Chapter 2

Atoms, Molecules & Ions

Two Schools of Thought

- Democritus
- All matter is made of small particles called atoms

- Zeno
- Matter is infinitely divisible

Who was correct?

- Matter is made of atoms
- Atoms can be divided into subatomic particles…
- But they lose their characteristic properties
- and are just a pile of electrons, protons and neutrons

Three Kinds of Matter

- Elements
- Compounds
- Mixtures

Pure Substances versus Mixtures

- Pure substance
- Always has same ratio of atom types
- It's an element or compound

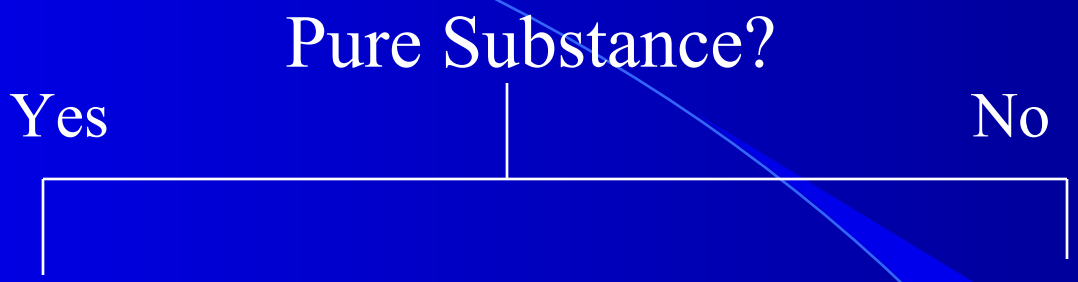
- Mixture
- Can have different ratios of atom types
- It's homogenous (smooth/transparent) or heterogeneous (chunky/translucent)

Classification of Matter

Classification of Matter

Pure Substance?

Classification of Matter



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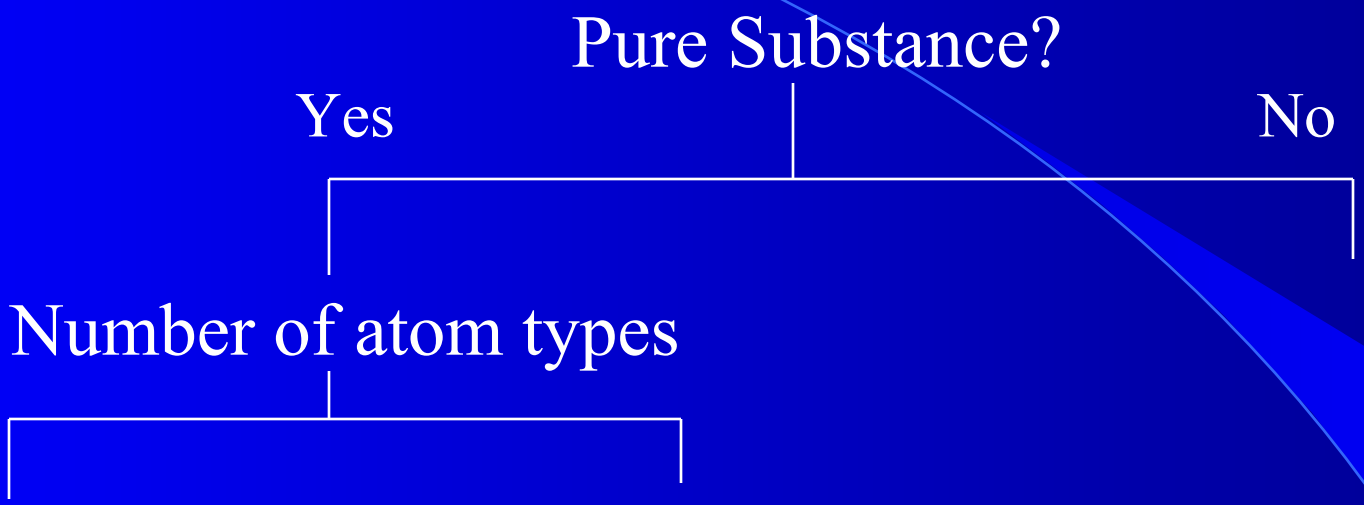

