

King of Dumbs

Level: ♠ Technical

What is a wall made of? Atoms and elements without fear

Protons, neutrons and electrons, elements and isotopes, diamond versus graphite and the mole, explained with building blocks, in three levels.

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<https://kingofdumbs.com/en/lessons/atoms-and-elements>

What you'll learn

- What's inside an atom
- Element, isotope and ion
- Molecule and bond: diamond versus graphite
- The mole

Symbols you'll meet

Δ change: how much it moved (♠) · E_a subscript: the label underneath (♦♠) · H° ° for standard, not degrees (♠) · Σ sum: add them all up (♠) · x_i index i: item number i (♠) · $\approx$ approximately equal (♦♠) · $\sim$ on the order of / distributed as (♠) · $\rightarrow$ arrow: turns into / tends to (♠) · 10^{-3} negative exponent: divide (♦♠) · J/(mol·K) compound units (♦♠) · α alpha: learning rate or particle (♦♠)

Look at a wall. It's made of bricks, and each brick is made of baked clay. Now imagine you keep breaking it: the brick into chunks, the chunks into grains, the grains into smaller and smaller bits. Keep going and you always end up at the same place: **atoms**.

The dumb question of this lesson is: **what is a wall made of?** The answer is surprising: just three kinds of piece. They're the same ones that make up your hand and the air you breathe. What changes is how many you use and how you put them together, just like a box of building blocks.

This lesson teaches four ideas: what's inside an atom, what makes an atom one element or another, how the same pieces give very different things, and how you count atoms by the heap.

Pick your card: ♣ if you're starting from scratch, ♦ if a simple formula doesn't scare you, ♠ if you want the notation. You can switch at any time.



Inside the atom

♦ → ♠ From intermediate to technical

In ♦ we said	In ♠ we write
on the order of 10^{-15} m	$R = r_0 A^{(1/3)}$, $r_0 \approx 1.2$ fm (1 fm = 10^{-15} m)
the protons and neutrons of the nucleus	A: number of nucleons
atomic mass units (u)	$u = m(^{12}\text{C})/12 = 1.660\,539\,068\,92(52) \times 10^{-27}$ kg
a proton weighs as much as 1,836 electrons	$m_p/m_e = 1836.152\,673\,426(32)$
positively charged	$q = +e$, $e = 1.602\,176\,634 \times 10^{-19}$ C (exact)
almost all empty	$V_{\text{nucleus}} / V_{\text{atom}} \sim (10^{-15} / 10^{-10})^3 = 10^{-15}$
almost all the mass in a tiny point	nuclear density $\rho \approx 2.3 \times 10^{17}$ kg/m ³

$$R = r_0 \cdot A^{(1/3)}, r_0 \approx 1.2 \text{ fm}$$

$$\rho \approx u / (4/3 \pi r_0^3) \approx 2.3 \times 10^{17} \text{ kg/m}^3$$

$$m_p / m_e = 1836.152\,673\,426(32)$$

$$(10^{-15} \text{ m} / 10^{-10} \text{ m})^3 \approx 10^{-15} \text{ (volume)}$$

Scattering measurements give a nuclear radius $R = r_0 A^{(1/3)}$, with $r_0 \approx 1.2$ fm and A the number of nucleons (OpenStax, *University Physics* vol. 3, 10.1). R growing as $A^{(1/3)}$ means the volume grows as A: nucleons pack at **constant density**, like drops of a liquid that won't compress.

That density comes from putting a mass u in a sphere of radius r_0 : $\rho \approx u / (4/3 \pi r_0^3) \approx 2.3 \times 10^{17}$ kg/m³, the same value OpenStax works out for iron-56 (HyperPhysics gives 2×10^{17}). One cubic centimetre of nuclear matter would weigh about 2.3×10^{11} kg.

With $m_p/m_e = 1836.15$ (CODATA 2022), in an atom with as many neutrons as protons the electrons are 0.03% of the mass. Volume goes the other way: with $R_{\text{atom}}/R_{\text{nucleus}} \sim 10^5$, the nucleus fills $\sim 10^{-15}$ of the volume.

