block of nonmetals, metalloids, and weak metals: groups 13–18 / the *p* block
17–20	middle block consisting of many familiar metallic elements: groups 3–12 / the *d* block
21	rare-earth metals: top row of the *f* block (often separate from the rest of the table)
22–24	most of the radioactive elements, including elements not found in nature: bottom row of the table, spanning *f*, *d*, and *p* blocks

PERIODIC TABLE OF ELEMENTS

Hydrogen *** H 1.008 1																	Helium *** He 4.003 2
Lithium * Li 6.941 3	Beryllium * Be 9.012 4											Boron * B 10.81 5	Carbon * C 12.01 6	Nitrogen *** N 14.01 7	Oxygen *** O 16.00 8	Fluorine *** F 19.00 9	Neon *** Ne 20.18 10
Sodium * Na 22.99 11	Magnesium * Mg 24.31 12											Aluminum * Al 26.98 13	Silicon * Si 28.09 14	Phosphorus * P 30.97 15	Sulfur * S 32.07 16	Chlorine *** Cl 35.45 17	Argon *** Ar 39.95 18
Potassium * K 39.10 19	Calcium * Ca 40.08 20	Scandium * Sc 44.96 21	Titanium * Ti 47.87 22	Vanadium * V 50.94 23	Chromium * Cr 52.00 24	Manganese * Mn 54.94 25	Iron * Fe 55.84 26	Cobalt * Co 58.93 27	Nickel * Ni 58.69 28	Copper * Cu 63.55 29	Zinc * Zn 65.39 30	Gallium * Ga 69.72 31	Germanium * Ge 72.63 32	Arsenic * As 74.92 33	Selenium * Se 78.96 34	Bromine ** Br 79.90 35	Krypton *** Kr 83.80 36
Rubidium * Rb 85.47 37	Strontium * Sr 87.62 38	Yttrium * Y 88.91 39	Zirconium * Zr 91.22 40	Niobium * Nb 92.91 41	Molybdenum * Mo 95.94 42	Technetium * Tc [98] 43	Ruthenium * Ru 101.07 44	Rhodium * Rh 102.91 45	Palladium * Pd 106.42 46	Silver * Ag 107.87 47	Cadmium * Cd 112.41 48	Indium * In 114.82 49	Tin * Sn 118.71 50	Antimony * Sb 121.76 51	Tellurium * Te 127.60 52	Iodine * I 126.90 53	Xenon *** Xe 131.29 54
Cesium * Cs 132.91 55	Barium * Ba 137.33 56	LANTHANIDES ⌄	Hafnium * Hf 178.49 72	Tantalum * Ta 180.95 73	Tungsten * W 183.84 74	Rhenium * Re 186.21 75	Osmium * Os 190.23 76	Iridium * Ir 192.22 77	Platinum * Pt 195.08 78	Gold * Au 196.97 79	Mercury ** Hg 200.59 80	Thallium * Tl 204.38 81	Lead * Pb 207.2 82	Bismuth * Bi 208.98 83	Polonium * Po [209] 84	Astatine * At [210] 85	Radon *** Rn [222] 86
Francium * Fr [223] 87	Radium * Ra [226] 88	ACTINIDES ⌄	Rutherfordium **** Rf [267] 104	Dubnium **** Db [268] 105	Seaborgium **** Sg [269] 106	Bohrium **** Bh [270] 107	Hassium **** Hs [269] 108	Meitnerium **** Mt [278] 109	Darmstadtium **** Ds [281] 110	Roentgenium **** Rg [281] 111	Copernicium **** Cn [285] 112	Nihonium **** Nh [286] 113	Flerovium **** Fl [289] 114	Moscovium **** Mc [289] 115	Livermorium **** Lv [293] 116	Tennessine **** Ts [294] 117	Oganesson **** Og [294] 118
		Lanthanum * La 138.91 57	Cerium * Ce 140.12 58	Praseodymium * Pr 140.91 59	Neodymium * Nd 144.24 60	Promethium * Pm [145] 61	Samarium * Sm 150.36 62	Europium * Eu 151.96 63	Gadolinium * Gd 157.25 64	Terbium * Tb 158.93 65	Dysprosium * Dy 162.50 66	Holmium * Ho 164.93 67	Erbium * Er 167.26 68	Thulium * Tm 168.93 69	Ytterbium * Yb 173.04 70	Lutetium * Lu 174.97 71	
		Actinium * Ac [227] 89	Thorium * Th 232.04 90	Protactinium * Pa 231.04 91	Uranium * U 238.03 92	Neptunium * Np [237] 93	Plutonium * Pu [244] 94	Americium * Am [243] 95	Curium * Cm [247] 96	Berkelium * Bk [247] 97	Californium * Cf [251] 98	Einsteinium * Es [252] 99	Fermium * Fm [257] 100	Mendelevium * Md [258] 101	Nobelium * No [259] 102	Lawrencium * Lr [262] 103	



Xenon — Name of element
*** — Element state
Xe — Chemical symbol
131.29 — Atomic weight
54 — Atomic number

■ Alkali metal
■ Alkaline-earth metal
■ Lanthanide
■ Actinide
■ Transition metal
■ Post-transition metal

■ Metalloid
■ Other nonmetal
■ Halogen
■ Noble gas
■ Unknown chemical properties

*	Solid
**	Liquid
***	Gas
****	Unknown

Table of Contents

Hydrogen
***
H
1.008
1

HYDROGEN

ELEMENTAL FACTS

- Hydrogen, which is element number 1, has one proton and one electron in its most common isotope, making it the simplest element in the universe—the mother of all other elements.
- Across the universe, hydrogen is by far the most common element, accounting for about 74% of all mass. That includes stars, galaxies, and even atoms in intergalactic space.
- Hydrogen is also the lightest element in the universe. Hydrogen gas is only about one-tenth as dense as the air around us, so any hydrogen gas that might be created or collected on Earth must be trapped immediately in a container or it will simply drift into space. Yet hydrogen is still very common on Earth. The catch is that it exists naturally only in compounds with other elements.

> THE THREE LIGHTEST ELEMENTS ON THE PERIODIC TABLE—HYDROGEN, HELIUM, AND LITHIUM—WERE THE ONLY THREE ELEMENTS CREATED IN THE BIG BANG THAT GAVE BIRTH TO OUR UNIVERSE.

- Hydrogen was first isolated in the 1600s and identified as an element in the 1700s. The first successful separation of pure hydrogen happened in 1671 at the hands of Robert Boyle, who discovered that reacting iron filings with dilute acid produces a gas that could be burned in air to form water.

- In 1766, English chemist Henry Cavendish collected hydrogen gas from a reaction between iron filings and acid. In 1781, Cavendish showed that when this new gas came into contact with a flame, it burned in air to form water. This tipped off French chemist Antoine Lavoisier that this new gas must be something simpler than water—an element that combined with others in the air to form water. And because the burning of this new element generated water, Lavoisier named it *hydro-gen*, which means "water generator."
- Hydrogen makes up two-thirds of the atoms in water (H_2O)—the most abundant chemical compound on the surface of our planet. A water molecule is far more stable than either oxygen gas or hydrogen gas alone, so when given the opportunity to combine, hydrogen and oxygen join in a chemical reaction that creates a more stable water molecule and releases a tremendous amount of energy, which is used to power rocket ships and space shuttles.
- But even more power is obtained from hydrogen in the form of nuclear reactions. On November 1, 1952, the United States detonated an explosive device code-named Ivy Mike on a small Pacific island called Elugelab. It was the world's first hydrogen bomb—a device that carried out a nuclear reaction, fusing hydrogen into helium and releasing the resulting energy in an instant, creating the most powerful explosion ever created by humankind.* In other words, the simplest of elements served as fuel for the largest bomb ever made.

THE PROCESS OF FUSION IN ORDINARY STARS CAN FUSE ATOMS OF HYDROGEN AND HELIUM TO PRODUCE NEW ELEMENTS AS LARGE AS IRON, NUMBER 26 ON THE TABLE.

---

* This explosion was about 1,000 times more powerful than the nuclear bomb that destroyed Hiroshima.

Helium
***
He
4.003 2

HELIUM

ELEMENTAL FACTS

- Helium, element number 2, has two protons and two electrons. While being the element with the smallest atomic radius, helium makes up about 24% of all the observable matter in the universe.

- Like hydrogen , helium is a small atom that is also very buoyant in air, escaping the atmosphere anywhere it is formed or released. But unlike hydrogen, which is highly reactive as a lone atom, helium is the least reactive element on the entire periodic table.

- Also unlike hydrogen, which can be extracted from compounds like methane, helium doesn't combine chemically with other elements, making it truly scarce on Earth. This explains its name, which comes from the Greek word *helios*: an homage to the sun god, Helios, and to its discovery in the outer reaches of the Sun's corona. Because any such element was assumed to be molten metal, the astronomer Norman Lockyer gave it what had been a metal-style name: *hel-ium*, making the name similar to sodium, titanium, and so on.

- Whether in a simple party balloon or a sophisticated weather balloon, helium is often the gas of choice to give buoyancy without the dangers of explosion that hydrogen produces.

- Liquified helium boils at a temperature that's very close to absolute zero, making it the coldest readily available liquid in the world. Its inertness, combined with its remarkably low temperature, makes liquid helium valuable for the demanding conditions required to explore extreme states of matter or to operate superconducting magnets, such as those employed in magnetic resonance imaging (MRI).

- Helium is such a coveted natural resource that the US maintains a strategic helium reserve to ensure that a steady supply is available for scientific and medical applications.

Lithium
*
Li
6.941
3

LITHIUM

ELEMENTAL FACTS

- Lithium is the third lightest of all the elements and one of only three that were created during the big bang (the other two being hydrogen and helium).

- Chemists have known for more than a century about lithium's strong tendency to ionize and its very small atomic mass. In fact, being from row 2 and group 1 of the periodic table makes lithium able to carry large amounts of charge in a relatively small mass of material. These properties have been employed in lithium-ion batteries—some of the most powerful and compact energy sources available—to provide electrical power whenever weight matters, as it does in portable electronic devices and vehicles.

- Lithium's light weight and metallic properties have made it valuable for other applications. Pure lithium metal is far too reactive to be used as a manufacturing material, but when alloyed with other light metals, such as aluminum, lithium's low density can be exploited without its vigorous reactivity getting in the way.

- In alloys between lithium and aluminum, the metallic bonding is much more stable than in pure lithium while being even lighter than aluminum without sacrificing strength. Such alloys have been particularly useful in aviation and have been responsible for an initial surge in global lithium production that began in the 1950s, long before the development of the lithium-ion battery.

Beryllium
*
Be
9.012
4

BERYLLIUM

ELEMENTAL FACTS

- With an atomic number of 4, beryllium is the fourth-smallest element on the table. Yet its natural abundance in our universe and solar system is staggeringly low when compared to other row-2 and row-3 elements. Its lithophilic characteristics have concentrated it in our Earth's crust, making it available and a valuable material as a native metal because of its low density and its strength.
- Beryllium—named for the mineral beryl—was first identified in emeralds, which are just the mineral beryl with about 2% chromium to make them green.
- A few hundred years ago, French chemists originally noted that compounds of this element tended to have a sweet taste and proposed the name glucinium, or glycinium (after the sugar glucose), and the elemental symbol Gl.
- But other known elements also produced sweet-tasting compounds, so this name met a lot of resistance. By the time elemental beryllium metal was isolated in 1828 by Friedrich Wöhler and Antoine Bussy, most countries changed the name to beryllium and the abbreviation to Be.
- We now know that inhalation or ingestion of significant amounts of beryllium can cause a medical condition referred to as berylliosis. This is where the body stages an overactive immune response to beryllium that can cause medical complications lasting years, or even decades, as the immune system needlessly attacks trace beryllium that the body simply can't get rid of.
- More than 200 metric tons per year worldwide of beryllium are extracted for use in making durable, lightweight metallic substances. Beryllium and its alloys can be used to produce fuselage parts for aircraft as well as electronics parts that might appear in computers, televisions, and mobile devices.

Boron
*
B
10.81
5

BORON

ELEMENTAL FACTS

- Boron, element number 5 on the periodic table, is the lightest of the metalloids and has the highest melting point of this class of elements.
- Boron's natural abundance in both our immediate environment and the solar system is fairly low. Although strikingly rare for such a small element, boron's abundance in our environment is still on par with many larger, familiar elements, such as copper, nickel, and zinc.
- Just like beryllium, boron is a lithophile, and it has become concentrated in the Earth's surface in a few regions of the world—perhaps most notably in Tibet, Persia, and the American Southwest.
- Boron was discovered at nearly the same time by French chemists Joseph-Louis Gay-Lussac and Louis-Jacques Thenard and by English chemist Humphry Davy. It was discovered in borax, and its atomic mass resembled that of carbon closely enough that Davy gave its name a similar ending, calling it boron.
- Elemental boron is very difficult to extract and recombines with oxygen quickly, making it highly flammable. Pure boron has proved useful as an igniter for rocket fuels.
- Boron was first recognized as an essential nutrient for plants in the 1920s. Fertilizers often add small amounts of boron-oxygen compounds, in part because boron apparently helps build the cell walls of plants, especially tall plants, such as trees.
- In the late 1800s, Otto Schott discovered that by including boron in the production of glass, he could make a product that was clear and colorless like the default soda-lime glass but had much greater resistance to thermal expansion and contraction. This led to the creation of a new material that is still used by lab researchers and home bakers today.

Carbon
*
C
12.01
6

CARBON

ELEMENTAL FACTS

- All atoms of carbon contain six protons in their nucleus, which means that carbon has an atomic number of 6. A carbon atom typically also has six neutrons, but it could have seven neutrons. Such atoms are called isotopes of one another and are often indicated by the total number of protons and neutrons they contain—for example, carbon-12 or carbon-13.
- Carbon provides an irreplaceable scaffold for the many biological molecules necessary for life to exist. Many biological molecules—including the nucleic acids of DNA; the amino acids that make up enzymes and proteins; as well as fats, sugars, and hormones—contain chains, branches, and loops of interconnected carbon atoms. Carbon's strong bonds to one another hold the molecule together and give it the unique shape that in part gives each molecule its specific function.
- Carbon makes up only about 0.5% of all the matter in the universe and only 0.02% of Earth's crust. Yet our bodies are about 18% carbon by mass. Nature and evolution have gone out of their way to concentrate this element about 900-fold in our bodies compared to our environment.

CARBON-14 IS AN UNSTABLE ISOTOPE OF CARBON THAT HAS A HALF-LIFE OF 5,730 YEARS, MEANING THAT AFTER 5,730 YEARS, 50% OF A SAMPLE OF CARBON-14 WILL HAVE DECAYED RADIOACTIVELY. (AFTER 11,460 YEARS, ONLY 25% REMAINS, AND SO ON.)

- Pure carbon is responsible for two familiar substances: graphite, the soft, dark so-called lead of a pencil; and diamond, which is one of the hardest natural materials on Earth. The complex atomic structures of graphite and diamond give them extremely high melting points, making them a favorite material for high-temperature applications. Graphite—which melts at a scorching 3,600° Celsius, a temperature on par with the surface of the Sun—is used in control rods in the cores of nuclear reactors, while diamond has uses as an insulator in high temperatures.

Nitrogen
***
N
14.01
7

NITROGEN

ELEMENTAL FACTS

- Discovered in 1772, nitrogen is element number 7. Like hydrogen and helium, nitrogen is one of the few elements whose atomic number also tells you how abundant it is, since nitrogen is the seventh most common element in the universe.

- Nitrogen received its modern name in 1790, one year into the French Revolution, when French chemist Jean-Antoine-Claude Chaptal successfully isolated pure nitrogen from saltpeter, a black potassium-nitrate mineral normally used in making gunpower. Saltpeter is also called niter, which is where nitrogen gets its name.

- Nitrogen is a gas at room temperature. In fact, nitrogen only turns to liquid at a frigid –195° Celsius—colder than the dark side of the Moon! And solid nitrogen can only exist below –210° Celsius. We have to go to the moons of Uranus or the dwarf planet Pluto to find the closest naturally occurring solid nitrogen.

- Liquid nitrogen is one of the most widely used cryogens—gases liquified at very low temperatures—in the world. Although not nearly as cold as liquid helium, liquid nitrogen's inertness makes it a much safer choice than oxygen for freezing samples or cooling electromagnets to about –160° Celsius.

- Nitrogen is essential to life. It appears in key biomolecules we rely on to stay alive, such as the bases of our DNA and the amino acids that make up essential proteins and enzymes.

- Nitrogen is also crucial to proper plant health. In the 1920s, Fritz Haber devised a way to convert atmospheric nitrogen into ammonia, which can be used to produce a wide range of nitrogen-containing products. In 2018, the Haber-Bosch process was responsible for the production of more than 200 million tons of ammonia, most of which is used as fertilizer.

Oxygen
***
O
16.00
8

OXYGEN

ELEMENTAL FACTS

- Oxygen was discovered in 1774, when Carl Wilhelm Scheele found that applying extreme heat to manganese dioxide could induce it to release a gas he proposed to call "fire air," which had a remarkable ability to support combustion of common fuels like charcoal. Almost simultaneously, English chemist Joseph Priestley conducted a similar experiment, making the same observations. What both of these men had actually discovered was oxygen—element number 8 on the periodic table.

- To determine the true nature of this gas, French chemist Antoine Lavoisier conducted a series of experiments and realized it was an element. He also noted that this new element seemed to appear frequently in compounds like vinegar, nitric acid, and sulfuric acid—compounds with acidic characteristics. It appeared in so many compounds with acidic characteristics that Lavoisier chose the name oxygen, a name derived from Greek terms meaning "acid producer."

> SWEDISH CALLS OXYGEN *SYRE*, LIKE THE ENGLISH WORD *SOUR*. AND THE GERMAN TERM FOR OXYGEN, *SAUERSTOFF*, MEANS "SOUR STUFF" IN ENGLISH.

- The third most abundant element in the universe, oxygen forms a diatomic molecule that we breathe on the surface of the Earth. In the oxygen atom, both bonds join the same two atoms, producing what is known as a double bond. This creates the O_2 molecule, the most common form of oxygen in our environment—the one you are breathing right now.

- Engineers at NASA have relied heavily on the reactive power of liquid oxygen, using huge tanks of it to enhance the combustion of common fuels like hydrogen or natural gas in booster rockets that provide enough thrust to take vehicles to the edge of space.

WITH ENOUGH LIQUID OXYGEN, THE SAME FUEL THAT PUSHES DELIVERY TRUCKS DOWN YOUR STREET CAN LOB A NUCLEAR WARHEAD FROM ONE SIDE OF THE GLOBE TO THE OTHER!

- But the reactivity of oxygen can be a double-edged sword. NASA engineers learned this to their horror during a ground rehearsal test with the Apollo 1 crew, whose command module was filled with pure oxygen to make breathing easier as well as reduce outward pressure on the hull in the vacuum of space. Unfortunately, there was a momentary surge of voltage in one of the module’s components, and that was enough to cause a fire. All three astronauts died within seconds.
- This tragedy illustrates the importance of having nitrogen and oxygen working together in our atmosphere. Later Apollo missions launched using a mixture of oxygen with nitrogen to reduce the risk of fire. Similarly, the oxygen in Earth’s atmosphere is essentially diluted with unreactive nitrogen, making our resulting atmosphere far less capable of supporting fires.

OXYGEN MAKES UP 21% OF OUR ATMOSPHERE.

- Elemental oxygen strikes a wonderfully useful balance between stability and reactivity: stable enough to remain available in the air for long periods of time but also reactive enough that we can harness its chemical potential in burning fuels and powering our bodies.

Fluorine
***
F
19.00 9

FLUORINE

ELEMENTAL FACTS

- Fluorine is one of the most dangerous and reactive elements on the table. The name *fluorine* was coined in 1812, and chemists literally made themselves sick while trying, unsuccessfully, to isolate it from the very dangerous compound hydrofluoric acid.
- In 1931, Colorado dentist Frederick McKay realized that a remarkable lack of cavities in local patients correlated with a high level of fluoride ions in the area's drinking water.
- The source of the fluoride was determined to be 10,000-year-old deposits of the mineral fluorite, or calcium fluoride, deposited in Colorado as the glaciers from the last ice age retreated northward. This mineral was slowly dissolving into the water supply.
- After extensive testing, it was determined that the same effect in patients could be produced by the addition of a small amount of the ionic compound sodium fluoride to drinking water or toothpaste. Fluoride ions have an amazing ability to toughen tooth enamel.
- The popular nonstick coating Teflon consists of chains of carbon atoms, where each carbon in the chain has two covalently bonded fluorine atoms. At normal cooking or baking temperatures, the tightly held electron clouds of the fluorine atoms interact very weakly with other materials, providing a nonstick surface that remains solid.[*]
- The now-infamous chlorofluorocarbons (CFCs) are compounds that bring carbon, fluorine, and chlorine together to form small molecules formerly used in refrigeration systems. Instead of CFCs, refrigerants now often use hydrofluorocarbons (HFCs). The chlorine is substituted with hydrogen, but the tightly held fluorine is still there.

---

[*] However, if scratched or heated above 300° Celsius, Teflon may begin to break down.

Neon
***
Ne
20.18 10

NEON

ELEMENTAL FACTS

- Neon is an inert, or noble, gas, meaning that it does not interact with other elements, including other atoms of itself!
- In the 1890s, Sir William Ramsay isolated and identified neon—as well as helium, argon, xenon, and krypton—using a process called distillation of air. He accomplished this by cooling a sample of gas to the point at which it liquified and then slowly warming the sample, collecting the gas as it reached its boiling point and vaporized. When he discovered a gas in the air that boiled at a lower temperature than nitrogen, he called this *new* gas neon (meaning "new").
- The first neon sign was made in 1910, only about a decade after neon's discovery. But neon gas in its ground state is invisible, so what you are seeing in neon lighting is the result of running through the gas a high-voltage electron discharge, which eventually emits various wavelengths that mix to form the bright glow of red-orange that is the visible emission spectrum of neon.
- Neon is the namesake for an entire class of lighting products that use noble gases. But neon has other uses beyond its most famous applications in lighting. Being the next smallest of the noble gases, neon has a boiling point close to that of helium—close enough that in certain applications where the extreme cold of helium isn't necessary, more affordable and abundant neon can be substituted, preserving the precious helium for only applications that require it.
- Neon is a liquid only over a very narrow temperature range, between 27 and 24.5 kelvin. Stray below that narrow range and neon becomes a solid. In fact, all noble gases stay liquid over just a very narrow range of temperatures before transitioning to a solid state.