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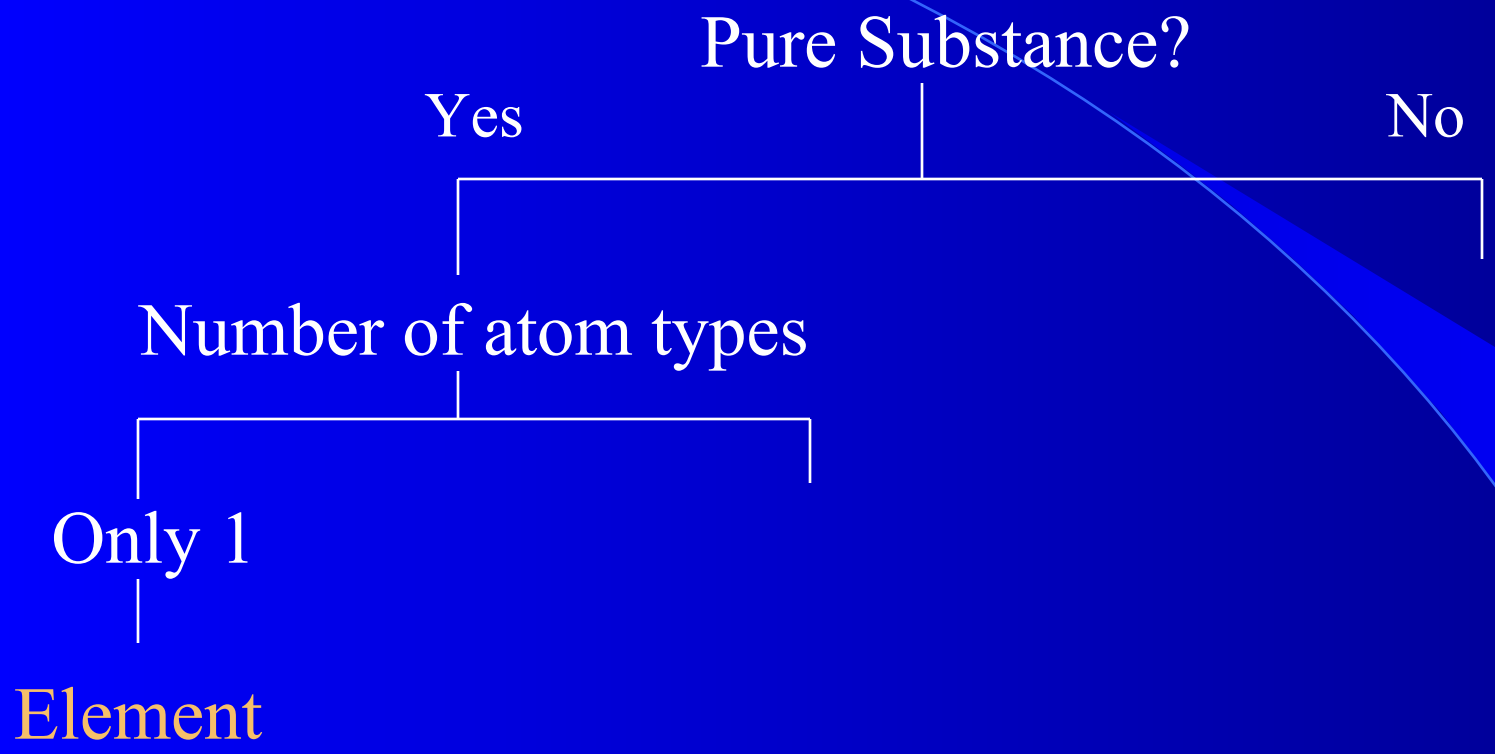