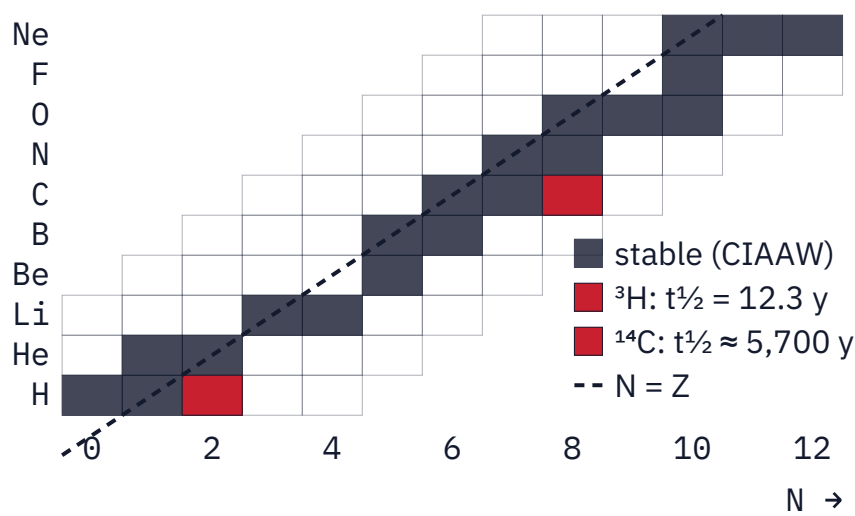
Rutherford inferred the nucleus (*Phil. Mag.* 21, 669, 1911) from α particles scattered at large angles, impossible in an atom with its charge spread out. Chadwick identified the neutron (*Nature* 129, 312, 1932). Since 2019, e is exact by definition; u is, by definition, one twelfth of the mass of a ^{12}C atom.



Elements and isotopes

♦ → ♠ From intermediate to technical

In ♦ we said	In ♠ we write
atomic number (Z)	Z
the neutrons are $A - Z$	$N = A - Z$
mass number (A)	$A = Z + N$; nuclide $^A_Z X$
whether the nucleus holds	chart of nuclides: stable and radioactive by (Z, N)
abundance	atom fraction x_i , with $\sum x_i = 1$
half-life	$t_{1/2}$: $N(t) = N_0 \cdot 2^{(-t / t_{1/2})}$
charge	$q = (Z - n_e) \cdot e$



A nuclide is fixed by (Z, N) . The chart of nuclides lays them out with N on the horizontal axis and Z on the vertical. Between $Z = 1$ and 10, CIAAW lists **20 stable nuclides**, all with N between $Z - 1$ and $Z + 2$: in light nuclei, stability hugs the diagonal $N = Z$. Beryllium and fluorine have just one each (^9Be and ^{19}F).

Being in the band isn't enough: nuclides missing from that list, inside or outside it, decay. Each nucleus does so with a constant probability per unit time, so the number of nuclei follows $N(t) = N_0 \cdot 2^{(-t/t_{1/2})}$. Two examples, both inside the band:

- **^3H (tritium):** $t_{1/2} = 12.32$ years (OpenStax, table 10.1); TUNL recommends 12.323 ± 0.020 years. It turns into ^3He .
- **^{14}C :** OpenStax gives 5,730 years and TUNL recommends $5,686 \pm 40$ (mean of recent measurements, $5,699 \pm 20$). With about 5,700 years, after 11,400 a quarter is left.

The abundances x_i aren't universal constants: they depend on where the sample comes from. CIAAW gives ^{13}C a range of 0.0096 to 0.0116 in normal terrestrial material.

An ion's charge is $q = (Z - n_e) \cdot e$. Changing n_e is chemistry (ionising); changing Z is nuclear physics.

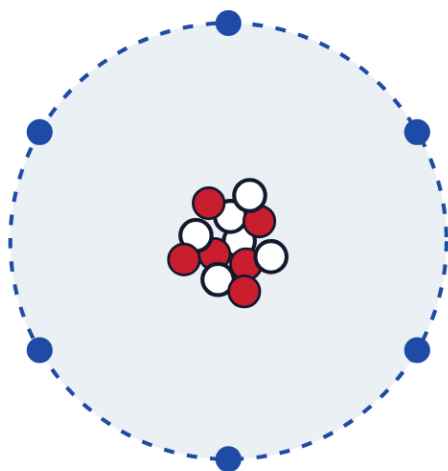
The King of Dumbs says:

Add neutrons to a carbon and it's still carbon. To change the element you have to touch the protons, and that's not chemistry anymore.