Sodium
*
Na
22.99 11

SODIUM

ELEMENTAL FACTS

- Compounds containing sodium—such as soda, also called natrium, which is where sodium gets its symbol, Na—are very common.
- Sodium is responsible for with the warm yellow glow of certain streetlamps and lighting in other industrial settings. When sodium vapor is stimulated by electricity, it emits intense yellow light. By enclosing sodium in an evacuated bulb, heating it until that sodium vaporizes, and passing an electric current through it, a handy lightbulb can be made.
- Sodium lamps were developed in the 1920s and were valued at the time by scientists who needed monochromatic light for their experiments. Decades before the laser, sodium lamps offered a simple, affordable source of nearly monochromatic light that often fit the bill.
- But the impact of sodium in lighting goes beyond just the laboratory. Because of their economy, availability, and easiness on the eye, sodium lights became a popular option for urban lighting in the mid-1900s. By the 1960s, many urban streets were bathed in the glow of sodium lamps each night.
- Astronomers used to love urban sodium lighting. Its single intense yellow wavelength minimized its impacts on their astronomical observations, and the impacts it did have on observations were easy to subtract because of its nearly monochromatic nature.
- But the problem these lamps posed was that monochromatic light can make certain objects difficult to see on the ground. So, in the interest of public safety—and much to the chagrin of stargazers—many communities have abandoned the use of sodium lights in favor of newer technologies that produce a broad spectrum of wavelengths. This improves visibility of road signs and obstacles, protecting motorists and pedestrians.

Magnesium
*
Mg
24.31 12

MAGNESIUM

ELEMENTAL FACTS

- Magnesium—which was named for a region of Greece called Magnesia—is one of the most common elements in our world. It appears most commonly in minerals that form dense rock on seafloors but also in volcanic rocks that are extruded onto the surface of the continents in eruptions. By mass, it is the seventh most abundant element in Earth's crust.

- Like many other elements concentrated on the Earth's surface, the minerals containing magnesium slowly weather chemically and release their magnesium into the sea. Each liter of seawater on average contains about 1 gram of dissolved magnesium.

- Magnesium's properties make it a popular choice for inclusion in metal alloys that need to be light, sturdy, and corrosion resistant. But if magnesium gets hot enough, its tendency to react with oxygen leads to one of its more famous uses. Though difficult to ignite, magnesium metal burns vigorously in air once it gets going and produces a strong white light.

- In 1864, this property led to the use of magnesium powder to conduct the world's first flash photography. The earliest example of this technology is so-called flash powder, which produced a quick burst of light when ignited. This required photographers to hold a tray of powdered magnesium above their head while taking the photo. The hot, bright, sometimes-violent reaction taking place so close to them made this photo-taking method dangerous.

- Magnesium is also biologically crucial in many ways. Perhaps most interesting is its role in photosynthesis and the beauty of fall foliage. Magnesium is at the center of a class of molecules called chlorophylls, which are essential compounds used by plants to gather energy from light to perform photosynthesis.

Aluminum
*
Al
26.98
13

ALUMINUM

ELEMENTAL FACTS

- Aluminum is a highly reactive element that locks on to oxygen tightly. Aluminum's relationship with oxygen is so strong that it is a member of the set of lithophilic elements that form rocks in Earth's crust.

> UNKNOWN TO ANCIENT CIVILIZATIONS, ALUMINUM IS EXTREMELY COMMON IN THE EARTH'S CRUST—A FACT THAT MAKES ALUMINUM AFFORDABLE TODAY, NOW THAT WE KNOW WHERE TO FIND IT AND HOW TO EXTRACT IT.

- Aluminum's high reactivity kept pure aluminum hidden from humankind until 1825, when the first metallic aluminum was obtained by reacting aluminum oxide with recently discovered potassium metal, which is even higher in reactivity.
- With the development of this method to obtain small amounts of aluminum, it quickly became a precious metal. By the mid-1800s, Emperor Napoleon III of France was famously using dinnerware made of aluminum for himself and his most honored guests, leaving gold and silver utensils to guests of lesser status. It was in the late 1880s that advances in the processing of the mineral bauxite and improved electrolysis techniques combined to make aluminum widely available to the masses.
- Today, aluminum is used in the production of transmission lines for electrical power. Aluminum is very light yet very strong. But aluminum is actually not the best electrical conductor on the table. Copper is a better conductor that offers half the electrical resistance of aluminum. Cost and availability tilt in favor of aluminum, but there is yet another property that makes aluminum wire so attractive: lower density. An aluminum wire of the same size is only one-third as heavy as copper.

Silicon
*
Si
28.09
14

SILICON

ELEMENTAL FACTS

- Like most small elements with even atomic numbers, silicon is around us in great supply. It is second only to oxygen as the most common element in Earth's crust. And silicon participates in the formation of a huge host of rock-forming minerals.
- In 1824, Jöns Jacob Berzelius isolated silicon by heating chips of potassium in a silica container. Once pure silicon was available for study, it quickly became clear that this was a special element. As a solid, it had a dull appearance like a nonmetal, yet it was hard and fractured like a metal. It conducted electricity much better than most nonmetals, yet not nearly as well as metals themselves. Silicon was in between a conductor and an insulator: It was a semiconductor.
- Silicon is a brittle, shiny semiconductor when pure. It can be alloyed with aluminum and other metals to create new metallic materials with beneficial properties used in aviation. In these alloys, silicon interacts through metallic bonding.
- But combine silicon with nonmetals, such as oxygen or fluorine, and it tends to form covalent bonds like nonmetals do. Compounds like silicon dioxide, which makes up quartz, are held together by covalent bonds.
- Silicon creates a vast network of covalent silicon-oxygen bonds to form the mineral known as silica. When pure, silica can appear in two forms: glass or quartz.
- Quartz does not conduct electricity. In fact, it's quite the opposite: Quartz is used in the manufacture of electrical insulators!
- The reason that silicon in its pure form is used extensively in the manufacture of computer chips is because it does not conduct electricity nearly as well as genuine metals like its neighbor, aluminum.

Phosphorus
*
P
30.97 15

PHOSPHORUS

ELEMENTAL FACTS

- In 1669, German physician Hennig Brand obtained the first samples of phosphorus while trying to produce the fabled philosopher's stone, a substance that alchemists believed could transmute less valuable elements into gold. He boiled a sample of urine—1,200 gallons of it—to concentrate it. This produced a solid substance that glowed, emitting light for long periods of time after it was isolated. He named his new substance phosphorus for the Greek term meaning "light bringing."

- Phosphorus is the driving chemical force behind the safety match. In 1826, the first chemical friction match was produced and soon followed by strike-anywhere matches, which contained a mixture of white phosphorus and potassium chlorate. When struck against a hard surface, the two compounds reacted to produce a flame.

- But with the phosphorus fuel and the oxidizing potassium chlorate on the same match head, it was too easy to unintentionally strike such matches.

- In 1844, Gustaf Erik Pasch removed the dangerous and toxic white phosphorus from the match head and added to the matchbox a red striking surface containing red phosphorus, which is much more stable. This invention keeps the fuel and the oxidizer safely separated until the reaction is needed.

- The reaction between phosphorus and oxygen creates bright light and highly visible smoke. This made phosphorus the material of choice for use in incendiary or tracer ammunition during World War I.

- Phosphorus serves a crucial role in energy management, where it combines with oxygen in the form of phosphates to make molecules like adenosine triphosphate, from which one of the phosphates can be removed to release biochemical energy when and where our bodies need it.

Sulfur
*
S
32.07
16

SULFUR

ELEMENTAL FACTS

- Sulfur is a substance that has been known since ancient times. This is because its elemental form occurs in nature and discovering it was likely as simple as happening upon a sample.
- Sulfur took its rightful place on the list of elements in the 1700s, when Antoine Lavoisier convinced the rest of the scientific community to begin looking at it as an element.
- Elemental sulfur can burn, though it is rarely an element that we burn on purpose, since the resulting sulfur oxide gases are both toxic and a source for acid rain. It is the toxicity of its combustion products that made sulfur one of the world's first chemical weapons. Historical accounts describe ancient Greeks tossing flaming pitch mixed with sulfur over city walls to "encourage" the inhabitants to surrender their city.
- Sulfur oxide gases also form during the burning of sulfur-rich coal, which can be problematic. These sulfur oxide gases react with moisture in the air to form strong sulfuric acid, which is carried back to the ground by precipitation. This results in the infamous acid rain that caused environmental concerns in areas downwind of coal-fired powerplants around the world beginning in the 1970s and 1980s.
- Sulfur is used in polymer production. Its electron configuration makes it ideal for cross-linking one polymer chain to another, as it does in vulcanized rubber. The cross-links provided by the sulfur add rigidity to the rubber product, making an excellent material for the production of automobile tires.
- Sulfur is found in the proteins and enzymes that provide structure and moderate chemical reactions in the body. It can influence protein structure through sulfur bridges, just like those in vulcanized rubber.

Chlorine
***
Cl
35.45 17

CHLORINE

ELEMENTAL FACTS

- In 1774, Swedish chemist Carl Wilhelm Scheele created the element chlorine. He was conducting a chemical reaction between manganese dioxide and hydrochloric acid that produced a pale green gas. What he had created was diatomic chlorine gas, the first element ever discovered from group 17, which contains some of the most reactive elements on the table.

- But chlorine was not recognized as an element until 1810, thanks to Humphry Davy, who took inspiration for its name from the Greek term *chloros* to describe its pale green color.

- Chlorine is a nonmetal element that would prefer to accept an electron, which makes it become a negatively charged chloride ion. These ions help to balance the charge associated with the metals dissolved in the ocean. In fact, chloride ions are extremely abundant in seawater, as they help provide charge balance for the dissolved metals. It is this sea of ions that gives seawater its taste and part of its interesting chemistry.

- The fact that chlorine is a third-row element with two atoms per molecule makes it a remarkably dense elemental gas—so dense that a sample of chlorine molecules actually sinks in air—a property that was exploited by one the most infamous chemists of the 20th century, the German Fritz Haber. During World War I, he counted on the density of chlorine gas to make it drift across the battlefield and sink into the trenches of the enemy as he ordered the release of thousands of buried tanks of pressurized chlorine gas at Ypres, Belgium, in 1915.

- Covalently bonded chlorine is found in the sugar substitute sucralose, which is just ordinary sucrose made sweeter by the substitution of several chlorine atoms for other groups of atoms on the molecule.

Argon
***
Ar
39.95 18

ARGON

ELEMENTAL FACTS

- In the late 1800s, Scottish chemist Sir William Ramsay managed to collect pure nitrogen from air that had the same density as nitrogen from other sources. This proved that nitrogen isolated from our atmosphere had remained about 1% heavier in previous samples because they had not actually isolated pure nitrogen. Instead, earlier samples of nitrogen from the air had also contained a previously undetected element. And because this new element was so unreactive that it had escaped detection by chemical methods, Ramsay decided to name this element for the Greek word *argos*, meaning “idle,” “lazy,” or “inactive.”

- Because argon was so different than all the other elements in its inertness, Ramsay wondered if it could be a member of a whole new group of lazy elements that simply didn’t react with their surroundings. As he refined the techniques he had used to isolate argon from air and studied argon more and more carefully, he identified neon, krypton, and xenon all hiding in air as well, albeit in much lower concentrations than argon.

- Argon gas is by far the most common of the noble gases in our atmosphere, mainly because it blends universal abundance with a density that allows it to be trapped by our atmosphere instead of floating into outer space like its smaller cousins, helium and neon, can.

- Argon’s abundance and air-like density have made it a popular choice as a fill gas anywhere an inert atmosphere is needed and density isn’t an issue. Argon works well for filling insulated windows and incandescent lightbulbs because it does not tend to settle much over time. Argon is always near the top of the list whenever ordinary air needs to be replaced with something less reactive.

Potassium
*
K
39.10 19

POTASSIUM

ELEMENTAL FACTS

- At the turn of the 19th century, British chemist and inventor Humphry Davy discovered that he could use a battery to isolate potassium from wood ashes. He collected wood ashes from various sources, soaking them in water and then isolating the resulting solid, which was known as caustic potash, or lye. Today this substance is called potassium hydroxide. After melting this product in a furnace, he then applied an electrical voltage across the sample to purify the potassium from the potash. This is how the element got its name—it's literally *pot-ash-ium*—and its symbol, K, as potash is also called kalium.

- Potassium is an essential nutrient for humans and plants alike. Because potassium is so abundant and ionizes so easily, the human body has evolved to use potassium transport to help maintain and establish the charge separations that create such essential functions as muscle contraction.

- In 2003, Roderick MacKinnon won the Nobel Prize in Chemistry for his characterization of potassium ion channels from cells. Ion channels are remarkable proteins that span the cell membranes in a variety of tissues, shuttling potassium back and forth as the body needs.

- But these ion channels make us vulnerable to certain venoms produced by predatory animals. For example, the venom of scorpions contains chemical compounds that stick to the opening of such ion channels, halting the transport of potassium, causing paralysis and even death in any animal unfortunate enough to receive a sting or a bite. Simply by halting the flow of this single element through the body, these venoms can paralyze or even kill.

Calcium
*
Ca
40.08 20

CALCIUM

ELEMENTAL FACTS

- Magnesium and calcium were the first alkaline-earth metals discovered. This is in part because their similarities lead to magnesium and calcium commonly accumulating together in nature.
- As far back as 4,000 years ago, ancient Mesopotamians used a very special substance that could be obtained by subjecting limestone to extreme heat in special kilns in a process called calcining.
- Natural limestone itself is made of a mixture of calcium and magnesium carbonates, and heating these substances drives off carbon dioxide gas, leaving behind a combination of metal oxides of both metals, known then as quicklime.
- In 1755, Scottish researcher Joseph Black studied these two components of limestone—calcium carbonate (known simply as chalk) and magnesium carbonate (known then as magnesia alba, or white magnesium)—and determined that they were different compounds. He called them magnesia and lime.
- In 1808, Humphry Davy used his famous electrolysis technique with a voltaic pile to force electrons back onto the metals of magnesia and lime. The newly discovered elements were named magnesium, for the magnesia starting material, and calcium, for the calcining process.
- Calcium's lithophilic nature ensures that geological processes are always dragging calcium from deep underground to the surface in the form of silicon-based rocks like granite. Those rocks will ultimately weather, releasing some of that calcium to seawater, where it is a favorite element for the formation of calcium carbonate shells used by many sea creatures for protection.
- Of course, calcium is important in bones, where it makes up about 40% of the mass of calcium hydroxyapatite, the principal mineral making up bone.

Scandium
*
Sc
44.96 21

SCANDIUM

ELEMENTAL FACTS

- Scandium is named for the Scandinavian Peninsula, where a strange, heavy black mineral was first discovered. This mineral proved to contain a number of undiscovered elements.
- In 1869, Dmitri Mendeleev correctly predicted the discovery of an element between calcium and titanium. That element turned out to be scandium, and it was discovered 10 years later.
- Scandium is the first *d*-block element and the first in its own column, group 3 of the modern table. Scandium is a soft, silver-white metal that tarnishes in air, not unlike its *s*-block neighbors, calcium and potassium. Scandium is a relatively low-density metal with good electrical conductivity, just as one might expect for an element on this left side of the block.
- Scandium is only a little less abundant in the Earth's crust than copper or nickel, but this element is more often used in small amounts to fine-tune the properties of other elements. A pinch of scandium added to aluminum makes a very strong, lightweight alloy that's valuable in jet fighters and high-end bicycles. Just a little bit goes a long way for this element. Globally, just a few dozen to a few hundred tons of scandium are produced annually.

Titanium
*
Ti
47.87
22

TITANIUM

ELEMENTAL FACTS

- Titanium is named for Greek mythological figures called Titans, who are children of Uranus, or Heaven, and Gaea, or Earth. They revolted against their father and are known as the golden race.

- Titanium is a metal that's valued for its durability. The reason it's durable is because it reacts with oxygen to form oxide compounds that are tough and hard, creating a very thin, passivating layer of oxide that protects the remaining metal beneath from further reaction. These tough oxide layers form almost immediately when metals like titanium are molded and cooled, protecting the rest of the metal inside from exposure to oxygen. This means that holding pure titanium metal in your hand is virtually impossible under normal conditions. What you are actually holding is pure titanium wrapped in a thin layer of protective metal oxide.

- Titanium is valued for its very low density. It's a remarkably lightweight element that can be used in alloys. Titanium is often used when low weight matters.

- Titanium dioxide is highly valued in paint and pigment industries because of its high opacity and white color when powdered. This makes titanium dioxide something of a blank canvas that can form opaque colored materials when pigments are mixed with it.

Vanadium
*
V
50.94
23

VANADIUM

ELEMENTAL FACTS

- In 1801, Spanish Mexican mineralogist Andrés Manuel del Río first discovered element number 23. In recognition of its similarity to chromium and its ability to produce compounds of nearly every color of the rainbow, one name he initially proposed was panchromium.
- But early attempts to validate his discovery erroneously concluded that his sample contained only chromium itself, an element discovered a few years earlier. Ultimately, del Río's discovery would be claimed and named by Swedish chemist Nils Gabriel Sefström some 30 years later. But once again, vanadium's array of beautifully colored compounds was the inspiration for its name—this time it was named after the Scandinavian goddess of beauty, Vanadis.
- Like titanium, vanadium is a metal that's famous for its toughness and durability. Just a tiny amount of vanadium can make a steel alloy much stronger. In 1908, Henry Ford chose vanadium steel as the material for high-stress components in his famous Model T and is even said to have once declared, "But for vanadium there would be no automobiles!"
- And 100 years later, a 2008 article in *Popular Mechanics* listed his choice of vanadium steel as second only to the adoption of the assembly line in the success of Ford's legendary Model T.

Chromium
*
Cr
52.00 24

CHROMIUM

ELEMENTAL FACTS

- Chromium—which comes from the Greek *chromos*, or “color”—was named for its ability to absorb colored light. Evidence of this can be seen in the many colorful gems that it makes possible. Emerald gets its green color from chromium. Ruby’s red happens when chromium replaces some aluminum ions in ordinary aluminum oxide. Jade gets its color from a mixture of chromium and iron. Spinel is an ordinary oxide of magnesium and aluminum, but colors like red, pink, and orange pop when chromium gets involved.

- Like titanium and vanadium, chromium is a metal that is famous for its toughness and durability. Chromium has the effect of hardening steel and increasing steel’s corrosion resistance. Chromium steel, whose more common name is stainless steel, and chromium-molybdenum steel, which is sometimes referred to as chromoly steel, are both lighter, tougher metals that owe many of their improved properties to the inclusion of chromium into the structure of iron.

Manganese
*
Mn
54.94
25

MANGANESE

ELEMENTAL FACTS

- Manganese was first identified in 1774, when Swedish chemist Carl Wilhelm Scheele was conducting a chemical reaction between a deep purple mineral we would call manganese dioxide and a colorless liquid we now know as hydrochloric acid. His reaction produced a pale green gas, which was chlorine.
- Around the same time, he found that applying extreme heat to manganese dioxide could induce it to release a gas he proposed to call “fire air,” which had a remarkable ability to support combustion of common fuels like charcoal.
- Manganese was used to produce one of the first steel alloys ever, combining it with iron to produce a product with the clever name of mangalloy.

Iron
*
Fe
55.84 26

IRON

ELEMENTAL FACTS

- Despite being the 26th element in the table, iron is the sixth most abundant in the cosmos. And given the way our early solar system sorted the heavier, metallic elements into the planets near the Sun, Earth is an iron planet—with iron as the single most abundant element making up the Earth. We see only a small fraction of Earth's iron at the surface, because its significant density caused most of it to sink into the core as the Earth cooled 4 billion years ago.

> THE INNER CORE OF OUR PLANET IS COMPOSED ALMOST COMPLETELY OF IRON.

- Most of the iron in our planet is concealed deep within its core, where it generates the planetary magnetic field that protects Earth's inhabitants from deadly cosmic rays. But there is so much iron in our planet overall that even the small fraction that remained near the surface, or was brought there later by geological processes, is enough to make it the fourth most abundant element in our planet's crust.

- Iron has been known to humankind since prehistory. Iron's high abundance at the surface long before oxygen became a major component of our atmosphere left behind many large bodies of native metal, protectively entombed in near-surface rock—ready to be discovered by early people.

- Artifacts suggest that iron was used as early as 3000 BCE by ancient Egyptians, and its introduction to society created such profound impacts that it has come to be the namesake for an entire epoch in human history: the Iron Age.

- *Iron* is an Anglo-Saxon–derived name dating back as far as the Crusades. But its symbol, Fe, pays homage to an even older name in Latin. Though no longer used to refer to iron itself, the name *ferrum* does inspire modern chemical references to element 26, such as the iron oxide mineral ferrite or the property of ferromagnetism.

- In its pure form, iron is a relatively soft metal that reacts slowly with both oxygen and acids. Pure iron left in the atmosphere will eventually become iron oxide, which is a brittle red material that we know as rust.

- Pure iron is relatively easy to obtain, thanks to a decently high crustal abundance, comparatively low melting point, and fairly weak bond with oxygen. Just by heating iron oxides in the presence of carbon, the oxygen reacts to form carbon dioxide, leaving behind metallic iron.

THE ROYAL SOCIETY OF CHEMISTRY ESTIMATES THAT ABOUT 90% OF ALL METAL REFINED IN THE WORLD IS IRON.

- And while pure iron itself is not the most ideal of building materials, when combined with other elements, such as carbon or boron, the properties of iron can be modified for the better.

- In this way, we can think of iron as a blank canvas for metallurgists to practice their art and create a vast array of alloy materials that we rely on every day.

- Iron also has tremendously important biological roles. Perhaps the most well-known of these is its crucial function in the transport of oxygen at the center of a hemoglobin molecule. The iron in your hemoglobin is encircled by an organic molecule to create a substance called heme, which is itself wrapped in a protein that helps finely tune the chemistry of iron to grab onto oxygen molecules in the lungs, move through your bloodstream, and then release the oxygen where it is needed in your body.

Cobalt
*
Co
58.93
27

COBALT

ELEMENTAL FACTS

- Cobalt gets its name from a German term referring to a goblin. This unusual namesake was given by German miners, who would often mistake an ore of cobalt for that of its more valuable neighbor a column farther right on the table, silver.
- Cobalt is an essential nutrient that's found in vitamin B_{12}. Cobalt has been used in aircraft alloys, glass coloring, radiological medicines, and magnet production.
- Cobalt's use in electrical vehicle batteries helped propel them to their current capabilities that compete with gas and diesel vehicles. However, the toxicity of cobalt, together with human rights issues surrounding its mining in the few countries with commercially viable deposits, make cobalt a less-than-ideal material for long-term use.
- A more speculative use for cobalt comes from 1950, when a Manhattan Project physicist named Leo Szilard, anticipating the worst, suggested that it might be possible to build a doomsday nuclear device capable of wiping the human race from the Earth—and the key element in his warning was cobalt. He proposed that this might be possible if the radioactive fallout from hydrogen bombs was not thought of as an unfortunate side effect but instead as a feature of the weapon.
- Cobalt-59 is a stable isotope of cobalt that can easily be included in the construction of a thermonuclear device. Its presence would not contribute to the explosive yield in any meaningful way, yet it could increase the bomb's death toll by orders of magnitude. The free neutrons released during a nuclear explosion could convert the cobalt-59 into cobalt-60, which, as it decays, releases deadly high-energy radiation that would be emitted for decades and spread around the globe.

Nickel
*
Ni
58.69 28

NICKEL

ELEMENTAL FACTS

- Nickel gets its name from a German term referring to the devil. Similar to cobalt, nickel was given its name by German miners, who would mistake an ore of nickel for an ore of the more valuable copper.