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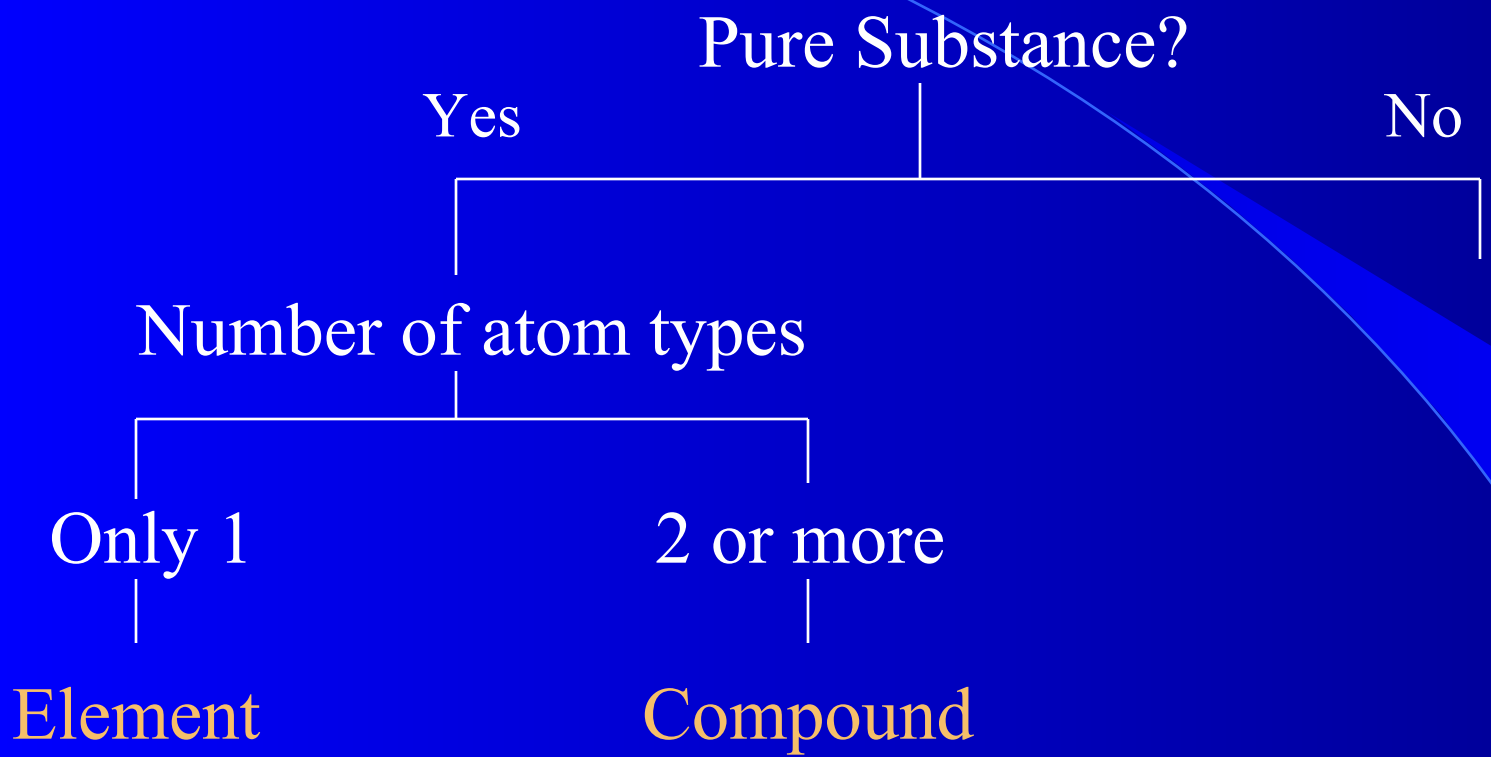