Try it: build an atom

Move the protons, neutrons and electrons. See which element you get, whether the nucleus holds and whether the atom ends up charged. Try 6 protons and 8 neutrons.



^{12}C

carbon-12

- proton
- neutron
- electron

Protons (they decide the element) 6

Neutrons 6

Electrons 6

Element Carbon (C)

Isotope carbon-12

Written as ^{12}C

Nucleus Stable: it doesn't fall apart.

Charge Neutral: as many electrons as protons.

Carbon-12. Stable: it doesn't fall apart. Neutral: as many electrons as protons.



Interactive widget. Try it on the web: <https://kingofdumbs.com/en/lessons/atoms-and-elements>

Same pieces, built differently

♦ → ♠ From intermediate to technical

In ♦ we said	In ♠ we write
chemical bonds	single C–C bond (1.54 Å) and double C=C (1.34 Å)
4, at the corners of a tetrahedron	sp^3 hybridisation, angle $\arccos(-1/3) \approx 109.5^\circ$
3, in flat sheets	sp^2 hybridisation, 120° angle
1.4×10^{-10} m	$d = 1.4 \text{ Å}$ ($1 \text{ Å} = 10^{-10} \text{ m}$)
weak forces	non-covalent interactions between layers
the most stable form	$\Delta G^\circ < 0$: $\Delta_r G^\circ(\text{diamond} \rightarrow \text{graphite}) = -2.9 \text{ kJ/mol}$
break its bonds	C–C bond energy $\approx 345 \text{ kJ/mol}$
doesn't turn	metastable (kinetic stability)



single C–C: 1.54 Å, 345 kJ/mol
 diamond → graphite: $\Delta G^\circ = -2.9 \text{ kJ/mol}$

In diamond, each carbon is sp^3 and bonds to 4 carbons at the corners of a tetrahedron; in graphite it's sp^2 and bonds to 3 in the plane (UW–Madison, Chem 109). The tetrahedral angle comes from two vectors to opposite corners, (1, 1, 1) and (1, -1, -1): $\cos \theta = -1/3$, $\theta \approx 109.47^\circ$. The three bonds of a hexagonal plane are at 120° .

OpenStax table 7.3 gives the single C–C bond an average length of 1.54 Å and 345 kJ/mol, and the double C=C bond 1.34 Å. The distance between neighbours in a graphite sheet, $\sim 1.4 \text{ Å}$, falls between the two. The sheets are held only by non-covalent interactions, which is why graphite marks paper.

Thermodynamics at 25 °C: diamond’s Gibbs energy is 2.90 kJ/mol above graphite’s (OpenStax, appendix G), so $\Delta_r G^\circ(\text{diamond} \rightarrow \text{graphite}) = -2.9 \text{ kJ/mol}$, the same figure UW–Madison gives. The sign says graphite is more stable. Kinetics says otherwise: rearranging the lattice means breaking C–C bonds of about 345 kJ/mol, some 120 times what is gained per mole. Diamond is **metastable**.



Counting atoms: the mole

♦ → ♠ From intermediate to technical

In ♦ we said	In ♠ we write
exactly $6.022\,140\,76 \times 10^{23}$	$N_A = 6.022\,140\,76 \times 10^{23} \text{ mol}^{-1}$
a number of things	amount of substance $n = N / N_A$
grams per mole	molar mass $M = m / n$
the same digits as the mass of one particle in u	$M = A_r \cdot M_u, M_u = 1.000\,000\,001\,05(31) \text{ g/mol}$
mixture of isotopes	$A_r(\text{C}) = \sum_i x_i \cdot A_r(^i\text{C})$

$$\begin{aligned} A_r(\text{C}) &= \sum_i x_i \cdot A_r(^i\text{C}) \\ &= 0.9893 \cdot 12 + 0.0107 \cdot 13.0034 \\ &\approx 12.0107 \in [12.0096, 12.0116] \end{aligned}$$

$$M = A_r \cdot M_u, M_u \approx 1 \text{ g/mol}; n = N / N_A$$

Amount of substance is $n = N / N_A$, with N_A fixed exactly since the 2019 SI redefinition. Molar mass is $M = A_r \cdot M_u$. Before 2019, M_u was 1 g/mol by definition. Now it’s measured: $M_u = 1.000\,000\,001\,05(31) \text{ g/mol}$ (CODATA 2022). The difference, one part in a billion, doesn’t show outside metrology. With that value, $M(^{12}\text{C}) = 12 M_u \approx 12.000\,000\,013 \text{ g/mol}$.