- Nickel is easily obtained and relatively resistant to corrosion. It will oxidize in the air over time, but the process is slow enough that it remains very useful to us as an elemental metal. In fact, nickel’s relatively good corrosion resistance has made it a metal of choice for electroplating of other, more active metals to protect them from oxidation for long periods of time.

- Nickel is one of just a handful of elements that exhibit ferromagnetism, which is the ability to persist as a “permanent” magnet. This property is especially important in the case of iron and nickel, as they make up the vast majority of the Earth’s outer core, where convection currents cause hot, liquid iron and nickel to slowly swirl about. The motion of these liquid metals deep in the Earth—1,800 miles (2,900 kilometers) below the surface—acts as a geodynamo, creating the global magnetic field that protects our planet from cosmic ray bombardment and helped early explorers navigate the globe.

- Hydrogenated oils are produced by the reaction of unsaturated fats with hydrogen to make a more shelf-stable product. Paul Sabatier accomplished this in 1899, when he was able to develop a reaction in which freshly produced nickel metal promoted the addition of hydrogen to oils, providing a means of mass-producing edible fats that would last much longer in storage than the original oils themselves. This development won Sabatier a share of the 1912 Nobel Prize in Chemistry.

Copper
*
Cu
63.55 29

COPPER

ELEMENTAL FACTS

- Copper's symbol, Cu, is an homage to its Latin cognate *cuprum*, referring to the island of Cyprus, where most of the Roman Empire's copper was mined.
- Copper was the metal of choice for tools as early as 5000 BCE in what came to be known as the Copper Age, as evidenced by copper tools and smelting equipment discovered in eastern European archaeological sites from this era.

TURQUOISE GETS ITS DISTINCTIVE COLOR FROM THE PRESENCE OF COPPER IN THE CRYSTAL.

- But sometime around 3000 BCE, the Mesopotamian civilization discovered that tin could be included with copper to produce bronze, a much harder and therefore more useful alloy.
- Copper's influence on the world around us extends beyond both its native metal and its alloys. Copper has some very interesting and useful chemistry when oxidized to copper ions. Probably the most iconic example of copper oxidation in action is the world-famous Statue of Liberty, a structure that was originally plated with a thin layer of elemental copper. For decades, that thin layer of copper has itself been covered in an even thinner layer of green copper (II) compounds—oxides, sulfides, and other compounds that formed as the copper reacted with components of the air and rainwater.
- Comparison of early color photography of the statue to modern images reveals a marked change over the years as this reaction slowly took place. The thin but equally colorful outer layer we see today, sometimes called a patina, is relatively tough and passivating. This change in the appearance of the statue wasn't discouraged, as the new green patina protects the underlying metal from the elements.

Zinc
*
Zn
65.39 30

ZINC

ELEMENTAL FACTS

- Zinc had been noticed by the ancient Romans, but only around 1100 CE did it begin to be refined in India. The origin of zinc's name is not entirely clear, but many believe that it may be tied to the Persian word for stone.

- Zinc's relatively high cosmic abundance, along with its sulfur-loving tendencies, means that a fair amount remains near Earth's surface, where it can be collected and used.

- Zinc is an essential nutrient for enzymes, DNA synthesis, and the immune system.

- Zinc's melting point of about 420° Celsius means that it can be liquified at temperatures well below the melting point of many other common metals. This gives metallurgists a simple way to create protective coatings on other metals that are more prone to corrosion.

- A classic example of this is what is known as hot-dip galvanization. In this process, an object made of metal with a higher melting point, such as iron, is dipped into a pool of molten zinc, where the zinc is incorporated into the outer layer of the object. There, zinc reacts with oxygen and carbon dioxide in the air to form a tough outer layer that protects the surface of the object beneath.

- Zinc can also be alloyed with other metals—most notably with copper to produce brass. Brass is a valued metal that combines the durability of bronze with the color and luster of gold. In *The Disappearing Spoon*, Sam Kean recounts the story of King Midas using chemistry. The legend of the king's famous golden touch is likely inspired by attempts to make bronze that led to golden-colored brass, an unintended consequence that might have seemed magical but was brought about by the high zinc content of ores native to the land ruled by King Midas.

Gallium
*
Ga
69.72 31

GALLIUM

ELEMENTAL FACTS

- Dmitri Mendeleev—the father of the periodic table—predicted that new elements would one day be discovered and placed them into empty spaces on his table. In the spaces below aluminum and silicon, he placed temporary names for the elements, invoking the prefix -*eka* from the Sanskrit word meaning "first," calling them eka-aluminum and eka-silicon for the first element below aluminum and the first element below silicon.

- In 1875, eka-aluminum was discovered in Paris, France, where it was renamed gallium, in honor of France's Gallic heritage. Reinforcing Mendeleev's prediction, the new element was discovered hiding in a sample of zinc ore, which is the element just to its left in Mendeleev's table. What's more, gallium's atomic mass and bonding characteristics perfectly matched Mendeleev's predictions for eka-aluminum.

- Gallium is a weak metal that has an unusually low melting point: 30° Celsius. With a boiling point of 2,204° Celsius, gallium then remains liquid over an incredible temperature range of 2,174°! This is a wider liquid-temperature range than that of any other element or any other common material. This—combined with its low toxicity compared to other metallic liquids, such as mercury—has made gallium a material of choice in alloys such as Galinstan, which replaces mercury in high-temperature thermometers.

- Gallium can be combined with nitrogen to form gallium nitride, a substance with properties similar to the intervening element between them, silicon. This new material may become the base material for a whole new class of semiconductors.

Germanium
*
Ge
72.63
32

GERMANIUM

ELEMENTAL FACTS

- Germanium, once given the provisional name of eka-silicon by Dmitri Mendeleev, was discovered in Germany in 1886, when a worker from a German silver mine found a sample of an unusual ore. This sample was sent to chemist Clemens Winkler, who characterized it and determined that only 93% of the mass of this ore could be attributed to known elements. After isolating and characterizing the remaining element, Winkler named it Germanium in honor of his homeland.
- Germanium is a brittle solid that conducts electricity poorly, but it is stable enough in air that even as a pure element it has found an array of uses, especially in the semiconductor industry. In fact, the seminal invention in microcomputing—the transistor—was first developed using the metalloid germanium.
- In the 1940s, William Shockley led the team of engineers working at Bell Laboratories in New Jersey that is widely credited with the invention of the transistor: a device that can conduct large amounts of electricity or practically none by applying a much weaker signaling voltage. Essentially, this creates a switch that can be on or off. Also known as a gated circuit, this produces the ones and zeros that make up the binary language of computers.
- To accomplish such a design, Shockley needed a material that had only a moderate ability to conduct electricity so that this ability could be amplified or reduced to nearly zero with relative ease. Metallic substances would be too conductive, and nonmetals would be not conductive enough, so he built his first transistor out of a metalloid: germanium.

MORE THAN 25 ELEMENTS HAVE BEEN NAMED IN HONOR OF PLACES, INCLUDING GERMANIUM, FRANCIUM, AND EUROPIUM.

Arsenic
*
As
74.92
33

ARSENIC

ELEMENTAL FACTS

- Arsenic compounds were noticed in copper ores for thousands of years before the outright discovery of elemental arsenic. Credit for the first separation of arsenic as an element sometimes goes as far back as the alchemist Albertus Magnus around 1250, but it had definitely taken place by 1649, when German pharmacists were regularly preparing the element in its pure form.

- Arsenic's famous toxicity comes at least in part from its ability to impersonate its nonmetal sibling, phosphorus. When arsenic—which belongs to the class of elements known as the metalloids—gets into the human body, it disrupts essential phosphorus-related biochemical processes, acting as a poison to every cell in your body.

- This once made arsenic the poison of choice for jilted lovers and greedy heirs alike—at least until 1836, when chemist James Marsh developed a simple test to detect even small quantities of arsenic. All it took was metallic zinc, sulfuric acid, and a flame. His test produced a dark deposit of arsenic that could be preserved and used in investigations and legal proceedings involving suspected arsenic poisoning. After the test became commonplace, many would-be assassins likely thought twice about using arsenic as a poison.

- But arsenic is much more than just a poison. It can also be added to metallic substances to alter their properties. Since ancient times, the addition of just a few percent of arsenic by mass to copper has been used to create a material known as arsenical bronze, in which arsenic is incorporated into the metallic structure of copper, providing a superior material for the production of cutting tools.

Selenium
*
Se
78.96 34

SELENIUM

ELEMENTAL FACTS

- Selenium was discovered in 1817 by Jöns Jacob Berzelius, who noticed a red-brown sediment at the bottom of a sulfuric acid works. Recently discovered tellurium had been named for the Earth, so Berzelius named this related element *selenium*, which comes from an ancient Greek term for the Moon.

- Selenium associates strongly with sulfur, the element just above it. In fact, the first pure sample of selenium was isolated from the iron-sulfide mineral pyrite, also known as fool's gold. When Berzelius extracted the iron from the sample, he discovered that this new element, selenium, was left behind.

- Selenium plays some interesting roles, most of which are linked to its structural similarity to sulfur. When selenium is combined with sulfur, selenium disulfide can be made. This compound has antifungal properties, making it useful in topical medications to treat infections of the skin.

- Selenium's ability to impersonate sulfur also plays a role in human health. The amino acid selenocysteine forms when a cysteine amino acid has had its sulfur atom replaced by a selenium atom, and it appears in as many as 25 different human proteins. Perhaps equally remarkable is that even though we know selenium is essential to our biochemistry in small amounts, we still don't know the function of many selenocysteine-containing enzymes.

- Selenium is both photovoltaic, meaning it can generate electricity from light, and photoconductive, meaning that exposing it to light changes its ability to conduct electricity. These properties have made selenium useful for light meters once used in camera technology and in recent years have made it a promising ingredient in new solar cell designs.

Bromine
**
Br
79.90
35

BROMINE

ELEMENTAL FACTS

- In 1829, German chemist Johann Wolfgang Döbereiner noticed that bromine—which was discovered in 1826—had certain chemical similarities to chlorine and iodine. Each is highly toxic as a pure element, yet all form nontoxic salts when mixed with metals like sodium.

- Around the same time, Swedish chemist Jöns Jacob Berzelius proposed the name *halogen* (from the Greek *hal*, meaning “salt,” and *gen*, “to produce”) to refer to this group of salt-generating elements.

- Halogen lights, invented at General Electric in 1955, often make use of the heavier halogens as a gas. Adding a small amount of bromine to the otherwise-inert gas inside a lightbulb improves the longevity of the tungsten filament and reduces the tungsten deposits that make the inside of the bulb look dirty. However, bromine needs higher bulb temperatures to remain in the gas phase, so while bulb performance improves with halogens, a large amount of heat is needed—and therefore energy is wasted.

- Bromine is used in a bromine-carbon-fluorine (BCF) compound called Halon, which is used to extinguish electrical fires in laboratories and aircraft. The bromine gives Halon a high density that keeps the extinguishing media near the base of a fire. Unfortunately, the BCF gas has ozone-depleting properties similar to the notorious chlorofluorocarbons (CFCs).

- Bromine reacted with vegetable oil produces a compound that helps prevent the oil-based flavorings in soft drinks from separating out of the water-based drink over time. However, Europe and Japan banned this additive and US companies have gradually removed it over concerns that the bromine may disrupt important biological reactions involving its similarly sized halogen counterpart, iodine.

Krypton
***
Kr
83.80 36

KRYPTON

ELEMENTAL FACTS

- In the 1890s, Sir William Ramsay isolated and correctly identified krypton, which got its name from the Greek *kryptos*, meaning “hidden.” In refining the liquid-air techniques he had used to isolate argon from air, he identified krypton hiding in air as well. Specifically, distilling samples of purified argon left behind a heavier gas—krypton.
- Like argon, krypton is another contributor to what most people call “neon” lighting, where krypton provides a blue-white set of wavelengths.
- Also like argon, krypton is used in tungsten filament lightbulbs. In fact, use of the denser krypton reduces evaporation of the tungsten, making incandescent bulbs somewhat more efficient.
- But krypton isn’t quite as “lazy” as argon. In 1933, Linus Pauling, creator of the electronegativity series, predicted that krypton’s outer electrons might react with fluorine. Pauling had shown that fluorine is the most electronegative element on the table and could therefore be regarded as the most reactive element.
- And in the 1960s, in a lab at Temple University in Pennsylvania, the irresistible force of fluorine met the immovable object of krypton, and Pauling was proven correct. That’s when it was discovered that krypton can indeed react under very special circumstances to form compounds like krypton difluoride.
- This is the reason why tables depicting Pauling electronegativity contain values for krypton and xenon but no values for their smaller cousins. Not even the unmatched hunger of fluorine for chemical bonds is enough to pry electrons from the clouds of helium, neon, and argon.

Rubidium
*
Rb
85.47 37

RUBIDIUM

ELEMENTAL FACTS

- Rubidium was discovered in 1861 by Robert Bunsen, who developed his special burner to create a hotter, less colored flame that would help him prospect for new elements' line emission spectra. Rubidium is named for the characteristic color it produced in his now-famous burner, as the rubidium spectrum is dominated by two *ruby*-red lines.

- Rubidium emissions may appear red to the unaided eye but actually contain many weaker emission lines of other colors. These so-called line emission spectra create something of a fingerprint for each element. This allows known elements to be identified more clearly and undiscovered elements to be detected with much greater precision. Rubidium's colorful emission spectrum makes its compounds an attractive additive to fireworks.

- In the fields of chemistry and physics, high-precision time measurements are often necessary to measure extremely fast chemical reaction rates and even observe the effects of relativity—so scientists in need of such measurements need a timepiece that ticks much faster than once per second!

- As early as the 1930s, physicists had suggested that the fundamental movements, rearrangements, and magnetic characteristics of subatomic particles might make certain atoms like rubidium useful for measuring the passage of miniscule amounts of time. And by the 1950s, the first atomic clock was born. Since then, rubidium has made its greatest impact on science as a neutral atom in atomic clocks.

RUBIDIUM REQUIRES VERY CAREFUL HANDLING. SAMPLES OF THIS ELEMENT ARE OFTEN STORED IN SEALED AMPULES TO BE CERTAIN THAT NO OXYGEN OR MOISTURE CAN REACH THE SAMPLE.

Strontium
*
Sr
87.62
38

STRONTIUM

ELEMENTAL FACTS

- The discoveries of strontium on row 5 and barium on row 6, both in group 2, were so closely linked that it was initially believed they were a single element. In 1790, Adair Crawford detected the pair of elements in a mineral sample named for the location where it was found: Strontian, Scotland. It then fell to Humphry Davy to first isolate pure strontium using his electrolysis method.

- Strontium's similar valence and size to calcium—also in group 2—allows strontium to impersonate calcium in our bodies, inserting itself into our bones. Fortunately, stable isotopes of strontium are relatively harmless when they do this.

- Unfortunately, however, there are unstable isotopes of strontium that you do not want replacing the calcium in your body, especially in your bones. These include the heavier isotope strontium-90, which is a significant product of nuclear fission that takes place in nuclear bombs and power plants. Those extra neutrons make strontium-90 radioactive. It has a half-life of 28.9 years, so when released into the environment, it has plenty of time to move around and ultimately find its way into us.

- Also unfortunately, strontium moves through the environment readily—just like calcium—and when it is inhaled or ingested, it can take up residence by displacing calcium in the bones. The strontium-90 then slowly decays, releasing high-energy electrons that can damage healthy cells and lead to cancer and other chronic health problems.

- Yet due to its lack of especially dangerous gamma radiation, medical science has harnessed strontium-90 with technologies that dispense safe, controlled, localized doses of beta radiation to help fight bone cancer and improve radiographic images.

Yttrium
*
Y
88.91
39

YTTRIUM

ELEMENTAL FACTS

- Yttrium is named for the location where it was discovered in 1787: a small quarry in the village of Ytterby, Sweden. It was there that a strange, heavy black mineral was first discovered. This mineral, named ytterbite, proved to contain a number of undiscovered elements.

- Finnish chemist Johan Gadolin isolated a substance from that mineral that he called "new earth." The alchemists' idea of earth/air/fire/water had not been entirely abandoned at the time, and the term *earth* was commonly used to refer to anything that could not be purified further. In that mineral were discovered oxides of yttrium. And that wasn't all that the minerals from Ytterby had to share. Yttrium oxide yielded oxides of terbium and erbium—all named for the same village.

- Yttrium is often used in small amounts to fine-tune the properties of other elements. Adding a bit of yttrium to aluminum plus chromium can make an alloy with unusual heat resistance. Yttrium added to aluminum plus garnet-type silicate minerals (a combination called YAG) makes a very hard, diamond-like gemstone that's used in high-power lasers.

Zirconium
*
Zr
91.22
40

ZIRCONIUM

ELEMENTAL FACTS

- Zirconium, which was discovered in 1787, is one of the most common elements in our environment.
- In 1864, magnesium powder was used to conduct the world’s first flash photography. The use of magnesium in photography lasted for more than a century before zirconium started to replace the magnesium in flashbulbs.

Niobium
*
Nb
92.91 41

NIOBIUM

ELEMENTAL FACTS

- Niobium and tantalum, vertical neighbors in group 5 of the table, share so many similarities that it was more than four decades after their initial discoveries in 1801 and 1802 that they were finally separated from one another in 1846 and conclusively proven to be separate elements.
- Even their names suggest this close relationship: *Niobium* refers to the Greek mythological goddess Niobe, daughter of King Tantalus, for whom the larger element tantalum is named.
- Niobium has significant strengthening effects when alloyed with steel and other metals. This property has made this element useful in alloys for manufacturing applications, from gas pipelines to the aerospace industry.
- Niobium can also deliver a pop of color to materials. For example, niobium has been used to produce selectively colored silver coins by several nations, including Canada and Austria. By alloying silver with niobium and then carefully and specifically oxidizing the niobium atoms in the alloy just the right amount, a range of brilliant colors can be created with the beauty and permanence worthy of collectible coins.
- Niobium also has a melting point that’s so high it originally competed with tungsten as the preferred metal for incandescent light filaments. Niobium’s high heat resistance even led to it being used as the principal metal for fabrication of rocket nozzles on some of NASA’s most famous vehicles, such as the Apollo Service Module.

Molybdenum
*
Mo
95.94
42

MOLYBDENUM

ELEMENTAL FACTS

- Discovered in 1778, molybdenum is one of the hardest metals with one of the highest-known melting points. Strangely, it was named using a Greek word for another element, lead, because one of molybdenum's common compounds, molybdenum sulfide, was known to have soft properties resembling actual lead.

- In its pure, metallic state, molybdenum is a silvery-white metal. But just like chromium above it on the table, molybdenum can adopt many different oxidation states.

- Scientists have developed ways to use molybdenum's remarkable chemistry and color to develop a sensitive test for the presence of other elements. The material commonly known as molybdenum blue, for example, is a complex substance containing both molybdenum (V) and molybdenum (VI) ions.

- When molybdenum blue is exposed to reducing materials—materials that give it some electrons—some of the molybdenum (VI) ions take on an extra electron, converting them into molybdenum (V). As the population of each oxidation state changes, so does its contribution to the color of the sample. By carefully measuring this color change, chemists can use molybdenum to determine the concentration of other elements, such as phosphorus, arsenic, and silicon.

- Although many transition elements are indeed capable of making beautifully colored compounds when combined with other elements, molybdenum and its neighbors on the table are probably best known for their uses as pure metals or alloys in engineering and construction.

Technetium
*
Tc
[98] 43

TECHNETIUM

ELEMENTAL FACTS

- Technetium was named for the fact that it does not exist in our environment and can only be created, atom by atom, in a laboratory—using technology.
- Dmitri Mendeleev's table famously predicted the existence of this element and named it eka-manganese for being the element below manganese. Some 70 years after Mendeleev's prediction, technetium was first discovered. In 1937, it was found in a piece of molybdenum foil used in other nuclear experiments that created free neutrons.
- When a stable molybdenum-98 atom captures a neutron, it becomes molybdenum-99, which is an unstable nucleus with too many neutrons. To alleviate this, molybdenum undergoes a fairly rapid beta decay to form technetium-99m, a metastable nucleus that releases gamma radiation with a half-life of 6 hours as the nucleus reorganizes itself to technetium-99. This isotope then slowly decays by a second beta emission to stable ruthenium-99, with a half-life of 211,000 years. This slow radioactive decay, paired with its remarkably powerful ability to provide corrosion resistance to steel, has actually made technetium—despite being radioactive—somewhat useful as a corrosion inhibitor.

> TECHNETIUM IS A LONE OUTPOST OF INSTABILITY SURROUNDED ON ALL SIDES BY STABLE ELEMENTS.

- Technetium is sometimes used for its radioactivity. For example, freshly prepared technetium-99m is a source of gamma rays for medical imaging.

- Studies have also shown that when cooled to about 11° above absolute zero, technetium becomes a superconductor—yet another property that may one day lead to technologies that are so valuable scientists are willing to tolerate the risks that its radioactivity poses.
- In 1952 , with technetium's help, American astronomer Paul W. Merrill proved that stars were the birthplace of heavy elements. Knowing technetium's emission spectrum and that the half-lives of its most stable isotopes—at about 4 million years—were short compared to the age of most stars, Merrill demonstrated that the technetium emission lines from certain long-lived stars were remarkably strong. He argued that since technetium's half-life was minuscule compared to the age of the stars in his study, it must have been actively forming within each star itself. It was this discovery that is widely pointed to as the first direct evidence that stars are the birthplaces of heavy elements.

> TECHNETIUM'S UNUSUAL TENDENCY TO BREAK DOWN BECAME THE KEY TO PROVING THAT STARS ARE WHERE IT IS BUILT UP, BRINGING THE ELEMENTAL STORY FULL CIRCLE.

Ruthenium
*
Ru
101.07 44

RUTHENIUM

ELEMENTAL FACTS

- Named in honor of Russia, ruthenium was discovered in 1844 by Russian-born scientist Karl Klaus.
- Six elements—ruthenium, rhodium, palladium, osmium, iridium, and platinum—make up the lion's share of a cluster of elements sometimes referred to as noble metals. The term is akin to noble gases, in that both groups are resistant to combining chemically with other elements. These metals are remarkably unreactive, even in the presence of oxygen, so no passivation is necessary to protect the noble metals from reacting further with the elements.

Rhodium
*
Rh
102.91 45

RHODIUM

ELEMENTAL FACTS

- Rhodium was named for the Greek *rhodon*, or "rose," because of the red color it contributes to several of its compounds. It is one of six very special elements—ruthenium, rhodium, palladium, osmium, iridium, and platinum—often collectively referred to as the platinum group. Elements in this group are practically unreactive. They are characterized by some desirable properties, including high melting points and corrosion resistance. These six elements, along with hanger-on neighbor rhenium, are the rarest nonradioactive elements in the Earth's crust.

- The precious metals of the platinum-group cluster together not only in the periodic table but also in nature. All five of the other metals in this cluster were discovered only in the first half of the 19th century, each of them hiding in platinum samples. Ruthenium, rhodium, palladium, osmium, and iridium were all identified in quick succession by chemists working to develop ways to dissolve platinum metal. When they succeeded, they found residues left behind that contained each of these elements.