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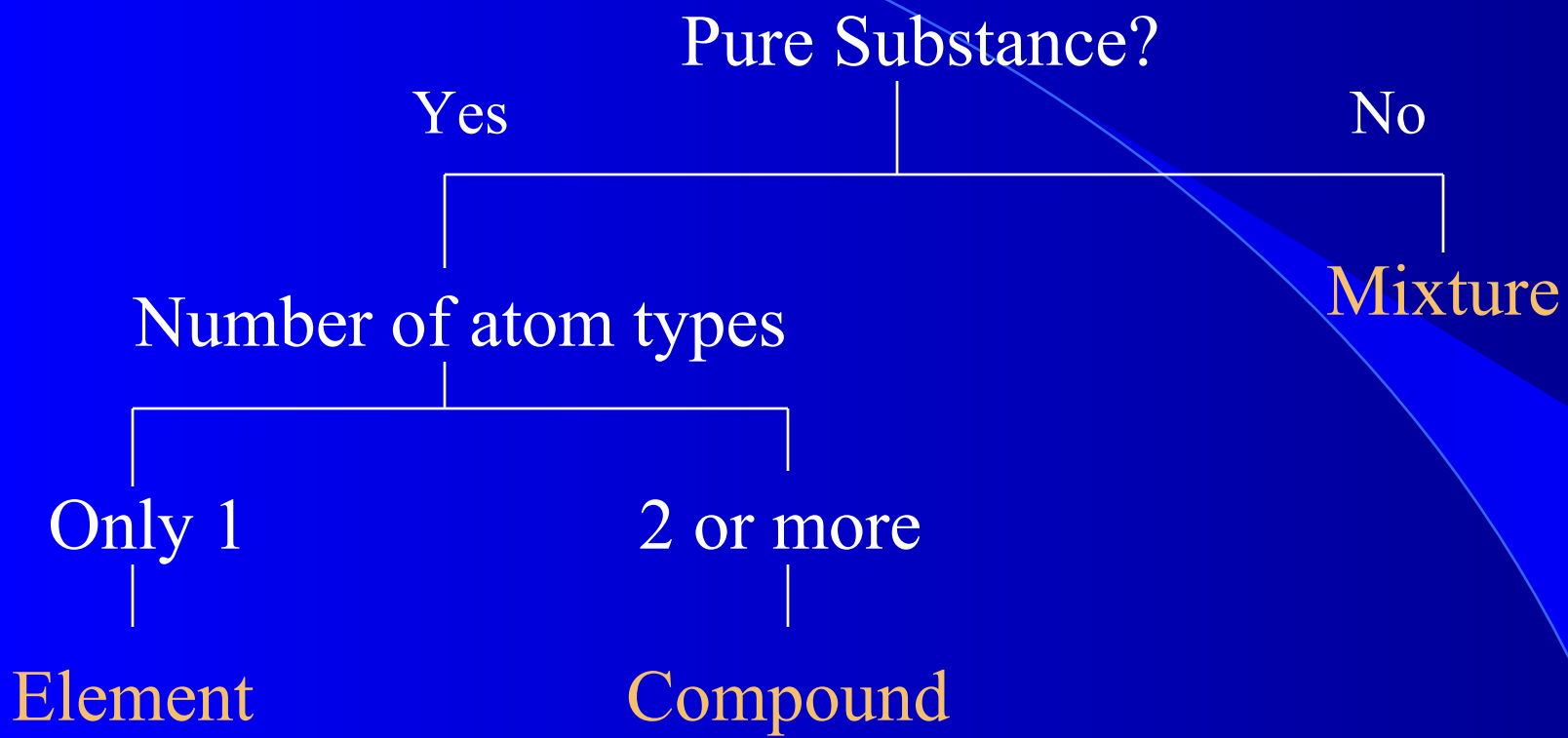