An element’s atomic weight is the mean of its isotopes’ masses, weighted by their abundance. For carbon, with NIST’s representative fractions, 0.9893 and 0.0107: $A_r(\text{C}) = 0.9893 \cdot 12 + 0.0107 \cdot 13.003\,355 \approx 12.0107$. Since the abundance of ^{13}C varies from sample to sample, CIAAW gives not a number but a range, [12.0096, 12.0116]. Routine calculations use the conventional value 12.011.



Final challenge

1. An atom has 6 protons and 8 neutrons. What is it?

- a. Nitrogen, because it has 14 pieces in the nucleus
- b. Carbon-14: 6 protons is carbon
- c. Oxygen, because it has 8 neutrons

2. What's the difference between a diamond and pencil lead?

- a. Diamond has an element graphite doesn't
- b. Both are just carbon, but their atoms hook together differently
- c. Graphite is dirty carbon

3. A mole of water and a mole of iron have...

- a. The same mass
- b. The same number of particles
- c. The same volume



In three sentences

1. Everything you touch is made of atoms, and every atom is three pieces: protons and neutrons in a tiny nucleus that holds almost all the mass, and electrons around it.
2. Protons decide the element, neutrons the isotope and electrons the charge: changing neutrons or electrons doesn't turn carbon into anything else.
3. The same pieces built differently give different things (diamond and graphite are just carbon), and to count them we use the mole, a giant dozen of 6×10^{23} .



Sources

- Atom, nucleus, particles and sizes: OpenStax, *Chemistry 2e*, [2.2](#) and [2.3](#) (table 2.2, the blueberry and the stadium), cross-checked with [OpenStax, University Physics vol. 1, 1.1](#). Molecules: [OpenStax, 2.4](#).
- Nuclear radius and density, and half-lives: [OpenStax, University Physics vol. 3, 10.1](#), cross-checked with [HyperPhysics](#) and with TUNL, [3H](#) and [14C](#). Carbon-14 in the atmosphere: [OpenStax, Chemistry 2e, 21.3](#).
- History: Rutherford, *Phil. Mag.* 21, 669 (1911), [doi:10.1080/14786440508637080](#); Chadwick, *Nature* 129, 312 (1932), [doi:10.1038/129312a0](#).
- Constants (CODATA 2022): [m_p/m_e](#), [u](#), [M_u](#) and [N_A](#). Definition of the mole and the elementary charge: [BIPM, SI Brochure](#).
- Stable isotopes and abundances: [CIAAW](#). Standard atomic weights (2024): [CIAAW](#). Representative masses and fractions for carbon: [NIST](#).
- Diamond and graphite: [OpenStax, Chemistry 2e, 10.5](#) and [UW–Madison, Chem 109, D26.1](#). Bonds: [OpenStax, 7.5, table 7.3](#). Formation energies: [OpenStax, appendix G](#).
- The mole as a dozen and molar mass: [OpenStax, Chemistry 2e, 3.1](#).

How this lesson was made: researched and written with help from Claude, from the sources above, checked and cross-checked against a second source between 13 and 15 October 2026. Numbers without their own link are calculations from them. The drawings are our own.

Answers

1. **b)** Carbon-14: 6 protons is carbon. That's it. Protons decide the element; neutrons, the isotope.
2. **b)** Both are just carbon, but their atoms hook together differently. Right. Same pieces, different build: 4 neighbours in diamond, 3 in graphite.
3. **b)** The same number of particles. Exactly. A mole is a number, like a dozen: 6×10^{23} . They weigh different amounts: 18 g and almost 56 g.

A King of Dumbs lesson, kingofdumbs.com. Offline version; the original, with widgets you can play with, is at: <https://kingofdumbs.com/en/lessons/atoms-and-elements>

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