- Since the mid-1970s, practically every vehicle produced in America, and many around the world, has been putting around town with a small sample of some of the most expensive metals on Earth in its tailpipe. There, in a small box just before the exhaust exits the system, are finely dispersed platinum-group metal coatings on heat-resistant supports. This makes it possible to harness the catalytic power of platinum—and later, palladium and rhodium—ensuring that the gaseous by-products of combustion are completely oxidized to less harmful compounds before they leave your automobile.

Palladium
*
Pd
106.42 46

PALLADIUM

ELEMENTAL FACTS

- First isolated from platinum in 1803, palladium—named for the asteroid Pallas, which was discovered the previous year—is a rare and precious metal.
- So-called noble metals—such as platinum, palladium, and gold—are often found and used in their native metallic state. These metals do not tend to rust, or combine with oxygen at all, because that would mean giving up one or more of their tightly held electrons to oxygen atoms. The higher first-ionization energies for elements like platinum, palladium, and gold suggests that this will be a difficult proposition, and oxygen just isn’t strong enough of an oxidizer to get the job done.

Silver
*
Ag
107.87 47

SILVER

ELEMENTAL FACTS

- Silver likely became part of human life by around 5000 BCE. Silver's modern name has roots in the Germanic language, but its symbol, Ag, is a nod to its Latin name, *argentum*. This name is also connected to Argentina, but in this unusual case, the country is named for the element—not the other way around. This happened around the same time that Spanish conquistadors came to believe that Argentina was home to a legendary mountain range of silver: the Sierra de la Plata.

CLASSIC COINAGE METALS—COPPER, SILVER, AND GOLD—ARE ALL NEIGHBORS ON THE TABLE.

- Silver is beautiful when in its pure form, but it will tarnish over time, slowly reacting with its environment to produce silver ions. The element reacting with silver is not oxygen—it's sulfur. The resulting silver sulfide gives silver an unattractive dark tarnish.
- Physical polishing of the object removes the silver sulfide. However, cleaning with an abrasive removes a little of the pure silver metal. It's much better to use some chemistry to convert the layer of silver sulfide tarnish back into pure silver. This trick involves the reaction of tarnished silver with aluminum foil in a hot solution of baking soda. Under these conditions, the silver ions in the tarnish and the aluminum atoms in the foil undergo a battle for electrons, with the solution acting as a medium for electron transfer. Silver is lower on the activity series than aluminum, and a lower level of activity allows the tarnished silver to take on electrons, transforming back into neutral silver atoms.

The resulting reaction converts silver sulfide back into neutral atoms while producing a bit of aluminum sulfide in the process. Producing silver in exchange for aluminum? Now that's a good deal.

- Silver's reluctance to become oxidized can be an asset in photography. Before the advent of the digital camera, photographic films relied heavily on silver. Black-and-white photographic films all contained silver halide, with silver in its +1 oxidation state. Yet when exposed to light, silver reclaims an electron from halide ions, releasing silver metal in the reaction.
- The act of developing photographic film involves chemically stripping away the remaining silver halide salts on regions of the film that were not exposed to light, leaving the metallic silver behind on the film. This creates a negative of the image on the film, with regions of the film exposed to light now darkened by the presence of metallic silver, while regions not exposed to light are transparent.

SILVER LACKS A DISTINCTIVE COLOR BECAUSE IT ABSORBS ULTRAVIOLET (UV) LIGHT. IF OUR EYES COULD DETECT UV LIGHT, SILVER WOULD INDEED APPEAR TO HAVE A UNIQUE "COLOR" AMONG THE ELEMENTS.

Cadmium
*
Cd
112.41
48

CADMIUM

ELEMENTAL FACTS

- Just below zinc on the periodic table, cadmium is named for an ore of zinc from which it was first extracted—called *cadmia* in the ancient Roman world—in 1817.

- Cadmium sulfide is a yellow pigment used by painters like Monet. In pottery glazes, cadmium can produce a distinct orange color.

- Cadmium is also featured in nickel-cadmium rechargeable batteries, which were once commonplace but have largely given way to newer technologies, such as those based on lithium and other lighter, more affordable metals. That is probably for the best, because like mercury beneath it on the table, cadmium is one of the more toxic elements.

- Although cadmium is now widely known to be toxic, sometimes cadmium's properties have remained just too useful to pass up. It makes appearances in solar panels and semiconductor technologies. The immediate cost of technologies like these can be affordable, but only time will tell if the environmental issues of working with cadmium can be mitigated to the point that they are truly viable.

Indium
*
In
114.82 49

INDIUM

ELEMENTAL FACTS

- Indium was named for an indigo spectral line that was present in an ore of zinc where it was discovered. Its low melting point makes indium (along with its neighbor tin) a go-to element in solder formulations. It has a melting point that one can achieve with a soldering iron, yet it forms a rigid, solid connection between wires that it joins.
- Some pairings of indium with other elements have shown some promise in semiconductor applications that traditionally use pure group-15 elements, whether indium with arsenic or indium with antimony. Combinations like these may even prove to be tougher and longer lasting than silicon- or germanium-based technologies.

Tin
*
Sn
118.71 50

TIN

ELEMENTAL FACTS

- Tin is one of the most common elements in the cosmos and one of the most familiar metals in our world. It's a classic metallic element that is malleable and conducts electricity and heat well. Its softness and low melting point have made it easy to find and use, even in ancient times. Evidence of tin's long relationship with humanity is enshrined on the table by its chemical symbol, Sn, which is based on its ancient Latin name: *stannum*.

- Tin was well known even in the ancient world for at least three reasons:

    1. Tin is abundant in the universe because, with an atomic number of 50, it's one of only six naturally occurring elements with a magic number of protons.

    2. Tin's chalcophilic character makes it abundant near Earth's surface, along with other sulfur-loving elements.

    3. Tin's low position on the activity series ensured that it would be accessible even to ancient peoples, who could easily smelt this element from its ore using charcoal fires.

- Beyond being easy to obtain and work with, tin does not oxidize readily. This is why tin foil and tin cans became the first widely available metal containers for foods in the 19th century.

- But tin is also a borderline metal that is so weak that pure tin metal can easily disappoint. If you put pure tin in a hot oven, expect it to melt at about 232° Celsius.

- Use of pure tin is further complicated by the fact that its physical properties can change. White tin is a shiny solid with metallike properties; gray tin is a more brittle solid. White tin can transition to gray tin when its temperature falls below just 13° Celsius.

Antimony
*
Sb
121.76 51

ANTIMONY

ELEMENTAL FACTS

- Antimony—which takes its name from Greek terms meaning “not found alone”— is commonly found mixed with other elements. In ancient times, antimony was often encountered as antimony sulfide, whereas in more modern times, antimony oxide was added to plastics as a flame retardant until concerns arose about toxicity.

- Antimony belongs to the class of elements known as the metalloids. Generally, pure metalloids are solids at normal temperatures and have a lustrous appearance. If you see a sample of antimony, you might think you’re looking at a metallic element.

- Just like the other metalloids, antimony’s behavior ranges from very metallike to very nonmetallike. When mixed with the nonmetal halogens, antimony can form a range of nonmetal compounds. Many of these compounds exist as discrete molecules with covalent bonds, such as antimony trichloride, also called butter of antimony. In this form, antimony is sometimes included in fire-retardant chemical preparations.

- Yet when antimony is mixed with metals, it forms alloys, acting like a metal. Being incorporated into the metallic bonds of lead, for example, it can significantly improve the mechanical strength of this very dense metal, making better materials for applications ranging from battery plates to boat anchors.

Tellurium
*
Te
127.60 52

TELLURIUM

ELEMENTAL FACTS

- Named for the ancient Roman earth goddess Tellus, tellurium has an especially low abundance that was a puzzle for scientists for many decades. In Earth's crust, tellurium's rarity is rivaled only by that of precious metals like gold, platinum, and palladium. Yet tellurium is a surface-tending chalcophile, not a siderophile that sinks to Earth's core.

- It turns out that tellurium's remarkable scarcity is due to its position in the oxygen-sulfur column: the chalcogens. Tellurium, just like its nonmetal siblings in group 16, tends to form small molecular compounds in combination with hydrogen. By combining so effectively with such small atoms, most of the tellurium in or near the newborn planet Earth had one of two fates:

    1. Most of the tellurium is thought to have suffered a surprising fate for such a large element. Much of the tellurium is thought to have reacted with more abundant hydrogen in the early atmosphere, making hydrogen telluride gas, which has a boiling point of –2° Celsius. On the hot, early Earth, this volatile, gaseous material could have escaped easily into space, leaving precious little tellurium in the crust for humans to discover 4.5 billion years later.

    2. But tellurium is also a chalcophile, which means it has a sulfur-loving character that would have allowed a small amount of it to find safe harbor in solid, sulfur-rich minerals that made their way to the surface and remained there. In some of those minerals, tellurium impersonates sulfur, taking its place in the mineral, while in others, it acts more like a metal, bonding with sulfur to form a solid.

- This two-sidedness is a recurring theme for metalloids like tellurium, which behave both like a metal and a nonmetal.

Iodine
*
I
126.90
53

IODINE

ELEMENTAL FACTS

- Iodine, which was discovered in 1811, is highly toxic as a pure element. Yet it forms nontoxic salts when mixed with metals. For example, sodium iodide is often added to table salt as a dietary supply of iodine, which is a crucial nutrient for human health.

- You might tend to think of iodine as a liquid, given the liquid solutions called “iodine” sold at the pharmacy, but pure iodine is a solid. Its very large electron clouds make its molecules stick to one another so well that they form a solid crystalline substance at room temperature. It’s almost like a metal.

- But heat pure iodine even gently and it becomes clear that it is no metal! Iodine melts at 114° Celsius, just above the boiling point of water. And that same iodine will boil at just 184° Celsius, where it forms a beautiful violet gas with properties and reactivities similar to chlorine and fluorine.

- Potassium iodide is a stable salt of iodine that has low toxicity and a long shelf life. It is sometimes used to treat thyroid disorders in which the thyroid gland is underproducing important hormones that contain iodine.

- The iodine-carbon bond is vitally important in our biology. The food we eat contains iodine largely as ionically bonded iodide, but this is raw material used by the thyroid to produce molecules that contain covalently bonded iodine. Iodine bonds to the carbon of an amino acid, tyrosine, to make a powerful hormone called thyroxine.

- Such iodine compounds play a crucial role in regulating human metabolism. Too many or too few of these compounds in our bodies can result in medical conditions that undermine healthy weight and energy levels.

Xenon
***
Xe
131.29 54

XENON

ELEMENTAL FACTS

- Like all of the lighter noble gases, xenon—named for the Greek word meaning “strange”—is useful in lighting applications, from automobile headlamps to theater projection bulbs, because of its inertness and its emission spectrum. Xenon’s emission spectrum has many lines that span the visible spectrum, making it appear nearly white when it is stimulated by an electrical current. This has made xenon particularly useful in applications requiring light that simulates daylight.

- The development of xenon lamps in the mid-1900s set the stage for their use in photographic flashes, ultimately pushing out the magnesium- and zinc-based flashcube technologies of the 1960s and 1970s. Instead of a metal filament that oxidizes to create light, small evacuated tubes filled with xenon are exposed to a burst of electrical current to create light that mimics daylight. Perhaps the most appealing aspect of this technology is that there is no chemical reaction taking place during the flash, so a xenon lamp can be used repeatedly without consuming the flash materials.

- Xenon has also found use in medicine as an anesthetic. It’s more soluble than its smaller noble gas cousins in a host of materials, including blood. This allows inhaled xenon to dissolve into the bloodstream and reach the brain, where it inhibits neurotransmitters.

- Shockingly, xenon participates in chemical reactions with certain electronegative elements. Xenon can react with fluorine under quite ordinary room temperatures while activated only by sunlight; it can even react with oxygen to form oxides. It has also been theorized that the formation of these or other xenon compounds deep inside Earth might partially explain xenon’s rarity in the atmosphere.

Cesium
*
Cs
132.91 55

CESIUM

ELEMENTAL FACTS

- Discovered in 1860, cesium is named for the characteristic color it produces in Robert Bunsen's now-famous burner. Cesium has strong lines in its emission spectrum that are sky blue in color, similar to a bluish-gray that in Latin was called *caesius*, which is why the element is sometimes spelled *caesium*.
- In 1955, British researchers Louis Essen and Jack Parry used cesium-133, its only stable isotope, to make the first atomic clock—one that "ticks" about 10 times a nanosecond! A cesium atomic clock ticks so rapidly and uniformly that lengths of time as short as a fraction of a nanosecond can be measured accurately.
- Cesium's dark side is due largely to one of its radioactive isotopes, cesium-137, which tends to form during human-made nuclear reactions. When these reactions release cesium-137 into the environment, very dangerous conditions result.
- Cesium-137 decays with a half-life of about 30 years. That's slow enough to ensure that once it is created and released into the environment, it will be around in gradually shrinking amounts for centuries before it's entirely gone. Even worse, radiation from cesium-137 is harmful to us whether the exposure happens inside or outside of our bodies.
- Because cesium is an alkali metal, it shares certain similarities with relatively harmless sodium and potassium. For example, cesium tends to be soluble in water, giving it a natural vehicle to distribute itself through the environment and into the tissues of animals or plants unfortunate enough to ingest it or take it in through their roots.
- All of this means that careful monitoring of environments and agricultural products is required for generations after a nuclear accident that releases cesium-137.

Barium
*
Ba
137.33 56

BARIUM

ELEMENTAL FACTS

- Barium is an alkaline-earth element obtained by British chemist Humphry Davy in 1808. In spite of its modest density for an element of its size, barium gets its name from the Greek term meaning “heavy,” in recognition of the fact that many of its compounds are extremely dense.

- Barium sulfate, for example, is added to slurries* that are pumped into wells during drilling. And because barium sulfate is nearly twice as dense as many rock-forming minerals, most rock chips generated during drilling will float to the surface of the barium sulfate slurry, where they can be removed to allow drilling to progress.

- Barium has a larger ionic radius than strontium, which makes barium sulfate more difficult for the body to absorb when swallowed. Instead, the barium sulfate coats the lining of the esophagus and digestive tract, where it can absorb x-rays, increasing the contrast in x-ray images. This can help physicians get a better picture of a patient’s digestive system.

---

* A slurry is a way to transport solid materials in a liquid.

Lanthanum
*
La
138.91 57

LANTHANUM

ELEMENTAL FACTS

- In 1839, a rare cerium mineral was discovered to also contain lanthanum, which was named for the Greek word *lanthanein*, meaning "to lie hidden." It would prove to be a great choice for the entire lanthanide series (which all behave like lanthanum)! In fact, "hidden-earth" elements might have been a better label for what are still referred to as "rare-earth" metals. They're not truly rare—they're just hidden.

- Around 1842, a near twin of lanthanum had been discovered, which was accordingly named didymium. Dmitri Mendeleev followed the best science of his day and indicated an elemental symbol of Di for an expected element with an atomic mass of 138, just between barium and cerium. But Mendeleev's choice of didymium to fill this slot in his table would prove to be a double mistake.

    1. The in-between element for his predicted slot was actually lanthanum.

    2. It finally was discovered in 1885 that didymium, far from being an element, was actually a mixture of other rare-earth metals—none of which had the predicted atomic mass of 138! It turns out that a total of five elements were hiding in the didymium.

- Hybrid and electric vehicles have large batteries that are sometimes made of nickel-metal hydride. The "metal" in the battery is mostly lanthanum, with more than 20 pounds used in each electric vehicle. They save space and weight, and they're about twice as efficient as traditional lead-acid batteries.

- Lanthanum oxide is used in the lenses of many modern cell phones, where it improves the optical quality of your snapshots.

Cerium
*
Ce
140.12 58

CERIUM

ELEMENTAL FACTS

- Discovered in 1803, cerium is an element whose name comes from the enormous asteroid Ceres, which was itself a new discovery that had excited the scientific world just two years earlier.
- A member of the so-called rare-earth elements, cerium—which most people, even today, have never heard of—is more abundant than copper. In fact, the top three most abundant members of the rare-earth group are more common than tin or lead, and the entire group (with one radioactive exception) is more abundant than silver and far more abundant than gold.
- And they're very useful, even though they're not chemical divas like gold. For example, an estimated 50 to 100 grams of cerium are used in every one of the millions of catalytic converters in vehicles around the world. In catalytic converters, cerium isn't the catalyst but rather part of the heat-resistant oxide mineral that supports it.
- Discovering these "rare" elements was only half the battle. Cerium, for example, was discovered in 1803, but it was not prepared as a pure metal until 1875. Some members of the group were not successfully purified until the 1950s.

Praseodymium
*
Pr
140.91 59

PRASEODYMIUM

ELEMENTAL FACTS

- In 1842, what was thought to be an element was discovered and named didymium—but it turned out to include a total of five elements. An Austrian scientist named Carl Auer von Welsbach cracked the separation of two of these previously hidden elements, which he named praseo-didymium (or “green” didymium) and neo-didymium (or “new” didymium). These names were later mercifully shortened to their current names, praseodymium and neodymium.

- Interestingly, the didymium mixture is still used today, as it turns out that a combination of neodymium and praseodymium strongly absorbs the intense yellow light emitted when sodium is heated to high temperatures, which is what happens during glass blowing. Protective eyeglasses are manufactured with didymium doped into the eyeglass lenses in order to protect glass blowers from eye damage that can otherwise result from the intense yellow light created by sodium in the glass.

Neodymium
*
Nd
144.24 60

NEODYMIUM

ELEMENTAL FACTS

- The most powerful permanent magnets that are readily available today are so-called neodymium magnets, a mixture of neodymium with iron and boron developed by General Motors in 1982.
- Neodymium magnets are the materials of choice in the design of electric motors for both cars and power tools. Tiny neodymium magnets are drivers for headphones, speakers, computer hard drives, smartphones, and many other modern technologies. Gigantic neodymium magnets are critical to the turbines of commercial wind power.

Promethium
*
Pm
[145] 61

PROMETHIUM

ELEMENTAL FACTS

- A quick glance at the rare-earth metals reveals that only one member of the light lanthanides subgroup sports an integer atomic mass: element 61, promethium.

- This is reminiscent of element 43, technetium, the lightest element for which there is no stable isotope. There's no natural abundance of isotopes to provide an average atomic mass.

- Instead, the mass of promethium's most stable known isotope, 145, is displayed in the corner of its cell on the table. Because no stable isotope of promethium exists, it gave elemental explorers all the same fits that technetium famously did.

- An element for this location was proposed as early as 1902 by Czech chemist Bohuslav Brauner, who noted that the significant gap in atomic mass between neodymium and samarium might leave room for a new undiscovered element. Shortly after that, atomic number measurements that were calculated by British physicist Henry Moseley made it clear that Brauner was right: Element 61 should exist but had not yet been observed.

- Yet for decades after that, one highly capable chemist after another—specializing in rare-earth elements—tried and failed to find element 61. It was not until 1945 when element 61 was first positively detected at what is now Oak Ridge National Laboratory in Tennessee as physicists there analyzed the by-products of uranium fission. As larger uranium atoms split into smaller pieces during test reactions, small amounts of element 61 were detected for the first time.

- In recognition that this element was forged in the most powerful "fire" ever created, element 61 was named promethium, for Prometheus, the Titan in Greek mythology who stole fire from the gods and delivered it into the hands of humanity.

Samarium
*
Sm
150.36
62

SAMARIUM

ELEMENTAL FACTS

- Discovered in 1879, samarium was named for samarskite, the mineral from which it was isolated.
- Samarium, a rare-earth metal, can be alloyed with the ferromagnetic element cobalt, from the so-called iron triad of magnetic elements, to produce remarkably strong permanent magnets. This made it possible to shrink electronic devices like headphones, effectively launching the portable music player market in the 1970s.
- Certain Fender guitars around the start of the 21st century used this alloy in the guitar pickups that translate the vibration of strings into electrical signals.

Europium
*
Eu
151.96 63

EUROPIUM

ELEMENTAL FACTS

- Europium, which is quite clearly named after Europe, was found hiding in samarium by French chemist Eugène-Anatole Demarçay in 1901. It is one of the rarest of the so-called rare-earth elements.
- Largely unnoticed, the rare-earth elements have become unsung heroes in a host of modern technology applications. For example, the red emission spectrum of europium made the breakthrough to color television possible in the 1960s. And europium has remained a cornerstone of vibrant reds in color monitors ever since.

Gadolinium
*
Gd
157.25
64

GADOLINIUM

ELEMENTAL FACTS

- Named for Finnish chemist Johan Gadolin, who first isolated many of the lanthanoid elements, gadolinium is ferromagnetic in its pure form at room temperature.

- Each individual gadolinium (III) cation is a powerful, atomic-sized magnet. Radiologists take advantage of this property, formulating gadolinium (III)–containing compounds that can accumulate in certain tissues of the human body, changing how the atoms and molecules in that tissue react to applied magnetic fields. In magnetic resonance imaging (MRI), gadolinium (III) compounds are often used to enhance contrast in the images that are produced.

- Gadolinium has six stable isotopes and the greatest ability to capture neutrons of any element. In medicine, neutron radiography uses a gadolinium screen for neutron imaging. In nuclear power plants, gadolinium's ability to absorb excess neutrons is the most powerful way to prevent a runaway chain reaction during fission.

Terbium
*
Tb
158.93
65

TERBIUM

ELEMENTAL FACTS

- Terbium is one of several elements that are named for the Swedish village of Ytterby, where a mineral named ytterbite was discovered in a small quarry in 1787. Finnish chemist Johan Gadolin isolated a substance from that mineral in which oxides of the elements scandium and yttrium were discovered. Yttrium oxide yielded oxides of terbium and erbium—which were so hard to tell apart that their names switched in around 1860.
- Terbium, which is ferromagnetic in its pure form at room temperature, is used in solid-state drives in computers and other electronics for data storage. Terbium also helps to make up the green and blue phosphors that make for full-color displays.
- Use of terbium in the phosphors of x-ray imaging screens made it possible for patients to receive radiation for only one-quarter of the time needed for earlier x-rays.

Dysprosium
*
Dy
162.50
66

DYSPROSIUM

ELEMENTAL FACTS

- Dysprosium, one of the most elusive of the many metals to come out of Ytterby, Sweden, is from the Greek *dysprositos* for the property of being “hard to obtain.”
- Like gadolinium and terbium, dysprosium is an element that’s ferromagnetic in its pure form at room temperature. But these rare-earth elements have other uses beyond the production of ferromagnetic materials. For example, dysprosium combined with the halogen element iodine makes halogen lighting. The dysprosium vaporizes under intense heat and offers a wide emission spectrum, similar to natural light.

Holmium
*
Ho
164.93 67

HOLMIUM

ELEMENTAL FACTS

- Four very similar elements—yttrium, terbium, erbium, and ytterbium—were all named for the village of Ytterby in Sweden. But when even more hidden elements were discovered together with erbium, the next names went broader: Holmium was named for Stockholm.
- Holmium, along with erbium and thulium, has the potential to be ferromagnetic if placed under sufficiently cold conditions. However, these elements only become ferromagnetic at extremely low temperatures—even colder than liquid nitrogen.