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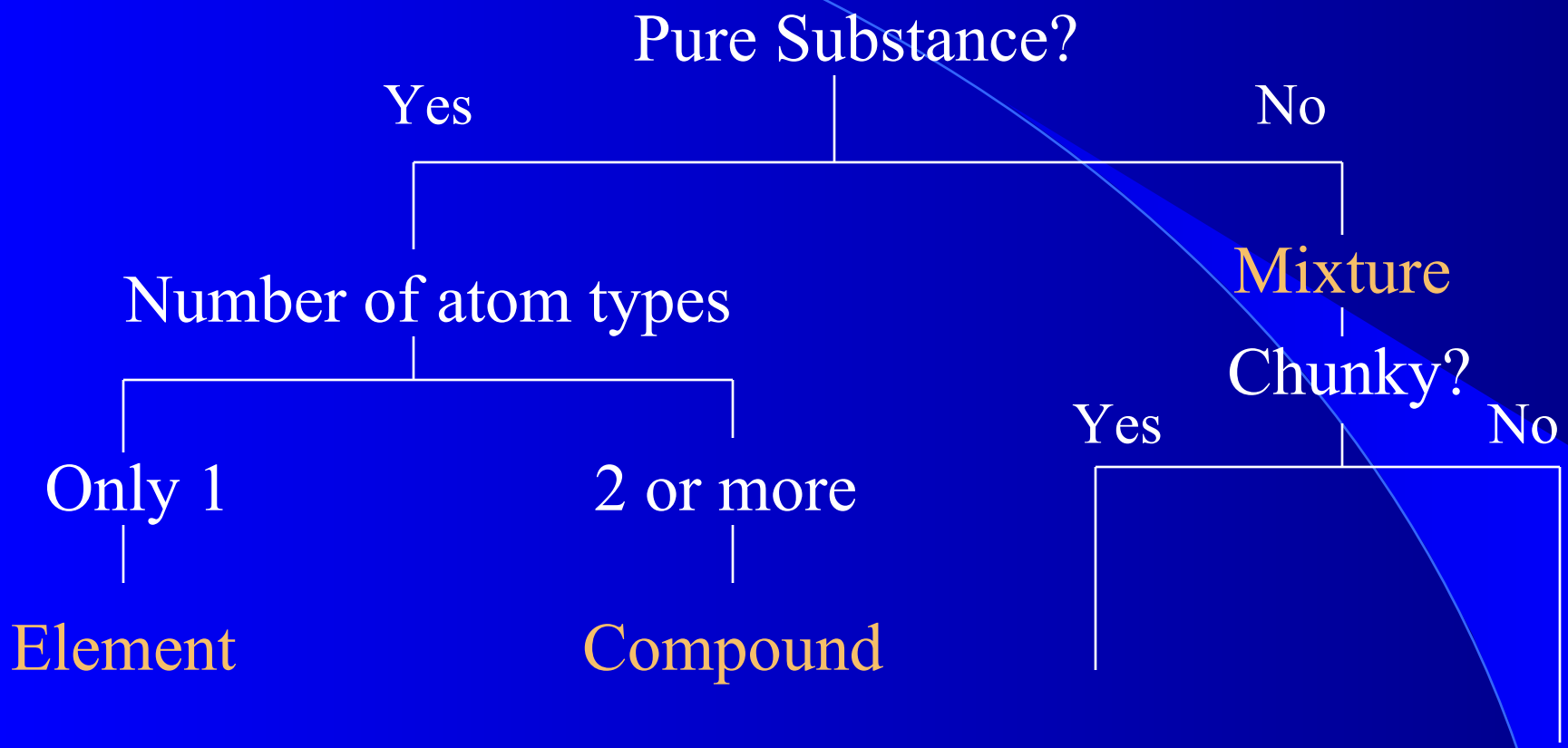