Erbium
*
Er
167.26
68

ERBIUM

ELEMENTAL FACTS

- Erbium is one of four elements named directly for the Swedish village of Ytterby, where they were discovered. Like holmium and thulium, erbium can become ferromagnetic at extremely low temperatures.
- Erbium is used to amplify light. This is useful both to amplify the signals carried by fiber-optic cables and to amplify the light of lasers that dentists and dermatologists can use without delivering a corresponding increase of heat.

Thulium
*
Tm
168.93
69

THULIUM

ELEMENTAL FACTS

- Thulium got its name from Thule, an old name for Sweden, which is where it was discovered. Like its neighbors holmium and erbium, if thulium is placed under sufficiently cold conditions—temperatures even colder than liquid nitrogen—it has the potential to be ferromagnetic.
- Out of all the rare-earth elements, thulium is the second rarest. It's used not only in high-temperature conductors but also in the manufacture of lasers and of ceramic magnetic materials for microwaves.

Ytterbium
*
Yb
173.04 70

YTTERBIUM

ELEMENTAL FACTS

- Ytterbium is one of no less than four elements named directly for the Swedish town in which they were discovered—Ytterby—with additional names marking even more elements found in that same location. Ytterbium was found contained in samples of erbium, another one of those four elements.
- Ytterbium is classified as a rare-earth element. Despite this name, such elements are actually pretty common on Earth's surface. They are rare compared to the most common elements, but compared to many of the elements that have been known since ancient times, calling them rare is a bit of a misnomer.

Lutetium
*
Lu
174.97 71

LUTETIUM

ELEMENTAL FACTS

- Lutetium’s name comes from the Roman name for Paris (“Lutetia”), which is where it was discovered in 1907.
- Lutetium is a heavy rare-earth element. The presence of heavy rare-earth elements like lutetium in minerals can increase the density of those minerals, causing them to partition deep within the Earth’s crust near (or possibly even in) the mantle—a place that no human drill has ever penetrated. Naturally, this makes heavy rare-earth elements harder to come by in our immediate environment.

Hafnium
*
Hf
178.49 72

HAFNIUM

ELEMENTAL FACTS

- Hafnium's name comes from the Latin name for Copenhagen ("Hafnia"), where it was discovered. Due to its similarity to the element zirconium, hafnium wasn't discovered for more than a century after zirconium was found: Small amounts of hafnium had been hiding in much more abundant zirconium samples the entire time.
- For elements like hafnium (including scandium, yttrium, and zirconium), a genuine noble gas configuration is reliably within reach. Because their path is so easy, these elements consistently form cations of just one common valence, which is +4 for hafnium.

Tantalum
*
Ta
180.95
73

TANTALUM

ELEMENTAL FACTS

- Tantalum and niobium aren’t just vertical neighbors on the table. These two elements in group 5 share so many similarities that it was more than 40 years after their initial discoveries in 1801 and 1802 that they were finally separated from one another in 1846 and conclusively proven to be separate elements.
- Their similar electron configurations and similarly sized atomic radii cause them to often be found comingled in nature, sharing similar spaces in minerals like columbite.
- Even their names suggest this close relationship: *Niobium* refers to the Greek mythological goddess Niobe, daughter of King Tantalus, for whom the larger element tantalum is named.
- Tantalum is a hard, high-melting-point metal with a colorful chemistry. Like niobium, tantalum is useful in alloys for manufacturing applications.

Tungsten
*
W
183.84
74

TUNGSTEN

ELEMENTAL FACTS

- Because tungsten was isolated from a mineral called wolframite, many 19th-century chemists adopted the name wolfram for this element—and so did the International Union of Pure and Applied Chemistry (IUPAC), after its founding in the 20th century. However, strong protests from the United States resulted in an exception permitting the use of *tungsten* in English. But then, as English became the official language of the IUPAC, *wolfram* eventually lost out to *tungsten* at the IUPAC as well. Still, the symbol W has persisted, almost like a consolation prize for the alternate name that's still favored in some parts of the world.

- Discovered in 1783, tungsten is the element with the highest melting point on the entire table. With its staggeringly high melting point, hardness, and electrical conductivity, tungsten is used in electrical lighting and industrial cutting tools where high-heat resistance is a must. Tungsten filaments can tolerate the extreme heat released when they generate light in incandescent lightbulbs without melting the filament.

> TUNGSTEN FILAMENTS CAN BE HEATED TO WHITE-HOT TEMPERATURES AND REMAIN SOLID.

- Thankfully, tungsten has two stable isotopes. This means that tungsten can be used, for example, to forge conventional military munition projectiles with the density and hardness of so-called depleted uranium—but without the radiological, toxicological, and environmental challenges that depleted uranium poses. Many modern armor-piercing munitions are made partially or completely of tungsten.

- Tungsten was even once considered for the payload of a weapon that could deliver the destructive force of a tactical nuclear bomb but without any of the radioactive fallout.

Rhenium
*
Re
186.21 75

RHENIUM

ELEMENTAL FACTS

- In 1925, an attempt to discover elements below manganese did succeed in finding an element just below technetium. That element is rhenium, element 75.
- Rhenium's detection in 1925 made it the second-to-last stable element ever discovered. German chemists Walter Noddack and his future wife, Ida, named element 75 rhenium in honor of the Rhine River in Germany, near Ida's birthplace.[*] They managed to find rhenium because stable atoms of element 75 are present, though rare, in Earth's crust. This heavy, iron-loving element with an odd atomic number has rare written all over it. And indeed, it is only about one part per billion in Earth's crust.
- Although it is rare, rhenium does have a stable isotope and is a valued element for its high melting point—third highest on the table after tungsten and carbon. It can be found alloyed with tungsten and molybdenum in oven and lamp filaments. Some of its alloys even have superconducting properties.

---

[*] The couple had hoped to name element 43 masurium after the region in Prussia that Walter had come from, which would have made them the only husband-and-wife pair with neighboring elements on the table. Unfortunately, they never actually discovered element 43 (technetium).

Osmium
*
Os
190.23
76

OSMIUM

ELEMENTAL FACTS

- Osmium—with a density nearly three times that of iron—is the densest element on the entire periodic table. Osmium is one of six very special elements that are often referred to as the platinum group, which is so named because each of the metals in this cluster were found hiding in platinum samples.

- All six of the platinum-group elements tend to cluster together, both on the table and in nature. But the pair of osmium and iridium is especially cozy. They mix so well and so easily that they are often found in nature as an alloy. These alloys historically have gone by name mash-ups reminiscent of a Hollywood couple. When the alloy has a greater percentage of iridium, it has been called osmiridium; when osmium is dominant, the alloy has taken the name iridosmine.

- Both have a relatively low abundance compared to many of the lighter transition metals; they are far less common than even the precious metals platinum or gold. Most of the iridium and osmium that was part of the early Earth more than 4 billion years ago sank into the iron-rich core along with the other siderophilic, or iron-loving, elements. Odd-numbered iridium is even more scarce than even-numbered osmium, as the Oddo-Harkins rule predicts.

- Despite their scarcity, osmium and iridium are sought-after metals for specialty applications. Their extreme hardness and high melting points, combined with their high resistance to corrosion, make them both a great choice for the manufacture of mechanical bearings and electrical contacts in spark plugs.

OSMIUM AND IRIDIUM, TWO EXCEPTIONALLY RARE ELEMENTS ON EARTH, ARE THE GOLD STANDARD OF DURABILITY AND HEAT RESISTANCE IN ENGINEERING.

Iridium
*
Ir
192.22
77

IRIDIUM

ELEMENTAL FACTS

- Because of its extreme scarcity on Earth’s surface, iridium offered a critical clue to unravelling the greatest murder mystery in Earth’s history.
- The detectives who solved the case were Luis Alvarez, a physics Nobel laureate and Manhattan Project veteran, and his geologist son, Walter. Together, they formulated the theory that a tremendous spike in iridium levels found in a layer of rock from 65 million years ago might explain the extinction of the dinosaurs.
- Although iridium is a siderophile that is rare in Earth’s crust, it is actually much more abundant in our solar system. Not only is there likely to be much more iridium trapped in the core of the planet, but there is also much more iridium in our solar system that didn’t begin on our planet.
- Countless meteoroids are in motion in our solar system. These rock and metal bodies sometimes got so large that they went through a process of differentiation—not unlike our planet did 4.5 billion years ago—only to be smashed into pieces again later. So, the individual pieces of these heavenly bodies can have elemental profiles that are often quite different from Earth’s surface. Those that are metallic in composition are much, much higher in iridium content than the surface of our planet.
- This means that when metallic meteoroids fall to Earth as meteorites, they can deliver huge quantities of scarce metals like iridium to Earth’s surface. If such an impact were of sufficient energy, that iridium could be scattered across the entire globe, leaving evidence of the impact that might endure in the geologic record for millions of years.

- The Alvarezes took samples from a stretch of limestone in central Italy that was known to have been deposited about 65 million years ago—the time period during which the dinosaurs suddenly vanished from Earth. Using a technique called neutron activation analysis, they were able to determine the iridium content of the geological samples.
- The results of their 1980 study were jaw-dropping: The iridium levels in the narrow band of clay dated to 65 million years ago were 100 times higher than nearby rocks formed just before and after the event was thought to have taken place.
- In the following years, others joined the search and found high levels of iridium in rocks from the same time period in many other places around the world.

PROBABLY THE GREATEST IMPACT OF IRIDIUM ON SCIENCE WAS ITS USE IN UNDERSTANDING WHAT CAUSED THE EXTINCTION OF THE DINOSAURS.

- Final vindication of their theory would come in 1991, when evidence connected the worldwide iridium anomaly to a massive crater just off the Yucatán Peninsula in Mexico. The meteorite that killed the dinosaurs had been tracked down, and a 65-million-year-old cold case solved, thanks to clues left by iridium.

Platinum
*
Pt
195.08
78

PLATINUM

ELEMENTAL FACTS

- From the Spanish word *platina*, or “little silver,” platinum occurs as a native metal in nature and was discovered by pre-Columbian Indians. For centuries, platinum was highly valued and used in South America as an ornamental material.
- Elements in the so-called platinum group have an interesting ability to accelerate certain desirable chemical reactions simply by being present. Chemists call the process catalysis.
- Part of the reason that platinum-group metals make such desirable catalysts is their own inertness. To be a catalyst, the material itself must simply promote chemical reactions without actually being consumed or produced.
- Probably nowhere has the catalytic power of the platinum-group metals been more influential in the past century than in the automotive industry.
- Fuel chemistry can be complicated, and the exact chemical composition of a motor fuel can profoundly impact fuel performance and cleanliness when used.
- By the 1950s, it was known that platinum had the ability to alter the chemical composition of hydrocarbons in petroleum products. However, most balked at the remarkably high cost of platinum.
- But American chemist Vladimir Haensel understood that platinum’s effect was catalytic—that the platinum itself would not be consumed in any process it promoted—and that the catalysis took place only at the surface of the metal.
- Haensel developed highly dispersed platinum coatings on tough, inexpensive support materials like alumina, creating a solid material that had the same catalytic power as a pure platinum ingot with similar surface area—but at a vast fraction of the cost.

Gold
*
Au
196.97
79

GOLD

ELEMENTAL FACTS

- Gold is famous for being found most often as a dense native metal that can be separated from surrounding rock and soil through the simple act of panning. This is only possible because gold is so unreactive that it is often classified as a noble metal.

- But given that gold is so dense and is classified as an iron-loving siderophile, why are we able to find any appreciable amount of gold on Earth's surface? Shouldn't most of it have sunk to the center of the planet?

- Geologists believe that most of the Earth's initial gold did, indeed, sink to the core during differentiation. However, it is believed at least some of the gold found on Earth's surface may have been delivered by extraterrestrial bodies that impacted the cooling Earth after differentiation took place.

- Being so far below hydrogen on the activity series, gold even resists dissolution in most acids, which is different from many other elements that are commonly alloyed with gold to provide hardness.

- Because of its softness, gold is often alloyed with copper, silver, nickel, and other metals to increase its durability without altering its appealing appearance.

- The noble nature of gold makes it fairly easy to test any object suspected to contain less-noble materials. This is, in fact, the origin of the term *acid test*. If the composition of a gold object is in question, a jeweler might scrape a small amount of the metal off using what is called a touchstone. The resulting metal dust is then exposed to increasingly strong acidic solutions in order to see if the metal dissolves or discolors. If it does, it must contain more-active metals that are closer to or higher than hydrogen on the activity series.

Mercury
**
Hg
200.59
80

MERCURY

ELEMENTAL FACTS

- Mercury—the only metallic element that melts below room temperature—is named for the planet, which is itself named for the Roman god. Mercury's symbol, Hg, refers to its Latin name, *hydra-gyrum*, or "liquid silver." Due to elemental mercury being such an unusual liquid, many ancient cultures believed that it had healing powers.

- But in reality, elemental mercury's liquid state makes it particularly dangerous to our health. Those health problems are thought to be linked to mercury's chalcophile, or sulfur-loving, nature. Mercury associates strongly with sulfur atoms in critical enzymes in the body, disrupting our biochemistry and making us sick. Acute mercury poisoning is sometimes treated with selenium, a much less toxic metalloid that can impersonate sulfur, interacting with the mercury and keeping it tied up, where it can't interfere with our biochemistry.

- Mercury is responsible for the famous trope "mad as a hatter," an expression that originated in 1830s England, where it was commonly known that those in the hat-making profession seemed to have a high incidence of mental illness in their later years. At the time, felt production for hats often involved mercurous nitrate, a salt of mercury that proved deadly when inhaled daily over the course of a career making hats.

- Yet elemental mercury's other properties have continued to make it a widely used material. Mercury used in thermometers can measure temperatures as low as −39° Celsius before the mercury freezes. Electrical switches used the movement of liquid mercury to create or interrupt a circuit. Barometers, in which dense liquid mercury shifts by just a few millimeters under changing pressure, allow for a more compact instrument.

Thallium
*
Tl
204.38 81

THALLIUM

ELEMENTAL FACTS

- Thallium—from the Greek *thallos*, meaning “green twig”—was named for the beautiful green glow it emitted during flame ionization tests when it was first discovered in 1861. As a chalcophile, thallium is more abundant in the Earth’s crust than most precious metals.

- Like mercury, thallium is a notoriously toxic heavy metal. Thallium poisoning can be rapid, severe, and often deadly. Agatha Christie wrote a detective story in 1961 that brought wide attention to the fact that thallium’s deadly effects can resemble illness and might be used to get away with murder. Thallium’s quick action also made it the active substance in rat poison for many decades in the mid-20th century—until its analogous toxicity in humans led many governments to ban or restrict its use in the 1970s.

- Thallium can lose just one electron to become the poisonous thallium (I), which has a charge of +1, just like potassium. And with four times as many protons in its nucleus, thallium pulls its electron cloud in, making thallium’s ionic radius about the same size as potassium’s. The result is that thallium (I) ions can go just about anywhere in the body that the essential element potassium can.

Lead
*
Pb
207.2 82

LEAD

ELEMENTAL FACTS

- Lead was a material of choice for the construction of plumbing systems as early as ancient Rome and as recently as the 1900s. Its chemical symbol, Pb, is based on its ancient Latin name, *plumbum*—which is also the origin of the word *plumbing*.
- Lead has the heaviest stable nucleus ever discovered. Because of this, lead finds itself as the final destination for virtually every radioactive decay chain associated with uranium or thorium.
- Lead is added to many products, such as paints and glass, to enhance durability, color, and workability. Unfortunately, lead is also a poison that can cause lifelong health problems, which is why many products using lead are heavily restricted or even banned.
- Part of lead's toxicity lies in the fact that once ingested, lead can impersonate calcium ions in the body, both in bones and in the nervous system. And lead has a biological half-life of about 25 years. This means that lead exposure at high levels can effectively cause lifelong medical problems—particularly for anyone exposed at an early age, when bone growth and nervous system development are at their height.
- In the early days of automotive engineering, engine knock was a pesky problem in which gasoline detonated prematurely in an engine cylinder, producing an annoying noise and ultimately increasing engine wear or damage. Thomas Midgley Jr., a chemist working for General Motors in the 1920s, created a gasoline formulation that reduced knocking in engines. He called his creation leaded gas: gasoline with lead dissolved in it. Unfortunately, the toxic nature of lead left a trail of sickness and death in the wake of this product.

Bismuth
*
Bi
208.98 83

BISMUTH

ELEMENTAL FACTS

- In the 1400s, the heavy metal bismuth was noticed as distinct from lead, just in time to be alloyed with lead to make cast type for the printing press.

- Metallic bismuth is famous for its tendency to form beautiful cubic crystals with a multicolored sheen produced by a layer of its oxide. But bismuth—whose name comes from the German *Bisemutum*, meaning "white mass"—is a weak metal that can occasionally behave more like a metalloid or nonmetal in compounds.

- Just like the metalloid antimony, bismuth can form discrete molecules in combination with nonmetals, such as bismuth chloride (butter of bismuth). This kind of bonding behavior is also observed in the over-the-counter medication bismuth subsalicylate, sold as Pepto Bismol.

EVERY ELEMENT AFTER LEAD—STARTING WITH ELEMENT 83, BISMUTH—EXISTS ONLY IN A RADIOACTIVE FORM.

- In 2003, a group of French physicists discovered that what had been thought to be bismuth's one stable isotope, bismuth-209, instead has a half-life that is 1 billion times the age of the universe so far! This decay is so slow that bismuth-209 is generally considered safe.

- Nuclear scientists can synthesize milligram quantities of polonium, which is vanishingly rare in the environment, using readily available bismuth-209 as the starting material. Bismuth-209 can be bombarded with neutrons to produce atoms of much less stable bismuth-210, which undergoes a beta decay with a half-life of just about 5 days. So, in a matter of a month, you have a deadly sample of pure polonium-210.

Polonium
*
Po
[209] 84

POLONIUM

ELEMENTAL FACTS

- Polonium was named for Poland, the homeland of its famed co-discoverer Marie Curie, who extracted it from a uranium ore known as pitchblende. It's easy to see how the polonium got there: Polonium makes multiple appearances in the decay chains for both primordial isotopes of uranium as well as primordial thorium-232.

- Polonium is a highly radioactive element that decays quickly, with half-lives as short as 100 days to as long as 100 years, depending on the isotope. Polonium decomposes so quickly that it leaves no significant isotopic abundance to report. Instead, the most stable isotope, synthetic polonium-209, is usually used for this value.

- Polonium may be vanishingly rare in the environment, but nuclear scientists can synthesize milligram quantities of polonium using readily available bismuth-209 as the starting material, resulting in polonium-210, with a half-life of about 138 days.

- In 2006, polonium-210 was implicated in the assassination of former Russian spy Alexander Litvinenko. It was estimated that less than 1 microgram of polonium-210 had been administered to Litvinenko by dissolving it in a cup of tea, ensuring that it was ingested by the victim.

Astatine
*
At
[210] 85

ASTATINE

ELEMENTAL FACTS

- The patterns in the properties of fluorine, chlorine, bromine, and iodine led Dmitri Mendeleev to predict an even heavier halogen he called eka-iodine in some of his earliest tables. But atomic number 85 has a nucleus that is too big to ever be stable. It was not until 1940 that Dale Corson, Kenneth MacKenzie, and Emilio Segrè finally succeeded in creating just a few atoms of this heavy halogen in a particle collider at the University of California, Berkeley.
- All 39 isotopes of astatine that have ever been investigated decay radioactively, with the longest lasting, astatine-210, decaying with a half-life of just 8.1 hours.*
- Even the simplest properties of this element, such as its melting and boiling points, can only be estimated based on calculations and trends in the periodic table. If a pure sample of astatine-210 were ever prepared, it is estimated that the heat given off by its extreme radioactivity would vaporize the sample before its physical properties could be studied—hence its name, which is from the Greek *astatos*, meaning "unstable."
- During its short life, astatine can bond to itself, forming diatomic molecules the way other halogens do. And it can bond with other halogens to form interhalogen compounds, such as astatine iodide. Researchers have proposed that astatine-211, which has the same halogen chemistry as iodine, might be useful in targeted radiation therapy for thyroid cancer. The thyroid naturally accumulates iodine to synthesize thyroid hormones, so a freshly prepared iodine-astatine compound might be able to reach the thyroid before decaying and trick it into accumulating the astatine at the site of the cancer, where its radiation might help kill cancer cells.

---

* This fact is acknowledged in most modern periodic tables, where astatine's atomic mass is reported simply with a parenthetical, "(210)," which indicates that astatine-210 has remained the most stable isotope observed.

Radon
***
Rn
[222] 86

RADON

ELEMENTAL FACTS

- Radon was the last of the naturally occurring noble gases to be discovered (in 1900). This shouldn't be too surprising, since radon's most stable isotope, radon-222, has a half-life of only about 3 days.

- Radon is itself radioactive, serving only as a link in the decay chains of the heavier elements uranium and thorium. In fact, radon is named in recognition of the element radium being the immediate source material for radon in the uranium decay chain.

RADON COMBINES THE HEALTH RISKS OF RADIOACTIVITY WITH THE MOBILITY OF A GAS.

- In regions that have significant uranium or thorium content near the surface, that radioactive material is constantly and slowly decaying away. When uranium's most common isotope, uranium-238, decays, one of the stops along its decay chain is radon-222. When thorium's most common isotope, thorium-232, decays, it passes through radon-220. Whichever path it takes, radon gas has a huge atomic weight, with a density roughly eight times that of air, so if radon gas happens to form under your house, it can easily remain trapped there for long periods of time.

- When breathed in, the decay products of radon atoms expose your lungs to several damaging alpha particles. And radon delivers this damage as it continues to decay, becoming polonium, thallium, mercury, and finally lead—all elements known to be toxic in their own ways.

- Avoiding long-term radon exposure is important to your health. So these days, for nearly every real estate transaction in areas with significant uranium or thorium content near the surface, a radon test is ordered and a remediation is put in place if levels of radiation are too high.

Francium
*
Fr
[223] 87

FRANCIUM

ELEMENTAL FACTS

- Francium plays hide-and-seek better than almost any other element. It was only discovered in 1939, even though Dmitri Mendeleev had predicted the existence of an eka-cesium element 70 years earlier. In fact, francium was the last element ever discovered in nature.

- The main reason francium was so elusive is that the nucleus of francium itself is unstable; francium's nucleus lacks any stable isotope whatsoever. The isotope that lasts longest, francium-223, forms as part of the decay chain of uranium-235, which is already a rare isotope of uranium. And each atom of francium-223 only lasts for about 22 minutes before undergoing a radioactive beta decay that converts it into its neighbor radium. That means that within about 4 hours, all of the francium-223 in any given sample is effectively gone!

- Because francium's radioactive decay happens so rapidly, only about 30 grams of naturally occurring francium are present anywhere in Earth's crust at any given time. At its estimated density, that would be enough francium to fill one-quarter of a shot glass. And if you could somehow amass all the world's francium atoms in a shot glass at breakfast, by dinnertime its contents would completely convert to radium!

- So the discovery of naturally occurring francium meant finding just a few atoms. This remarkable accomplishment was made by Marguerite Perey* of the Curie Institute in Paris, France—where the element got its name.

- To this day, there is no practical use for francium, since not even a weighable amount of the element has ever been obtained from nature or produced in a lab.