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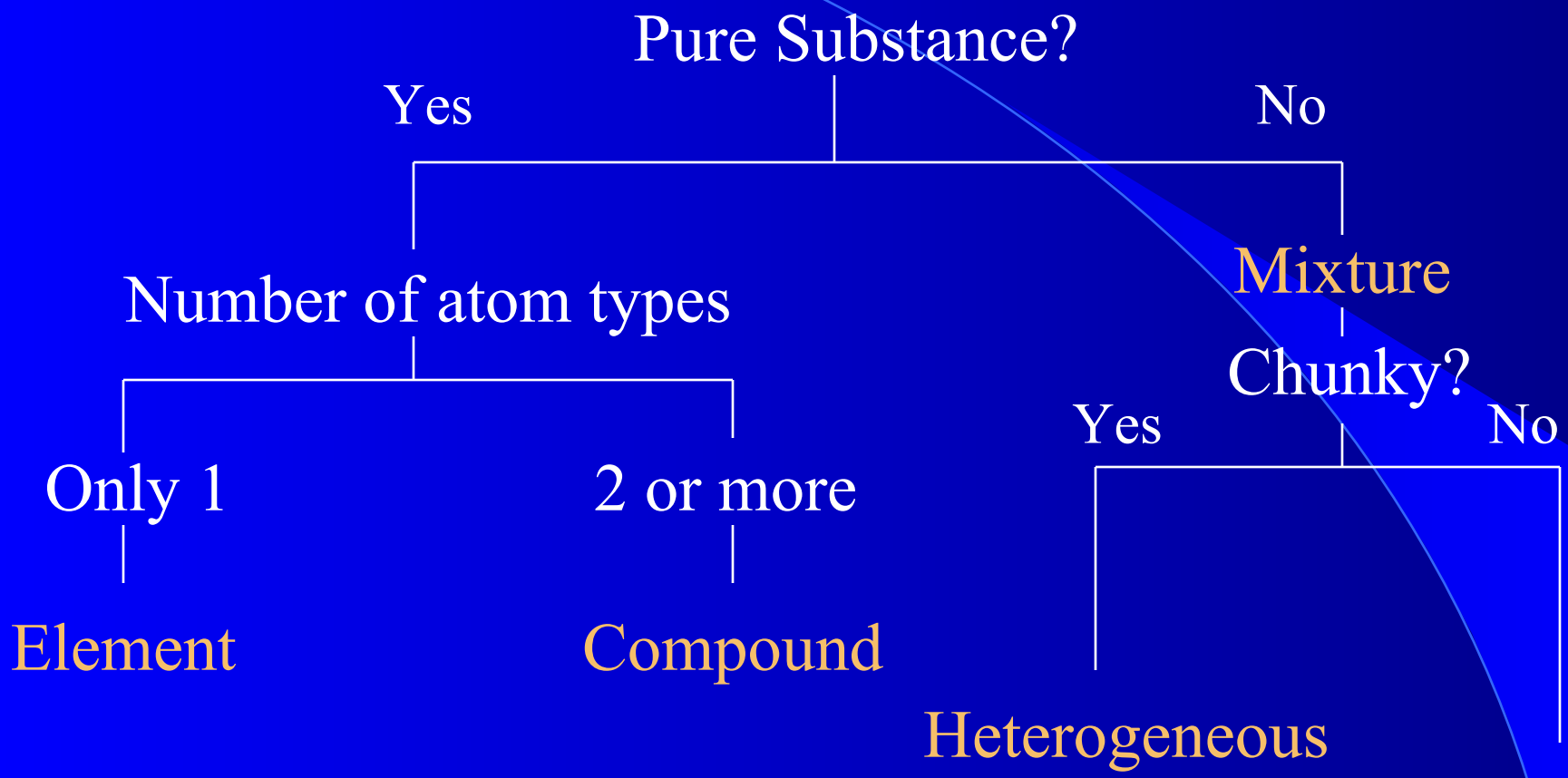

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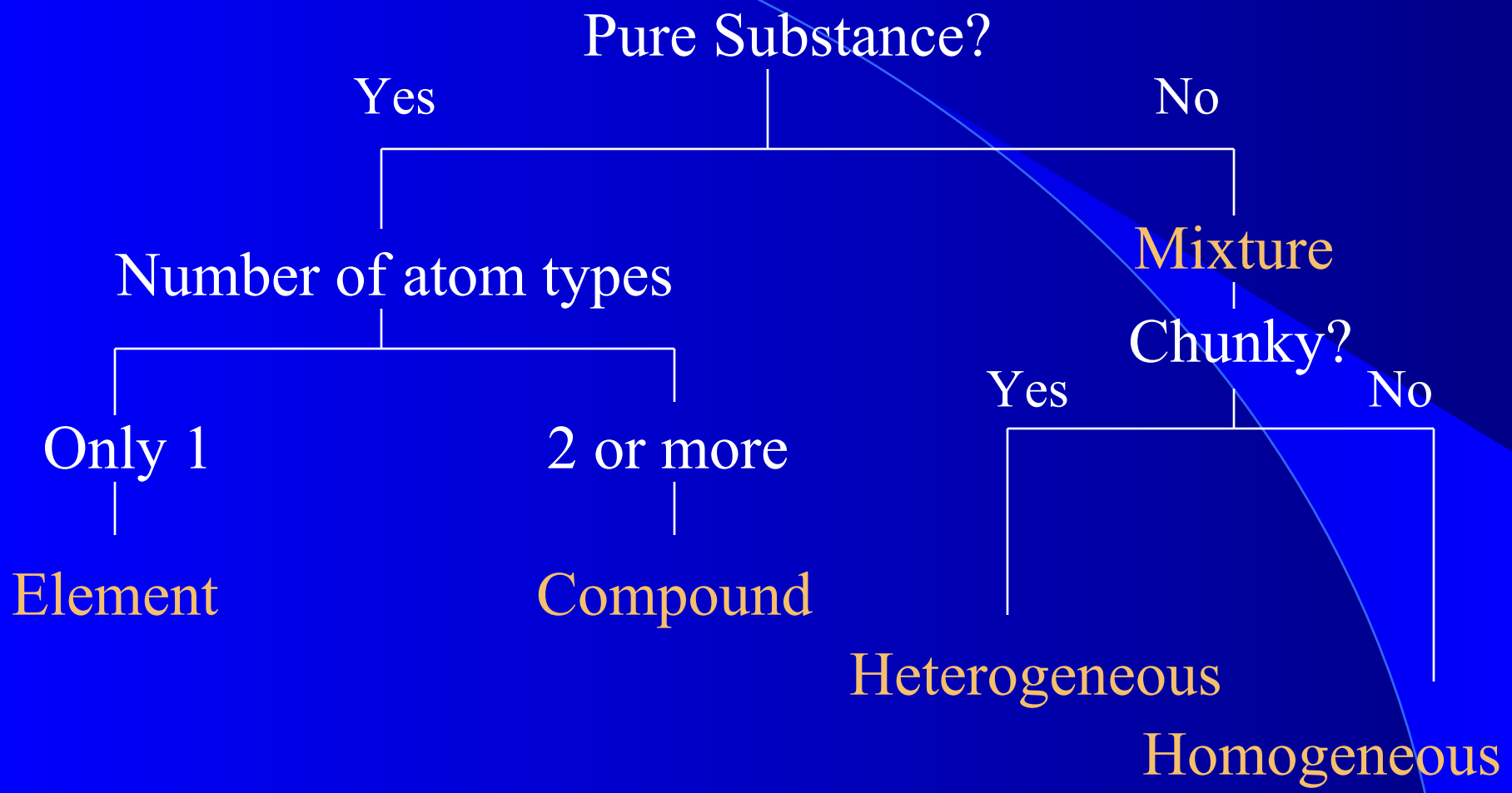

Samples...

- Native copper (Cu) a metallic element
- Sulfur (S) a nonmetallic element
- Lithium (Li) a metallic element
- Galena a compound
  - a.k.a. lead(II) sulfide
- Belt Mountain ore a heterogeneous mixture

Elements

- 118 known at this time; 94 occur in nature
- Most only discovered in last 200 years
- The periodic table lists the atomic symbols for the elements
- Learn those on the handout for Monday's quiz (spelling counts!)
- Here are all their names pronounced for you!
- http://www.privatehand.com/flash/elements.html
- Fun info about each element at
- http://www.periodicvideos.com

Element Forms

- Monatomic elements
- He, Ne, Ar, Kr, Xe, Rn
- Diatomic molecules
- H_2, N_2, O_2, F_2, Cl_2, Br_2, I_2
- Polyatomic molecules
- P_4, S_8

Element Forms

- Network elements
- C* (graphite, diamond)
- Metals (e.g., Cu, Au, Fe)
- There is no such entity as a molecule for network elements

  * C_{60}, one type of buckyball, is a molecule

Mixtures...

- Can be separated by physical means
- Common methods include
- filtration (coffee)
- evaporation (salt)
- distillation (vinegar)
- fractional crystallization (fresh water ice out of sea water)

What is Gatorade?

1. An element
2. A compound
3. A homogeneous mixture
4. A heterogeneous mixture

Element, Compound or Mixture?

- Gatorade - it's a HETEROGENEOUS (murky) MIXTURE of sugar, water flavoring, electrolyte salts, etc.
- Baking soda, $NaHCO_3$
- Cl_2 gas

What is baking soda, $NaHCO_3$?

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- Baking soda, $NaHCO_3$ - it's a COMPOUND named sodium bicarbonate or sodium hydrogen carbonate
- Cl_2 gas

What is chlorine gas, Cl_2?

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Element, Compound or Mixture?