---

* Perey was able to detect the formation and subsequent decay of francium atoms in a sample of actinium-227, its precursor in the uranium-235 decay chain.

Radium
*
Ra
[226] 88

RADIUM

ELEMENTAL FACTS

- Radium was discovered in 1898 by Marie Curie, who had been working with a uranium-containing mineral called pitchblende when her sample continued producing radiation after she extracted the uranium. This led her to conclude that there must be a second radioactive element within the pitchblende. Her hypothesis proved correct when she finally isolated that element in 1910, naming it radium.
- There are no stable isotopes of radium. Radium-226, for example, forms from the decay of uranium-238 and boasts a half-life of 1,600 years, giving it plenty of time to accumulate in pitchblende. As radium decays, it produces ionizing radiation—gamma radiation intense enough to rip electrons from air molecules—which can be used to excite some compounds to the extent that they emit visible light. In other words, when radium is combined with the right materials, such as zinc sulfide, the mixture will glow.
- Shortly after radium's discovery, manufacturers began producing paints containing radium and zinc sulfide that would glow in the dark for years, or even decades, until the light-emitting compounds degraded.
- In the late 1910s and early 1920s, companies opened factories to produce luminous, glow-in-the-dark watch dials using this newly developed technology. The factories were staffed by about 4,000 women hired to apply the companies' luminous paint formulations to the hands and dials of watches or clocks.
- But before long, workers began to fall ill and even die from mysterious illnesses, such as bone cancer, anemia, and a condition known as radium jaw. Several lawsuits resulted and ultimately led to a significant surge in stronger protections for American workers.

Actinium
*
Ac
[227]
89

ACTINIUM

ELEMENTAL FACTS

- Actinium was discovered in 1899 by André-Louis Debierne, one of Marie Curie's proteges. Debierne's work is especially impressive, as he successfully isolated the only known naturally occurring actinium isotope, actinium-227. And it wasn't easy! Pitchblende itself is about 85% uranium by mass, but this isotope of actinium forms as a decay product of uranium-235, which itself makes up only about 0.7% of all uranium atoms in nature. With a half-life of just 21.7 years, actinium-227 is also fairly quickly consumed as the decay chain continues on its way to lead-207.

> THE ACTINOIDS WITH ODD ATOMIC NUMBERS, STARTING WITH ACTINIUM AND PROTACTINIUM, HAVE ROLES IN MAJOR NUCLEAR DECAY CHAINS THAT MAKE THEM OF INTEREST TO NUCLEAR SCIENTISTS. BUT THEIR VANISHINGLY LOW ABUNDANCE MAKES THEM RELATIVELY USELESS AS RAW MATERIALS.

- Because of the low abundance of its parent nucleus, uranium-235, and the short half-life of actinium itself, 1 ton of pitchblende is expected to contain only about 150 milligrams of actinium.

Thorium
*
Th
232.04
90

THORIUM

ELEMENTAL FACTS

- Because the atoms making up thorium and uranium on Earth have mostly existed since before the creation of our planet, these elements can be called primordial. Thorium's most stable isotope has a half-life of 14 billion years—nearly the age of the universe!
- As a proportion of Earth's crust, thorium and uranium are about as common as lead or tin. Thorium, in part because it decays even more slowly, is roughly three times more abundant than uranium. More than 99.98% of thorium on Earth occurs as its most stable isotope, thorium-232.
- Thorium was discovered in its oxide form in 1828 by Jöns Jacob Berzelius. Before the discovery of neutrons and the isotopes they create, thorium was mistaken for a new element. In 1908, it was determined that element 88, radium, forms from the alpha decay of a then-unknown larger nucleus. The unknown parent atom for radium was hastily named ionium by its creators. After the discovery of the neutron two decades later, it was realized that so-called ionium was simply a second, much less common isotope of thorium: thorium-230. This isotope has a half-life of 75,000 years and is itself produced by the nuclear decay of the long-lived uranium-238.
- Thorium is used in geologic dating. In fact, the technique of ionium-thorium dating relies on the assumption that both thorium-230 and thorium-232 are chemically identical but one is primordial while the other is a product of uranium decay. Once locked in a mineral or sediment, each isotope decays but at vastly different rates: 75,000 years versus 14 billion years. By comparing the ratio of these two isotopes in geologic samples, dates up to 400,000 years can be accurately determined.

Protactinium
*
Pa
231.04 91

PROTACTINIUM

ELEMENTAL FACTS

- Element 91 first went by another name when it was discovered in 1913. Its discoverers found it as an intermediate in the uranium-238 decay chain and suggested the name brevium in recognition of its 1.17-minute half-life.

- Over the next several years, the name brevium and the elemental symbol Bv were widely adopted and actually published in more than a few tables.

- Ironically, the name brevium would itself have a short life. Just a few years later, in 1917, Lise Meitner uncovered the much more stable, longer-lived isotope of element 93 that precedes actinium in uranium-235's decay chain. The isotope that would have been called brevium-231 actually has a much longer half-life of more than 10,000 years. Since this was not so brief, and indeed it was much longer-lived than any isotope of actinium, Meitner and collaborator Otto Hahn published a paper suggesting the name protoactinium to recognize its position prior to actinium in the same uranium-238 decay chain.

- Protoactinium was quickly adopted as the preferred name of element 91, as can be seen in a periodic table authored by H. G. Deming and published in the US by Wiley in 1923. It uses our current elemental symbol, Pa, but still reports only the larger atomic mass of its most stable isotope, 234. Ultimately, the name was shortened to protactinium, which is the name that's still used today.

Uranium
*
U
238.03
92

URANIUM

ELEMENTAL FACTS

- *Uranium* was the name originally given to a uranium oxide compound isolated in 1789 by German chemist Martin Klaproth. Uranium was named for the planet Uranus, which itself had recently been discovered and named—after the Greek mythological personification of heaven.
- Uranium is about 500 times more common in our environment than the precious metals gold, platinum, or palladium. More than 99% of uranium on Earth takes the form of uranium-238, with a half-life of almost 4.5 billion years—roughly the same amount of time as Earth's entire life so far.
- By the late 1800s, it had already been discovered that uranium samples had the curious property of emitting a type of radiation that could expose photographic plates. French physicist Henri Becquerel had theorized that uranium, much like other phosphorescent materials he had been studying, had the ability to absorb sunlight and convert it into a much higher-energy form of light, which was reemitted from the uranium atoms.
- He tested his idea by placing uranium samples into sunlight, exposing photographic paper to the uranium, and finding that an image was produced. But one cloudy day in 1896, Becquerel decided to forgo his experiment and placed it in a dark desk drawer. To his surprise, when he developed the photographic paper, he again found a distinct image, just as he had in the samples exposed to sunlight. Thus, he disproved his own hypothesis that uranium's high-energy emissions were merely reemitted light derived from an external source. Instead, the radiation originated with the uranium atoms themselves.

NONE OF THE REMAINING ELEMENTS IN THE TABLE—FROM ATOMIC NUMBER 93 TO 118—HAS EVEN A SINGLE PRIMORDIAL ISOTOPE THAT CAN BE OBTAINED FROM NATURAL SOURCES.

Neptunium
*
Np
[237] 93

NEPTUNIUM

ELEMENTAL FACTS

- In the 1930s and 1940s, nuclear physicists started to ask whether new elements—even more massive than uranium—might be created by bombarding uranium itself with neutrons. In theory, captured neutrons could throw the ratio of protons to neutrons outside the optimal ratio. Could nuclei with a big excess of neutrons respond by emitting a beta particle (a high-energy electron), converting one or more of the extra neutrons into protons? If so, would that reestablish a more optimal proton-to-neutron ratio and produce new, heavier nuclei with higher atomic numbers?

- Proof of this concept was offered in 1940 by Edwin McMillan and Philip Abelson, who achieved the synthesis of element 93 using this technique of irradiating uranium with low-energy neutrons. During this process, several nuclear reactions take place, but the reaction of interest is the capture of two neutrons by uranium-235. The resulting uranium-237 is more strongly radioactive and decays by the emission of a beta particle with a half-life of just 6.75 days. The resulting neptunium-237 has 93 protons and a half-life of a little more than 2 million years!

- Since the name *uranium* had been coined when the planet Uranus had recently been discovered and named, it made sense when the discoverers of the next element on the table proposed the name *neptunium* in honor of the next planet discovered in the solar system, Neptune.

- Both uranium and plutonium can be used to produce nuclear fission reactions. Because neptunium is sandwiched between these two elements, it must have similar properties. Yet the manufacture of a neptunium-based nuclear bomb—while theoretically entirely possible—has never been publicly acknowledged by any government.

Plutonium
*
Pu
[244] 94

PLUTONIUM

ELEMENTAL FACTS

- Plutonium, though virtually absent in nature, can be synthetically produced as long-lived isotopes by neutron bombardment. Plutonium-239 can be produced by bombardment of the most common isotope of element 92, uranium-238. The resulting uranium-239 undergoes two beta decays over time, converting two neutrons to two protons, raising the atomic number from 92 to 94 and forming plutonium-239.

- This element was discovered just a few months after neptunium, so that made it especially natural for its discoverers to name this next element after Pluto, which had been regarded at the time as the planet discovered after Neptune.

- Elements as large as plutonium can be produced in supernovas, but the plutonium produced in this process is radioactive. Its most stable known isotope decays with a half-life of about 80 million years. This may sound like a long time, but you can take it as a rule of thumb that any radioactive material is effectively gone after 10 half-lives, so any plutonium that may form would be long gone within 10 times 80 million half-lives, or 800 million years.

- The first and only nuclear devices ever deployed in wartime used extremely concentrated samples of fissile nuclei. Uranium-235 was used in the Little Boy bomb dropped on Hiroshima during World War II. But refining enough uranium-235 from uranium-238 was difficult, so as a second source of fissile material, scientists took the depleted uranium-238 and bombarded it with neutrons to make plutonium, which made possible additional bomb designs. Plutonium-239 was used in the Fat Man bomb dropped on Nagasaki and a month earlier in a bomb test that took place in Alamogordo, New Mexico.

Americium
*
Am
[243]
95

AMERICIUM

ELEMENTAL FACTS

- In 1944, Manhattan Project physicist Glenn T. Seaborg, along with a team of colleagues, successfully created element 95 by bombarding a sample of plutonium-239 with neutrons.
- Under the right conditions, plutonium-239 captures two neutrons to become the more massive plutonium-241 isotope. Plutonium-241 is too neutron-rich, so one of its neutrons decays by the emission of a beta particle. This effectively converts that neutron into a proton, which changes the plutonium-241 into a new element with 95 protons and one fewer neutron.
- Because its discovery took place in the United States—and given the element's location on the table just below europium—Seaborg named the new element *americium*.
- The half-life for the decay process from plutonium-241 to americium-241 is about 14 years, so the collection of Seaborg's new element took time. Americium's challenging synthesis makes it an expensive element. At a cost of about $42,000 per ounce, americium is somewhere around 30 times as expensive as gold.
- Yet most people own a sample of this element—in smoke detectors, in which a small amount of americium is used to generate a stream of alpha particles between two electrodes charged by a conventional battery. Americium's ionizing radiation can cause molecules in the air to become charged. As these charged particles form, they flow to the positive or negative end of the ionization chamber, creating a steady, measurable amount of electrical current. Smoke molecules tend to be large and more resistant to ionization, so if they infiltrate the ionization chamber, they impair the smoke detector's ability to produce that steady current. As the current drops, the smoke detector makes noise—and possibly saves lives.

Curium
*
Cm
[247]
96

CURIUM

ELEMENTAL FACTS

- Using a recent invention called the cyclotron at the University of California, Berkeley, Glenn T. Seaborg and a group of physicists collaborated to successfully crash, at extremely high speeds, a helium nucleus into plutonium-239. After assimilating the helium nucleus and rapidly losing a single neutron, element 96 was observed for the first time. Having discovered another element, Seaborg continued his practice of naming the element in homage to the lanthanoid above it in the table, which in this case was gadolinium.* Seaborg decided to pay homage to the wife-and-husband team of Marie and Pierre Curie, whose pioneering work in isolating radioactive elements seemed to make this an appropriate choice.

> BEGINNING WITH CURIUM IN 1944, A TOTAL OF 15 ELEMENTS CREATED IN LABORATORIES WERE NAMED IN HONOR OF IMPORTANT SCIENTISTS, INCLUDING EINSTEIN, MENDELEEV, AND COPERNICUS.

- Seaborg's curium was abundant enough, and the half-life of more than 150 days was long enough, that a sample of pure curium was produced and analyzed back in Chicago at his laboratory.
- Two decades later, curium-242 would find itself on the surface of the Moon, acting as a source of alpha particles used in experiments conducted by the NASA Surveyor missions, a series of robotic lunar landings intended to characterize and explore the surface of the Moon.

---

* Gadolinium was named for Johan Gadolin, who first isolated many of the lanthanoid elements.

Berkelium
*
Bk
[247] 97

BERKELIUM

ELEMENTAL FACTS

- Berkelium was named in honor of Berkeley, California, where the element was created in the lab.
- In the latter half of the 1940s, as World War II came to a conclusion, many Americans, including the scientists participating in the Manhattan Project, were returning to their civilian lives.
- Glenn T. Seaborg returned to California, to continue his work on nuclear chemistry. Having discovered americium and curium and developed ways to produce them in quantities that would allow him to experiment with these new elements, he set about pushing the limits of the periodic table yet again.
- Seaborg and his colleagues—including Albert Ghiorso, who would much later become the leader of the Berkeley group—took the next logical step, using their new heavy-element products as targets again. Firing helium nuclei at their new creations, americium (element 95) and curium (element 96), would, they hoped, help them produce elements 97 and 98, respectively.
- The strategy was a success! In 1949, 7 milligrams of americium was bombarded with helium nuclei to produce element 97. The team rushed to claim their right to name this new element and called it berkelium in recognition of the town of its origin, much like terbium just above it in the lanthanoids was named for the village of Ytterby.

Californium
*
Cf
[251] 98

CALIFORNIUM

ELEMENTAL FACTS

- Like berkelium, californium was named in honor of Berkeley, California, where these two elements, and others, were created in the lab.

- In 1949, Glenn T. Seaborg and his colleagues bombarded 7 milligrams of americium with helium nuclei to produce element 97. Shortly thereafter came element 98. This time, they had just 8 micrograms of element 96, curium, which they bombarded with helium nuclei to produce a scant 5,000 atoms of element 98. If it were possible to line up all of these atoms side by side, they would stretch only about 1.3 microns across—about 1/100 the width of a human hair.

- The team published their findings in rapid succession in the journal *Physical Review*. The element dysprosium, just above element 98, came from the Greek *dysprositos*, meaning “hard to obtain.” Had Seaborg stuck to his tradition of naming new actinoids in the same vein as their lanthanoid homologs, he would need to name element 98 after one of its properties.

- Perhaps he felt that 5,000 atoms weren’t enough material to determine any properties of his new element. Or maybe he just thought it would be fun to continue immortalizing the address of his lab where all of these elements were being discovered, as had happened with scandium and all the other element names pointing to Ytterby, Sweden. For whatever reason, the group responsible for americium and berkelium recommended the name californium for their third element.

TWO US STATES HAVE MADE THE TABLE IN CALIFORNIUM AND TENNESSINE. BUT CAROLINIUM, ALABAMINE, ILLINIUM, AND EVEN VIRGINIUM WERE ALL ONCE PROPOSED ELEMENT NAMES THAT WERE DISCARDED AS THEIR WOULD-BE DISCOVERER’S RESEARCH WAS DISPROVEN.

Einsteinium
*
Es
[252] 99

EINSTEINIUM

ELEMENTAL FACTS

- On November 1, 1952, the first thermonuclear device, code-named Ivy Mike, was detonated in the Pacific Proving Grounds in the Marshall Islands.
- The hydrogen bomb uses the fusion of hydrogen to helium as its main payload, but getting the fusion reaction started requires the kinds of temperatures and pressures that can only be generated by a fission device.
- The explosion created a fireball 5 kilometers wide. The unimaginably high pressure and temperature,* along with a neutron flux that could never be generated in a lab, transmuted some of the heavy elements from the fission stage into never-before-seen elements.
- Glenn T. Seaborg, a Nobel laureate with a proven track record of elemental discovery, got his hands on samples of soil and air from the area surrounding the blast, and in short order elements 99 and 100 were discovered.
- Under the unprecedented conditions of the Ivy Mike explosion, it appeared that a few atoms of uranium-238 absorbed a staggering 15 neutrons each, resulting in 7 beta decays, or 17 neutrons absorbed, followed by 8 beta decays.
- Seaborg couldn’t rush to press with his discovery and secure naming rights to the two elements because any scientific results related to the fusion-bomb project were classified by the US government. Ultimately, his team named them einsteinium and fermium, after Albert Einstein and Enrico Fermi—two of the most revered physicists of the 20th century. Perhaps ironically, or maybe on purpose, both were vocally opposed to the production of the hydrogen bomb itself.

---

* The temperature within the fireball reached an estimated 150 million degrees Celsius, and the pressure climbed to 73 million atmospheres.

Fermium
*
Fm
[257] 100

FERMIUM

ELEMENTAL FACTS

- Although the results of thermonuclear testing showed that neutron bombardment can be used to produce elements 99 and 100, the tremendous number of neutrons that must be captured by the target nucleus led to diminishing returns in these larger nuclei, even in the lab.

- But as cyclotron and synchrotron technology progressed in the 1950s, these newer and better designs were allowing scientists to use larger and larger ions as bombardment projectiles in the quest for heavier elements.

- In 1954, after Glenn T. Seaborg's classified discovery of element 100 but before his ability to publish his team's work, another group joined the race to discover new elements.

- In Sweden, scientists at the Nobel Institute for Physics** used state-of-the-art cyclotrons to accelerate the nuclei of ever-larger elements. They were able to fire oxygen ions at uranium, thereby directly adding the 8 protons needed to leapfrog from element 92 to 100.

- The Swedish experiment was published just days before Seaborg and Albert Ghiorso's extended team of collaborators at Berkeley, Los Alamos, and Chicago produced element 100 by neutron bombardment. Unaware of the classified American work that had taken place, the Nobel Institute scientists recommended their namesake with *nobelium*. But Ghiorso and Seaborg were careful to mention in their published work on fermium that their group had in fact years earlier detected and isolated fermium-255. This claim, and their reputation as heavyweights in element discovery, is likely the reason the scientific community gave the nod to their name, *fermium*.

** This is not to be confused with the organization that awards Nobel Prizes.

Mendelevium
*
Md
[258] 101

MENDELEVIUM

ELEMENTAL FACTS

- In 1955, Albert Ghiorso and Glenn T. Seaborg were still working with their team in Berkeley, now led by Stanley Thompson. In their quest to continue expanding the periodic table, they successfully produced element 101 using a cyclotron to smash helium nuclei into an einsteinium target, creating just 17 atoms of the newest heavy actinoid.

- Their discovery went uncontested by competing labs emerging in Sweden and Russia. Although several international labs had the ability to produce high-energy helium particles in cyclotrons, the target material—einsteinium, element 99—was remarkably rare and decays with a half-life of just 20 hours. Only Berkeley had the luxury of using it as a target.

- Although element 101 was discovered in America, Thompson, Ghiorso, and Seaborg decided to give their new element a Russian namesake: Dmitri Mendeleev. Choosing a Russian namesake for an American-discovered element early in the Cold War was a bold suggestion—so bold that Thompson's team consulted with the US government before doing so.

- But this would prove an important olive branch to offer, since each side knew that the other would almost certainly be necessary to verify findings going forward. Mendelevium may have created just enough goodwill and cooperation among competing labs to balance the strong desire each had to be the first to discovery.

Nobelium
*
No
[259] 102

NOBELIUM

ELEMENTAL FACTS

- With the discovery of mendelevium, the Berkeley team had made just a few atoms of element 101 with the time-tested method of bombarding the most recently discovered element with fast-moving helium nuclei. But to make the next two elements—102 and 103—by alpha bombardment seemed virtually impossible. Only picograms of fermium existed to make targets for element 102, and for element 103, only 17 atoms of the target mendelevium had ever been made using the already-rare element einsteinium.

- Clearly, if other labs—such as the Nobel Institute for Physics in Sweden and the Joint Institute for Nuclear Research in Russia—were going to compete with the Berkeley juggernaut, they would have to come up with methods that used smaller heavy elements as targets. But to make up for the smaller target atoms, they would need larger projectile nuclei as the bullets.

- Fortunately, cyclotron technology had progressed rapidly in the 1950s. The Swedish group found that they could sufficiently accelerate oxygen ions with 8 protons, which made it possible to use the much-more-available element 94, plutonium, as a target to produce element 102.

- In 1957, the Swedish team conducted their experiment and observed alpha radiation of a previously unobserved energy—one of the hallmarks of a new element forming—followed by almost-instant radioactive decay. Already slighted once over their claim to element 100, they rushed to press with their discovery to secure their prize of immortality on the table at position 102 with nobelium.

Lawrencium
*
Lr
[262] 103

LAWRENCIUM

ELEMENTAL FACTS

- In 1961, the group led by Albert Ghiorso and Glenn T. Seaborg at the lab in Berkeley, California, produced element 103. Appropriately, it was named for Ernest Lawrence, another Berkeley scientist and the inventor of the cyclotron—without which this element could never have been made.
- The later actinides, including lawrencium, likely do not occur naturally in any meaningful quantity. There is little evidence to suggest that these actinides—with a half-life of just 4 hours for lawrencium—ever existed in more than the most miniscule amounts until they were produced synthetically in a laboratory.

COLLECTIVELY, THE 15 ELEMENTS IN THE SEVENTH ROW BEYOND LAWRENCIUM ARE REFERRED TO AS THE SUPERHEAVY ELEMENTS, OR THE TRANSACTINIDE ELEMENTS.

Rutherfordium
****
Rf
[267] 104

RUTHERFORDIUM

ELEMENTAL FACTS

- The long trek to the completion of row 7 began in 1964. By then, heavy ion accelerators were becoming more efficient and able to accelerate ever-heavier ions to strike targets in the search for superheavy elements. It was then that the team led by Georgy Flerov at the Joint Institute for Nuclear Research in Russia bombarded element 94, plutonium, with element 10, neon. They were hoping that 94 + 10 = 104, and, sure enough, they detected fission products consistent with element 104 having formed briefly.
- Naturally, Flerov's team leapt to publish their finding and claim their prize on the table. The name that they proposed was kurchatovium, in honor of Igor Kurchatov, the leader of the Soviet nuclear bomb project.
- The name was never officially recognized by the IUPAC, but that didn't stop Russian tables in the late 1960s from proudly sporting its symbol, Ku, at the end of the then-known elements in row 7.
- Meanwhile, the scientists in Berkeley, California, had a new tool at their disposal: the heavy ion linear accelerator (HILAC), which allowed them to launch ions as large as argon at targets. Using the HILAC, 5 years later they successfully created element 104.
- An argument ensued about who deserved rightful credit, with the American team claiming that the earlier Russian study was substandard and riddled with flaws.
- Credit and the name remained in question for more than three decades, until an IUPAC group convened in 1992 and ruled that both sides were somewhat justified in their claims and declared the element rutherfordium—after British physicist Ernest Rutherford, who discovered the atomic nucleus and introduced the concept of a half-life.

Dubnium
****
Db
[268] 105

DUBNIUM

ELEMENTAL FACTS

- In 1968, the team of physicists at the Joint Institute for Nuclear Research in Dubna, Russia, reported the first successful synthesis of element 105. Although the Russian team did not propose a name in their initial publication, the name of this new element—dubnium—eventually would pay homage to the Russian town of Dubna, where it was first produced.

Seaborgium
****
Sg
[269] 106

SEABORGIUM

ELEMENTAL FACTS

- In the quest for element 106, the physicists at Berkeley continued with the previous strategies that yielded elements 104 and 105, using their accelerator to shoot element-8 (oxygen) atoms at an element-98 (californium) target using their newly upgraded SuperHILAC.
- But over in Russia, Yuri Oganessian—realizing that the lab in Dubna might be reaching its technical limitations for using currently accepted techniques—suggested a whole new strategy: low-energy fusion.
- Oganessian's idea was to fuse two large nuclei, one shot at the other, with just enough energy that it could barely overcome the force repelling the two nuclei. Reducing the energy would reduce the likelihood of a productive collision, but it would also reduce the likelihood of smashing the target to bits when one happened.
- He posited that in this scenario, he just might be able to produce superheavy elements a few atoms at a time without the need for the astronomical projectile speeds that only the SuperHILAC could offer.
- Oganessian used element 24 (chromium) for a low-energy collision with lead and was able to successfully observe the fission products of element 106—at nearly the same time that the Berkeley group achieved their synthesis with the SuperHILAC.
- The stage was set once again for a brawl over the rights to claim discovery and name element 106, but it was agreed that neither lab would make an immediate recommendation for a name.
- Once all of the results had been confirmed, the American team suggested the name seaborgium, in honor of Glenn T. Seaborg, the godfather of heavy-element discovery in the US. There was surprisingly little pushback from the Russian team, and the name stuck.

Bohrium
****
Bh
[270] 107

BOHRIUM

ELEMENTAL FACTS

- In the 1970s, at the GSI Helmholtz Centre for Heavy Ion Research in Germany, senior researcher Peter Armbruster acquired the most versatile linear accelerator in the world. The device, known as the universal linear accelerator (UNILAC), would allow GSI to exploit the techniques favored by both the American and Russian teams who were working on discovering new elements.

- From 1981 to 1984, Armbruster's program would prove a rapid success, using low-energy fusion techniques pioneered by Yuri Oganessian to produce the next three heavy elements in rapid succession. Element 24 (chromium) plus element 83 (bismuth) created 107; element 26 (iron) plus element 82 (lead) created 108; and element 26 plus element 83 created 109. Thanks to Germany's top-of-the-line technology, there were no arguments over who discovered these three superheavy elements.

- Element 107 was initially called nielsbohrium, after the Danish physicist Niels Bohr. This name was unusual because, when it was in use, this was the only element to bear both the first and last name of its namesake. But adding the first name in this case made some sense, as the last thing one might want is a chemist confusing bohrium with boron.

- This was yet another naming debate that was settled in the 1990s by the IUPAC, which decided that since no known isotope of bohrium has a half-life longer than a few minutes, it was unlikely that a lot of chemistry would be performed on it. Nonetheless, students of chemistry in the early 1990s had chemistry books with a periodic table bearing the element Ns, or nielsbohrium, in position 107.

Hassium
****
Hs
[269] 108

HASSIUM

ELEMENTAL FACTS

- In 1984, element 108 was created at the GSI Helmholtz Centre for Heavy Ion Research, located just outside of Darmstadt, Germany. The element was made using low-energy fusion techniques in the universal linear accelerator (UNILAC), the best accelerator in the world at the time.
- Element 26 (iron) plus element 82 (lead) created element 108. The naming honors for this element went to Hesse, the German state in which the Darmstadt lab resides.

Meitnerium
****
Mt
[278] 109

MEITNERIUM

ELEMENTAL FACTS

- Element 109 was created in 1982 at the GSI Helmholtz Centre for Heavy Ion Research in Germany using the universal linear accelerator (UNILAC).
- Element 26 (iron) plus element 83 (bismuth) created element 109, which was named for the very deserving Lise Meitner, the prolific Austrian-born nuclear scientist who is widely credited with the co-discovery of nuclear fission.
- While six elements on the table had been named for female deities and one for the husband-and-wife team of Pierre and Marie Curie, meitnerium was the first element on the table named solely for a female scientist.

ALTHOUGH THE GERMANS AT THE GSI HAD INDISPUTABLE CLAIM TO ELEMENTS 107, 108, AND 109, DISAGREEMENTS WERE STILL RAGING OVER ELEMENTS 104 THROUGH 106. VARIOUS NAMES WERE BEING PUT INTO USE REGIONALLY, AND IT WAS CLEAR BY 1985 THAT IT WAS TIME FOR THE IUPAC TO STEP IN. THE IUPAC HELPED TO ESTABLISH A PANEL KNOWN AS THE TRANSFERMIUM WORKING GROUP, WHOSE JOB WAS TO FINALLY PUT AN END TO ANY BICKERING OR UNCERTAINTY OVER THE NAMES AND DISCOVERY CREDIT FOR SUPERHEAVY ELEMENTS. OUT OF THIS EXERCISE CAME THE FINALIZED AND ACCEPTED NAMES FOR ALL ELEMENTS THROUGH 109.

Darmstadtium
****
Ds
[281] 110

DARMSTADTIUM

ELEMENTAL FACTS

- In the 1990s, the race to find new superheavy elements heated up once again. The GSI Helmholtz Centre for Heavy Ion Research—located just outside of Darmstadt, Germany—had the momentum, but American and Russian labs were close on their heels, and innovating would be critical to staying ahead.

- Leading the German effort to reach even larger elements was Sigurd Hofmann. With the best accelerators already at his disposal, Hofmann turned his attention to detection, developing a new and better technique to look for the handfuls of superheavy atoms that were being prepared at GSI.

- While American and Russian groups chased the next batch of superheavy elements, Hofmann's attention to detector design paid off handsomely. In a remarkable period of a little more than one year, from late 1994 to early 1996, the team successfully produced and detected three more new elements.

- In November 1994, element 28 (nickel) struck a lead target to form a single atom of element 110, which the German group named darmstadtium, honoring the location of the GSI lab.

Roentgenium
****
Rg
[281] 111

ROENTGENIUM

ELEMENTAL FACTS

- In a little more than a year, from November 1994 to February 1996, a team of German scientists at the GSI Helmholtz Centre for Heavy Ion Research successfully produced and detected three new elements.
- After the German group created element 110 by striking a lead (82) target with element 28 (nickel), the target was changed from lead to bismuth, with 28 plus 83 (bismuth) producing three atoms of element 111 in late 1994. The German group named the new element roentgenium, after German physicist Wilhelm Conrad Röntgen (also spelled Roentgen), who received the first Nobel Prize in Physics for discovering x-rays.

Copernicium
****
Cn
[285] 112

COPERNICIUM

ELEMENTAL FACTS

- From late 1994 to early 1996, German scientists at the GSI Helmholtz Centre for Heavy Ion Research successfully produced and detected three new elements.
- After the German group created element 110 and element 111 in late 1994, in February of 1996, they used element 30 (zinc)—the biggest projectile yet—in a low-energy collision with lead (82) to form a single atom of element 112.
- The German group’s preferred name for the element, copernicium—after Nicolaus Copernicus, the astronomer who theorized that the planets revolved around the Sun—was accepted without challenge.
- In fact, all six of their discoveries, stretching over a decade, were undisputed. Only six elements remained to be created from the seventh period.

Nihonium
****
Nh
[286] 113

NIHONIUM

ELEMENTAL FACTS

- By the 1990s, Japan’s national lab, known as RIKEN, had its own ion accelerator and was ready to take its shot at immortality on the periodic table by attempting to produce element 113.
- But RIKEN’s methods were still a bit behind the times. RIKEN scientists would have to rely on Yuri Oganessian’s low-energy fusion techniques if they were going to be able to prove that they had made their target element. In 2004, they bombarded bismuth (83) with zinc (30) ions and observed decay products consistent with element 113.
- Next, the American-Russian team—who had become collaborators after the Cold War—produced element 115 using calcium-48 (with 20 protons) and americium (element 95) targets. In an exciting additional development, their element 115 appeared to decay into element 113 through an alpha emission. It was a two-for-one discovery for them, and RIKEN’s claim to discovery was in peril.
- Both sides raced to shore up their data and stake their claim to element 113. The final experiment that put the RIKEN team over the top was conducted in the aftermath of the Fukushima nuclear power plant disaster of March 2011. In the wake of the national catastrophe, energy prices surged in Japan, making the accelerator at RIKEN more expensive to run.
- But in a twist of fate, that actually worked to their advantage. Many other RIKEN experiments were cancelled, so the team looking for element 113 a second time would actually have more access to the sought-after device. The team successfully detected the decay of element 113 again in 2012, earning the nod for the discovery from the IUPAC and cementing their rights to name their creation. They chose nihonium, which is a Japanese way of saying “japanium.”

Flerovium
****
Fl
[289] 114

FLEROVIUM

ELEMENTAL FACTS

- By the late 20th century, technology had progressed, and a new bombardment projectile was available: calcium-48. With 20 protons and 28 neutrons, calcium-48 is unusually stable and consequently able to survive the energetic collisions associated with hot fusion, shooting highly accelerated particles at targets to form heavy elements.
- Using this newly selected projectile, Yuri Oganessian's team at the Joint Institute for Nuclear Research in Dubna, Russia, succeeded in fusing neutron-rich calcium-48 with plutonium-244—that's 20 plus 94—to form element 114.
- It was an exciting moment for both the Russian and American teams, who after the Cold War ended had become collaborators more than rivals in the superheavy synthesis game.
- The single atom of element 114 lasted a mind-boggling 19 seconds. It was promptly named flerovium, in honor of Georgy Flerov, who had died in 1990 but had played an important role in founding and leading the Dubna group for decades.
- In 1999, authors from both the Joint Institute for Nuclear Research in Russia and Lawrence Livermore National Laboratory in California appeared in the bylines of a single article claiming shared credit for the discovery of flerovium.

Moscovium
****
Mc
[289] 115

MOSCOVIUM

ELEMENTAL FACTS

- In the early 2000s, an international team of scientists from American labs and Russia's Joint Institute for Nuclear Research collaborated to produce element 115. They used targets of calcium-48, with 20 protons, and americium, which is element 95, to make element 115. The element was named for the Moscow oblast, which is where the Joint Institute is located (in the small "science city" of Dubna, north of Moscow).

Livermorium
****
Lv
[293] 116

LIVERMORIUM

ELEMENTAL FACTS

- In the year 2000, authors from both the Joint Institute for Nuclear Research in Russia and Lawrence Livermore National Laboratory in California appeared in the bylines of a single paper claiming that element 116 had been prepared by the bombardment of curium (element 96) with calcium-48 (which has 20 protons). The new element was named for the American lab.

Tennessine
****
Ts
[294]
117

TENNESSINE

ELEMENTAL FACTS

- By the early 2000s, the Russian team at the Joint Institute for Nuclear Research was eager to try making element 117 using calcium-48. Since calcium-48 has 20 protons, the target material would have to be element 97, berkelium, a heavy actinoid with essentially no known commercial use, even though it was known for six decades. This meant that even when it was produced, it was rarely collected.

- There were only two facilities on Earth that had the ability to produce berkelium in the quantities that the Russian team would need. One was a Russian reactor facility, which had expressed no interest in providing what they needed. The other was the high-flux reactor team at Oak Ridge National Laboratory in Tennessee, which was convinced to provide the target sample.

- But to make the superheavy element 117, the projectile and target would both need to be as rich in neutrons as possible. That means using the most neutron-rich berkelium isotope available: berkelium-249, which forms as californium beta decays in high-flux reactors. Because berkelium-249 has a half-life of just 330 days, the target material for any meaningful attempt would have to be synthesized and collected in Tennessee and then shipped to Russia and bombarded with calcium-48 ions before most of the berkelium itself radioactively decayed and was lost.

- In April 2010, the Russian team finally achieved success. By that time, about two-thirds of the berkelium that had been extracted from the Oak Ridge reactor would have already decayed into lighter elements. But six of the remaining berkelium atoms had been successfully converted into element 117, which was named tennessine to acknowledge the generosity of the Oak Ridge lab.

Oganesson
****
Og
[294] 118

OGANESSON

ELEMENTAL FACTS

- In the early 2000s, physicists from the Joint Institute for Nuclear Research in Russia and Lawrence Livermore National Laboratory in California collaborated to produce element 118 from californium using the same method that was followed to create element 116, livermorium. But instead of bombarding curium (element 96) with calcium-48 (which has 20 protons) like they did to create element 116, this time they bombarded californium (element 98) with calcium-48 to produce element 118.
- And with the creation of element 118—named for Yuri Oganessian, who pioneered low-energy fusion techniques—the American-Russian collaboration endured to the end, filling row 7 of the periodic table of the elements.

QUIZ

LECTURE 1

1 The table arranges elements into horizontal rows called periods (numbered sequentially from 1 to 7 from top to bottom) and vertical columns known as groups (numbered from left to right from 1 to 18). Which of the following choices accurately describes the location of the indicated element on the periodic table?

a. calcium (Ca): group 2, period 3

b. potassium (K): group 4, period 1

c. oxygen (O): group 16, period 2

d. beryllium (Be): group 1, period 2

2 See how many elements you can identify from the list of symbols not based on English: Ag, Au, Cu, Fe, Hg, K, Na, Pb, Sb, Sn, W.

3 Imagine a fictitious element called unobtanium that has two naturally occurring isotopes, unobtanium-50 and unobtanium-52, both equally abundant. What will the periodic table report as unobtanium's atomic mass?

a. 50

b. 52

c. 51

d. 102

› Answers can be found on page 147.

4 Suppose the imaginary unobtanium has two naturally occurring isotopes, unobtanium-50 and unobtanium-52, but the lighter isotope accounts for 25% of the abundance and the heavier isotope is the remaining 75%. What will the periodic table report as unobtanium's atomic mass in that case?

a. 50

b. 52

c. 50.5

d. 51.5

LECTURE 2

1 Which classical element is the namesake for hydrogen and also was disproven to be an element by hydrogen's discovery?

a. air

b. water

c. earth

d. fire

2 Which scientific breakthrough made it possible to finally resolve small inconsistencies in ordering in Mendeleev's table, such as cobalt/nickel and iodine/tellurium appearing to be out of order?

a. more accurate atomic mass measurement

b. the discovery of atomic numbers

c. the development of the telluric helix

d. adoption of the law of octaves

LECTURE 3

1 Based on their locations on the periodic table, which of the following elements is most likely to form ions with a charge of −2 in compounds with other elements?

a. fluorine

b. oxygen

c. magnesium

d. potassium

2 No element large enough to have a fifth principal energy level has ever been observed. However, if such an atom is ever created, in theory what is the maximum number of electrons that a 5*g* subshell could hold?

a. 2

b. 9

c. 18

d. 32

3 Based on their positions on the periodic table, which of the following pairs of elements is most likely to form ionic bonds when combined in a chemical compound?

a. iron and potassium

b. fluorine and astatine

c. silicon and germanium

d. rubidium and fluorine

LECTURE 4

1 Which of the following elements is expected to have the highest Pauling electronegativity (the greatest pull on electrons when in a chemical bond)?

- **a.** astatine
- **b.** fluorine
- **c.** lithium
- **d.** francium

2 Which of the following choices accurately ranks the four elements indicated in order of decreasing atomic radius?

- **a.** Fr > Ra > Al > O
- **b.** Li > Co > Tl > Rn
- **c.** Na > K > Rb > Cs
- **d.** F > O > N > C

3 Based on the activity series, which of the following pairs of materials is expected to react by an exchange of electrons? (Hint: Potassium is located very high on the activity series, aluminum is fairly high, and gold and platinum are near the bottom.)

- **a.** potassium metal with aluminum ions
- **b.** acid with platinum metal
- **c.** gold metal with aluminum metal
- **d.** potassium ions with aluminum ions

LECTURE 5

1 Which of the following elements would you predict is most abundant in our solar system? The nuclear binding energy curve (which peaks at iron) and the Oddo-Harkins

rule (which shows that even-numbered elements are more common than odd-numbered elements of similar size) both offer clues.

- **a.** vanadium
- **b.** chromium
- **c.** niobium
- **d.** molybdenum

2 Which of the following elements is most siderophilic (iron loving)?

- **a.** ruthenium
- **b.** sulfur
- **c.** silicon
- **d.** potassium

LECTURE 6

1 Which of the following nuclear reactions depicts nuclear fission taking place?

- **a.** $^{239}\text{Pu} \rightarrow {}^{235}\text{U} + {}^{4}\text{He}$
- **b.** $^{240}\text{Pu} \rightarrow {}^{134}\text{Xe} + {}^{103}\text{Zr} + 3\,{}^{1}n$
- **c.** $^{206}\text{Tl} \rightarrow {}^{206}\text{Pb} + {}^{0}\beta$
- **d.** $^{238}\text{U} + {}^{1}n \rightarrow {}^{239}\text{U}$

2 Protactinium has an atomic number of 91. Which elemental nucleus will be produced when a nucleus of the isotope protactinium-231 undergoes four sequential alpha decays?

- **a.** americium
- **b.** plutonium

c. francium

d. bismuth

LECTURE 7

1 In which way does hydrogen act more like a group-17 halogen than a group-1 alkali metal?

a. It can take on metallic properties at high pressures.

b. It tends to form positively charged ions by losing its one valence electron.

c. It forms a 2-to-1 compound with oxygen (H_2O).

d. At ordinary conditions of pressure and temperature, it forms a diatomic gas joined by a single bond.

2 Although helium has a valence electron configuration that's similar to those of group-2 metals like calcium, why is helium almost universally placed at the top of group 18 of the table?

a. because of its full valence shell

b. because its chemical properties differ so significantly from those of hydrogen

c. because of its tendency to form negatively charged ions

d. because of the presence of neutrons in its nucleus

LECTURE 8

1 Many pure metals can be obtained by applying a voltage to a solution of dissolved metal ions to encourage the conversion of metal ions to neutral metal atoms. Based on their position on the activity series, which of the

alkali-metal elements do you think would require the largest voltaic pile (the highest voltage) to collect a pure metal by electrolysis from a solution?

- **a.** lithium
- **b.** sodium
- **c.** potassium
- **d.** All three would require the same voltage.

2 Alkali metals readily lose a single electron to become a +1 ion. When sodium (atomic number 11) undergoes this process, which element's electron configuration does it take on?

- **a.** magnesium
- **b.** neon
- **c.** argon
- **d.** potassium

LECTURE 9

1 The reaction of magnesium with oxygen is vigorous enough to use in camera flash technology. Based on its position on the table, which alkaline-earth metal would you expect to react most energetically with oxygen from the air?

- **a.** beryllium
- **b.** magnesium
- **c.** calcium
- **d.** strontium

2 The useful radioactive isotope strontium-90 is often obtained as a fission product of uranium-235. Assuming a single fission produces strontium from uranium, what is the identity of the other nucleus that forms in this reaction?

$^{235}\text{U} + {}^{1}n \rightarrow {}^{90}\text{Sr} + {}^{144}\textbf{?} + 2\ {}^{1}n$

- **a.** krypton (Kr)
- **b.** xenon (Xe)
- **c.** barium (Ba)
- **d.** tellurium (Te)

LECTURE 10

1 Of the compounds listed below, select the only one that should be impossible to create.

- **a.** PCl_5
- **b.** SH_2
- **c.** OF_2
- **d.** CF_5

2 Which of the following types of elements are not represented in the *p* block of the table?

- **a.** nonmetals
- **b.** metalloids
- **c.** weak metals
- **d.** alkali metals

LECTURE 11

1 Only a few atoms of element 118 (oganesson) have ever been made. Assuming that general trends addressed in this lecture hold, if enough of this element were ever collected to measure its properties, how would you expect those properties to compare to other noble gases?

a. It would have the lowest density.

b. It would have the highest boiling point.

c. It would be the least chemically reactive.

d. It would be the most stable nucleus.

2 Which of the following does not help explain why helium and neon are commonly used as cryogens (extremely cold liquids)?

a. their lack of reactivity

b. their weak van der Waals forces

c. their very low boiling points

d. their even atomic numbers

LECTURE 12

1 Interhalogen compounds are diatomic molecules that contain two different halogen atoms bonded to one another. Assuming ideal gas behavior (that gas molecules move independently of one another), which of the following interhalogen compounds would be expected to be the densest when in the gas phase?

a. F-Cl

b. F-Br

c. Cl-Br

d. Br-I

2 If astatine were ever isolated as a pure substance, how would its properties be expected to compare with those of the other halogens?

- a. It would have the lowest boiling point.
- b. It would be the most chemically reactive.
- c. It would have the lowest melting point.
- d. It would form similar salts when combined with metals like sodium.

LECTURE 13

1 Which of the following compounds is expected to form hydrogen bonds as a pure substance?

- a. benzene (C_6H_6)
- b. phenol (C_5H_5OH)
- c. nitric oxide (NO)
- d. hydrogen cyanide (HCN)

2 Which of the following is an example of fixed nitrogen?

- a. ammonia (NH_3)
- b. nitrogen gas (N_2)
- c. hexazine (N_6)
- d. octaazacubane (N_8)

LECTURE 14

1 Which of the following best explains why the melting point of carbon (graphite) is the highest of any known element?

- a. Carbon atoms have particularly strong van der Waals forces.

b. Carbon can participate in hydrogen bonding.

c. Graphite is a network covalent solid.

d. Carbon forms metallic bonds in graphite.

2 Based on the structure of each allotrope, which type of phosphorus would be expected to have the lowest melting point?

a. white phosphorus

b. black phosphorus

c. red phosphorus

d. phosphorus pentoxide

LECTURE 15

1 Which of the following element combinations is expected to produce a *p*-type semiconductor (one that is electron deficient)?

a. arsenic doped with phosphorus

b. germanium doped with arsenic

c. silicon doped with phosphorus

d. germanium doped with indium

2 Which of the following is the most direct consequence of the more nonmetallike behavior of metalloids?

a. the difficulty Davy experienced in obtaining them by electrolysis

b. their ability to form alloys such as arsenical bronze

c. their lustrous appearance when pure

d. their chalcophilic nature

LECTURE 16

1 Based on indium's position on the periodic table, which two oxidation states are expected to be most common for indium? (Hint: Remind yourself of the valence shell electron configuration of a group-13 element.)

- **a.** +1 and +3
- **b.** +2 and +4
- **c.** +1 and +2
- **d.** +3 and +4

2 Which of the following nuclear reactions is associated with the extreme toxicity of polonium-210 when ingested?

- **a.** alpha emission
- **b.** beta emission
- **c.** gamma emission
- **d.** nuclear fission

LECTURE 17

1 Which of the following pairs of elements is expected to be the most closely associated with one another in nature?

- **a.** titanium and chromium
- **b.** hafnium and iron
- **c.** molybdenum and tungsten
- **d.** zinc and yttrium

2 Use the periodic table to predict which of the following *d*-block elements is expected to have the highest melting point.

- **a.** rhenium

b. titanium

c. mercury

d. iron

LECTURE 18

1 Based on their locations on the table, which of the following elements is likely to take on the greatest number of common oxidation states?

a. yttrium

b. niobium

c. aluminum

d. copper

2 Which of the following *d*-block metal ions has a noble gas electron configuration?

a. Cr (VI)

b. Cr (III)

c. Ti (II)

d. V (IV)

LECTURE 19

1 Based on their position in the periodic table, which of the following metallic elements is most likely to have useful catalytic properties?

a. iridium

b. tantalum

c. iron

d. manganese

2 When Luis Alvarez conducted his studies on the iridium anomaly, he used neutron activation analysis, in which iridium captures a neutron before undergoing a beta decay. The element cadmium can be detected using a similar technique. When cadmium is analyzed by neutron activation analysis, which element is formed as a result?

- **a.** palladium
- **b.** platinum
- **c.** indium
- **d.** silver

LECTURE 20

1 Which of the following phenomena is most closely tied to relativistic effects?

- **a.** the yellow hue of gold
- **b.** the brown hue of copper
- **c.** the reactivity of silver sulfide with aluminum
- **d.** the toxicity of cadmium

2 Which of the following features of zinc atoms leads to them being useful in the technique of hot-dip galvanization (allowing solid iron to be dipped into molten zinc without itself melting)?

- **a.** its closed *s* and *d* subshells
- **b.** strong relativistic effects
- **c.** its position in the third row of the table
- **d.** its even number of protons

LECTURE 21

1 Which of the following rare-earth metal pairs is expected to be most difficult to separate?

a. lanthanum from lutetium (elements 57 and 71)

b. thulium from ytterbium (elements 69 and 70)

c. praseodymium from lutetium (elements 59 and 71)

d. thulium from cerium (elements 69 and 58)

2 When it was finally observed in the fallout from nuclear explosions, promethium (element 61) was found to undergo fairly rapid beta decay. Which element forms as a result of this decay?

a. neodymium

b. samarium

c. praseodymium

d. neptunium

LECTURE 22

1 Uranium is known to undergo a fission reaction in which a pair of elements, barium and krypton, is formed. Assuming that neptunium can undergo a similar fission reaction, producing krypton as one of the product nuclei, what would be the identity of the second nucleus produced?

a. barium

b. cesium

c. lanthanum

d. argon

2 Which of the following actinide elements (on the bottom row of the *f* block) have primordial isotopes?

- **a.** thorium and uranium
- **b.** actinium and protactinium
- **c.** uranium and plutonium
- **d.** neptunium and plutonium

LECTURE 23

1 When a uranium-238 nucleus captures 9 neutrons and subsequently undergoes 5 beta decays, which isotope is expected to form?

- **a.** berkelium-247
- **b.** mendelevium-243
- **c.** plutonium-252
- **d.** uranium-242

2 Which of the following nuclear fusions might be expected to produce the heavy actinide nobelium?

- **a.** uranium with oxygen
- **b.** uranium with neon
- **c.** plutonium with carbon
- **d.** californium with helium

LECTURE 24

1 Certain isotopes of copernicium (element 112) have been prepared by directly fusing two nuclei together. Heavier isotopes of copernicium, however, have only been observed as decay products of even heavier nuclei. One

such isotope is copernicium-285, which forms as its parent nucleus undergoes an alpha decay. What is the parent isotope for this process?

- **a.** flerovium-289
- **b.** nihonium-286
- **c.** roentgenium-281
- **d.** copernicium-289

2 Like calcium-48, nickel-78 is a neutron-rich, doubly magic nucleus (with 28 protons and 50 neutrons). If a nickel-78 nucleus could somehow be made to collide and fuse with californium-249 (the target material previously used to make oganesson-294), what would be the atomic number of the resulting superheavy nucleus?

- **a.** 118
- **b.** 124
- **c.** 126
- **d.** 132

ANSWERS

LECTURE 1

1 **[c]** Oxygen appears in the 16th column of the table, which is designated by the IUPAC as group 16. It also appears in the second row, or period. Group 2, period 3 would be magnesium, not calcium (which is period 4). Group 4, period 1 does not correspond to any known element (which would have surprised Mendeleev!). Group 1, period 2 indicates lithium, not beryllium (which is group 2).

2 silver, gold, copper, iron, mercury, potassium, sodium, lead, antimony, tin, tungsten

3 **[c]** Atomic mass is a weighted average of all the isotopes, but since they are equally abundant, both are weighted equally, and the answer is [(50 × 0.5) + (52 × 0.5)] / 2 = 51 amu.

4 **[d]** [(50 × 0.25) + (52 × 0.75)] / 2 = 51.5 amu.

LECTURE 2

1 **[b]** Hydrogen literally means “water generator,” and the ability to break water down into simpler substances (such as hydrogen) and recombine them to form water proves that water is not an element.

2 **[b]** Atomic numbers, discovered by Moseley, ultimately proved to be the determinant in proper ordering of elements in the periodic system. Atomic numbers show that even though the average atomic mass of cobalt is greater, cobalt has fewer protons (27) than nickel (28), so cobalt belongs ahead of nickel. Similarly, tellurium (atomic number 52, with 52 protons) belongs ahead of iodine (atomic number 53).

LECTURE 3

1 **[b]** Oxygen's position in group 16 leaves it just 2 electrons short of a completed valence shell, like its nearest group-18 (noble gas) neighbor, neon.

2 **[c]** Each orbital can hold 2 electrons. Based on the trend of 1 orbital per *s* subshell, 3 orbitals per *d* subshell, 5 orbitals per *d* subshell, and 7 orbitals per *f* subshell, a *g* subshell should have a total of 9 orbitals with a total capacity of 18 electrons.

3 **[d]** Because rubidium is located in the lower left of the table and fluorine is located in the upper right, rubidium very easily loses an electron to obtain an octet, while fluorine very eagerly accepts that electron. The atom that loses an electron becomes a positively charged ion, and the atom that gains an extra electron becomes a negatively charged ion, and the attraction of these opposite charges results in ionic bonding.

LECTURE 4

1 **[b]** Because fluorine resides in the upper right of the table, its highly charged nucleus and nearby valence shell make it the most electron-hungry element on the table.

2 **[a]** Atomic radius generally decreases as you move from left to right and bottom to top across the table. In the order presented, elements 87, 88, 13, and 8 (francium, radium, aluminum, and oxygen) follow such a pattern, always stepping to the right and up on the table.

3 **[a]** The activity series can be used to predict reactions between an ion and a neutral metal. Choice *b* has an ion in the form of an acid, but platinum is too unreactive a metal, located near the very bottom of the activity series. Only in choice *a* is the neutral metal (potassium) higher on the series than the ions it reacts with (aluminum ions). Choices *c* and *d* do not include both an ion and a neutral metal.

LECTURE 5

1 **[b]** Niobium and molybdenum are much larger atoms that are well beyond the peak of the nuclear stability curve at iron, making them less abundant than vanadium or chromium. Vanadium (element 23) and chromium (element 24) are similar in size, while the Oddo-Harkins rule predicts the even-numbered element of the pair, chromium, will be more abundant.

2 **[a]** Ruthenium, located directly below iron in the periodic table, is from the iron group of elements. This means that ruthenium's atomic structure is more similar to iron than any of the other choices. This similar atomic structure makes ruthenium associate more strongly with iron than the other choices do. Sulfur is the leader of the sulfur-loving group (the chalcophiles); silicon along with oxygen makes up the silica that shuttles lithophiles; and potassium is itself a lithophile, which associates strongly with silica instead of iron.

LECTURE 6

1 **[b]** Only in choice *b* does one large nucleus (plutonium) break into two nuclei of substantial size (xenon and zirconium). Choices *a* and *c* depict alpha and beta radiation, respectively. Choice *d* illustrates a neutron capture.

2 **[d]** The answer is element 83, which is bismuth. Each alpha decay reduces the atomic number by 2. Therefore, four decays will reduce protactinium's atomic number by 8 units. $91 - 8 = 83$.

LECTURE 7

1 **[d]** Halogens achieve a full valence shell by covalently bonding to one another in a diatomic molecule with one shared pair of electrons (a single bond). Hydrogen can do this as well, because its first energy level is just one electron shy of being full.

2 **[a]** Helium's full valence shell makes a chemically inert gas. Its behavior and properties are much more similar to other elements in group 18 (the noble gases) than to those in group 2 (the alkaline-earth metals).

LECTURE 8

1 **[a]** Lithium is the highest element on the activity series in part because in solution the small lithium atom associates strongly with water molecules, which stabilize it even further. Because lithium is so active, this means that it would require the greatest amount of energy to force an electron back onto lithium ions and produce pure lithium metal.

2 **[b]** Losing a single electron from its valence shell to become a +1 ion causes the electron configuration of sodium (element 11) to become the same as that of a neutral atom of the noble gas neon (element 10).

LECTURE 9

1 **[d]** Strontium is lower on the table than the other alkali-metal choices, predicting that it will have a lower first ionization energy and will react more easily to form ionic compounds like strontium oxide. Furthermore, strontium appears higher on the activity series than other members of the same group (Sr > Ca > Mg).

2 **[b]** The identity of each nucleus is based on the number of protons it contains. Uranium has 92 protons, 38 of which go into formation of the strontium nucleus, leaving 92 − 38, or 54 protons in the remaining nucleus. An atomic number of 54 corresponds to xenon.

LECTURE 10

1 **[d]** Choice *d* requires five bonds to carbon, placing 10 electrons in its valence shell and creating a hypervalent second-row element, which is not possible for carbon

(or any other second-row element). Choices *b* and *c* follow the octet rule. Although choice *a* violates the octet rule, phosphorus is a third-row element, which can accommodate hypervalency.

2 **[d]** Alkali metals are found only in the *s* block of the table, on the left side. Nonmetals and metalloids reside exclusively in the *p* block, while most of the weak metals are also in the *p* block.

LECTURE 11

1 **[b]** The very large electron cloud of oganesson would result in even stronger van der Waals forces than those in radon, leading to "stickier" atoms that vaporize even less easily, making for an even higher boiling point. (One prediction from the lab at Los Alamos suggests a boiling point similar to that of water.)

2 **[d]** The even atomic numbers of helium (atomic number 2) and neon (atomic number 10) have little to do with their utility as a cryogen. Their inertness, weak van der Waals interactions, and low boiling points that result from those weak interactions are all attractive features in a cryogen.

LECTURE 12

1 **[d]** Br-I would have the greatest molecular mass, so a molecule consisting of one bromine atom bonded to one iodine atom would also have the greatest density when in the gas phase.

2 **[d]** Astatine's electron configuration is similar to other halogens, suggesting that it would still have similar chemical properties, including the formation of salts when it reacts with metals. But astatine would have the highest boiling and melting points of the group due to its larger electron cloud, which would give it the greatest van der Waals forces. Also, because it is lowest in the column, astatine's electronegativity would most likely be lower than the other halogens, making it less reactive.

LECTURE 13

1 **[b]** Hydrogen bonds are special types of interactions that are weaker than covalent or ionic bonds. Hydrogen bonds can only take place when a hydrogen is directly bonded to an oxygen, nitrogen, or fluorine. Among the choices, only phenol contains a hydrogen directly bonded to an atom of oxygen, while none have hydrogen bonded directly to nitrogen or fluorine. The compound in choice *c* has no hydrogen at all. Choice *d* contains both hydrogen and nitrogen atoms, but those atoms are bonded to the carbon, not directly to one another in an N-H bond.

2 **[a]** Fixed nitrogen refers to nitrogen that has become chemically bonded to other elements, making it useful to most organisms. The remaining choices are all allotropes of pure nitrogen, which would not qualify as fixed nitrogen.

LECTURE 14

1 **[c]** Being a nonmetal with a valence of 4 causes carbon to seek out 4 covalent bonds in a network arrangement, leading to materials with very high melting points.

2 **[a]** Because it consists of discrete molecules of P_4, white phosphorus molecules can be easily separated from one another. Black and red phosphorus are network covalent materials with much higher melting points. Phosphorus pentoxide is a compound of phosphorus and oxygen and not an allotrope of the pure element phosphorus.

LECTURE 15

1 **[d]** *P*-type semiconductors are formed when a small amount of a group-13 element is doped into a sample of a group-14 metalloid, reducing the number of electrons in the bond network holding the material together. Options *b* and *c* represent *n*-type semiconductors (which in contrast are rich in electrons and commonly doped with group-15 elements), and option *a* is a combination of two group-15 elements that is not likely to semiconduct at all.

2 **[a]** Because the bonds between most metalloids and oxygen are more covalent in nature (like a nonmetal), early attempts at electrolysis failed to separate the metalloids from their oxygen compounds. Metals have a lustrous appearance and are commonly alloyed with one another. Although some metalloids are classified as chalcophiles, others are not. Furthermore, the Goldschmidt classification of elements does not correspond well with metallic versus nonmetallic behavior.

LECTURE 16

1 **[a]** Like thallium, indium is a group-13 element. Indium's $4s^2 4p^1$ valence shell means it commonly loses a single *p* electron, leaving it with a closed *s* subshell, or all three of its valence electrons to become a +3 ion.

2 **[a]** Polonium is particularly dangerous when ingested or inhaled because large alpha particles emitted from ingested polonium contain sufficient energy to damage nearby cells of internal organs.

LECTURE 17

1 **[c]** Molybdenum and tungsten hail from rows 5 and 6 of the same group in the *d* block. This means that their size and valence shell configurations are very similar, causing them to appear together in many naturally occurring materials.

2 **[a]** Rhenium's position in row 6 of group 7 gives it one of the highest melting points of all the *d*-block metals. Elements appearing near the middle of the *d* block but in lower rows tend to have valence electrons most available for metallic bonding.

LECTURE 18

1 **[b]** Elements near the middle of the *d* block most often take on a larger number of oxidation states. With 2 electrons in the 5*s* subshell and 3 electrons in the 4*d* subshell, niobium can commonly take on charges of +2, +3, +4, and +5.

2 **[a]** Chromium (VI) has an [Ar] electron configuration. After the removal of 6 electrons from a neutral chromium atom, you are left with 18 electrons in a noble gas configuration. Chromium (III) has an $[Ar]3d^3$ configuration. Titanium (II) has an $[Ar]3d^2$ configuration. Vanadium (IV) has an $[Ar]3d^1$ configuration.

LECTURE 19

1 **[a]** Hailing from the platinum group, iridium (element 77) combines a partially filled *d* subshell with resistance to oxidation that is the hallmark of good metal catalysts.

2 **[c]** Beta decay changes a neutron into a proton. Cadmium has 48 protons, so this change would result in element 49, which is indium. Neutron activation analysis of the isotope cadmium-112, for example, proceeds through this nuclear reaction: ${}^{112}\mathrm{Cd} + {}^{1}n \rightarrow {}^{113}\mathrm{Cd} \rightarrow {}^{113}\mathrm{In} + {}^{0}\beta$.

LECTURE 20

1 **[a]** Relativistic effects begin to take hold in row-6 elements with highly charged nuclei like gold. In the case of gold, relativistic effects reduce the energy gap between the 5*d* and 6*s* subshells, giving gold a visible absorption spectrum and its resulting yellow color.

2 **[a]** Zinc's electron configuration of $[Ar]4s^2 3d^{10}$, which contains closed *s* and *d* subshells, leads to weak metallic bonding. This in turn leads to lower melting points. That difference in melting points is what allows solid iron to be dipped into molten zinc without melting.

LECTURE 21

1 **[b]** Thulium and ytterbium are adjacent elements and both are heavy rare-earth metals, which will have similar size and valence. Their structural similarity makes them the most difficult to separate.

2 **[b]** The answer is samarium (element 62). Beta decay results in conversion of a neutron to a proton, causing the nucleus to take one step to the right on the table. This converts the isotope promethium-147 into samarium-147.

LECTURE 22

1 **[c]** With one additional proton compared to uranium, the fission product for neptunium would be one atomic number greater than barium (element 56), which would be lanthanum (element 57).

2 **[a]** Consistent with their smaller size compared to plutonium and their even atomic numbers, thorium (element 90) and uranium (element 92) are the only two actinides with half-lives long enough to be considered primordial.

LECTURE 23

1 **[a]** Nine neutron captures increases the mass of the nucleus to 247. Five beta decays then moves the nucleus of uranium (element 92) five steps to the right on the table, to berkelium (element 97).

$$^{238}\mathrm{U} + 9\ ^{1}n \rightarrow {}^{247}\mathrm{U} \rightarrow {}^{247}\mathrm{Bk} + 5\ ^{1}n$$

2 **[b]** It is possible that uranium and neon, with atomic numbers 92 and 10, respectively, could combine to form nobelium (element 102). The other three choices would each result in the formation of fermium (element 100).

LECTURE 24

1 **[a]** Flerovium-289 is two atomic numbers and four mass units greater than copernicium-285. This difference corresponds to an alpha particle emission.

$^{289}\text{Fl} \rightarrow {}^{285}\text{Cn} + {}^{4}\text{He}$

2 **[c]** If a fusion reaction took place, element 98 (californium) plus element 28 (nickel) would produce a nucleus with an atomic number of 126, which is predicted to be a magic number of protons as well!

BIBLIOGRAPHY

Aldersey-Williams, Hugh. *The Most Beautiful Molecule: The Discovery of the Buckyball.* Wiley, 1997. A narrative account of the discovery and uses of these unusual carbon allotropes.

Chapman, Kit. *Superheavy: Making and Breaking the Periodic Table*. Bloomsbury Sigma, 2019. A detailed account of the worldwide quest to create superheavy elements from the bottom row of the periodic table.

Dalton, John. *A New System of Chemical Philosophy, Part 1–2.* London, 1808. The author's seminal chemistry text, written in 1808, provides a remarkable window into the thinking that catalyzed the transition from alchemy to chemistry. The author explains and illustrates many of the scientific techniques used to argue for the existence of atoms. (Note that many of the elemental names, symbols, and physical data are erroneous by today's standards.)

Fontani, Marco, Mariagrazia Costa, and Mary Virginia Orna. *The Lost Elements: The Periodic Table's Shadow Side.* Oxford University Press, 2015. A compendium of stories related to the misidentification of elements; detailed notes and references follow each account.

Hager, Thomas. *The Alchemy of Air.* Random House, 2008. In this look at the history of humanity's centuries-long quest for fixed nitrogen, the author details why nitrogen is one of the most sought-after elements in nature and how scientists learned to obtain it in its fixed form.

Kean, Sam. *The Disappearing Spoon.* Back Bay Books, 2015. In this entertaining text, the author considers the influence of the elements on human history, organizing his stories by the type of influence each element has had on history rather than the position on the table.

Le Couteur, Penny, and Jay Burreson. *Napoleon's Buttons: 17 Molecules That Changed History*. Penguin Group, 2014. A collection of stories outlining the societal impact of some influential compounds of elements through history.

Livio, Mario. *Brilliant Blunders: From Darwin to Einstein*. Simon and Schuster, 2013. A survey of some of history's greatest failed scientific theories. From the big bang and the age of the Earth to DNA and genetics, the author highlights our current understanding of the cosmos by analyzing earlier erroneous scientific theories and how they were ultimately disproven.

Scerri, Eric. *The Periodic Table: Its Story and Significance*. 2nd ed. Oxford University Press, 2020. The author explores the evolution of the periodic table in exquisite detail. The link between atomic structure and the table is examined thoroughly throughout. A comprehensive bibliography is included for those interested in tracking down original peer-reviewed research reports.

Wothers, Peter. *Antimony, Gold, and Jupiter's Wolf*. Oxford University Press, 2019. The author explores the history behind how many of the elements were named, with particular attention to some of the earliest-discovered elements.

LECTURE-SPECIFIC READINGS

Lecture 1

Wothers, *Antimony, Gold, and Jupiter's Wolf*, ch. 1.

Wothers, *Antimony, Gold, and Jupiter's Wolf*, p. 83–86.

Wothers, *Antimony, Gold, and Jupiter's Wolf*, p. 148–156.

Lecture 2

Scerri, *The Periodic Table*, ch. 1–5.

Scerri, *The Periodic Table*, p. 180–190.

Lecture 3

Scerri, *The Periodic Table*, ch. 6–8.

Lecture 4

Scerri, *The Periodic Table*, ch. 8.

Lecture 5

Scerri, *The Periodic Table*, ch. 10.

Livio, *Brilliant Blunders*, ch. 4.

Lecture 6

Chapman, *Superheavy*, ch. 11.

Scerri, *The Periodic Table*, p. 175–179.

Lecture 7

Livio, *Brilliant Blunders*, ch. 8.

Scerri, *The Periodic Table*, p. 153–156.

Lecture 8

Wothers, *Antimony, Gold, and Jupiter's Wolf*, p. 145–148.

Lecture 9

Wothers, *Antimony, Gold, and Jupiter's Wolf*, p. 165–171.

Lecture 10

Kean, *The Disappearing Spoon*, p. 36–40.

Kean, *The Disappearing Spoon*, p. 158–160.

Lecture 11

Wothers, *Antimony, Gold, and Jupiter's Wolf*, ch. 8.

Lecture 12

Kean, *The Disappearing Spoon*, p. 83–87.

Le Couteur and Burreson, *Napoleon's Buttons*, p. 313–319.

Wothers, *Antimony, Gold, and Jupiter's Wolf*, ch. 7.

Lecture 13

Hager, *The Alchemy of Air*.

Le Couteur and Burreson, *Napoleon's Buttons*, ch. 4.

Lecture 14

Aldersey-Williams, *The Most Beautiful Molecule*.

Wothers, *Antimony, Gold, and Jupiter's Wolf*, p. 74–82.

Lecture 15

Kean, *The Disappearing Spoon*, p. 41–46.

Wothers, *Antimony, Gold, and Jupiter's Wolf*, p. 45–47.

Lecture 16

Kean, *The Disappearing Spoon*, p. 156–161.

Lecture 17

Scerri, *The Periodic Table*, p. 259–268.

Lecture 18

Fontani, Costa, and Orna, *The Lost Elements*, p. 14–16.

Kean, *The Disappearing Spoon*, p. 88–94.

Kean, *The Disappearing Spoon*, p. 112–114.

Lecture 19

Haber, *The Alchemy of Air*, p. 187–191.

Lecture 20

Kean, *The Disappearing Spoon*, p. 152–156.

Lecture 21

Fontani, Costa, and Orna, *The Lost Elements*, p. 161–177.

Lecture 22

Chapman, *Superheavy*, ch. 1–3.

Kean, *The Disappearing Spoon*, p. 161–166.

Lecture 23

Chapman, *Superheavy*, ch. 5–8.

Lecture 24

Chapman, *Superheavy*, ch. 12–21.

IMAGE CREDIT

Page iv: © Jakub Rupa/iStock/Getty Images Plus;

Page 4: © pialhovik/iStock/Getty Images Plus

THE GREAT COURSES®

Printed in the United States of America

4840 Westfields Boulevard
Suite 500
Chantilly, VA 20151-2299
USA
1-800-832-2412
www.thegreatcourses.com