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- Baking soda, $NaHCO_3$ - it's a COMPOUND named sodium bicarbonate or sodium hydrogen carbonate
- Cl_2 gas - it's an ELEMENT since only one kind of atom is present

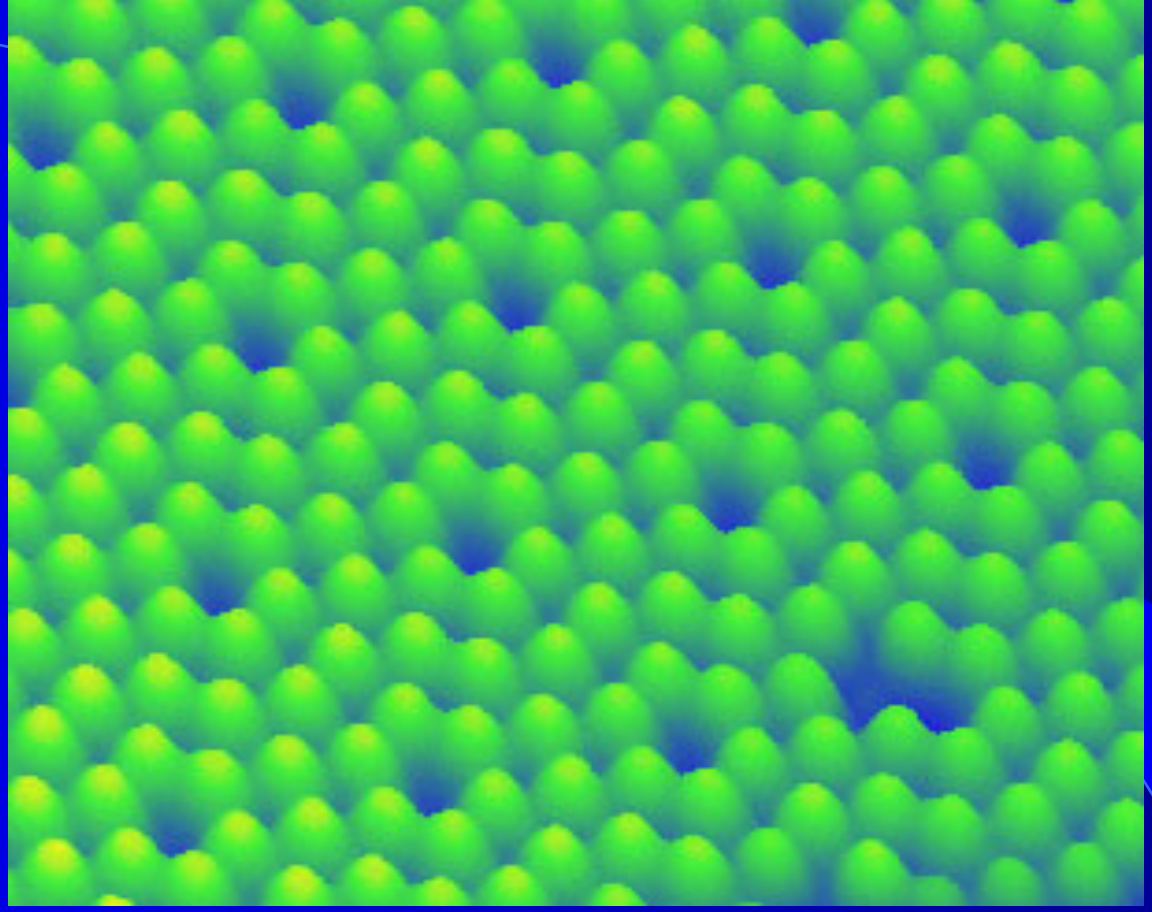
Dalton's Atomic Theory

- John Dalton (English chemist) proposed theory in 1808
- Built on Lavoisier's conservation of mass
- Matter is neither created nor destroyed
- Used Proust's law of constant composition
- Compounds always have same atom ratio

2.4 INSIDE THE ATOM!

Atoms are tiny

- Size range
- 7.4×10^{-11} m for hydrogen (74 pm)
- 5.2×10^{-10} m for cesium (520 pm)
- Mass range
- 1.67×10^{-24} g for hydrogen
- 3.95×10^{-22} g for uranium



Silicon atoms arranged on a face of a crystal. It is impossible to "see" atoms this way using ordinary light. The image was made by a Scanning Tunneling Microscope, a device that "feels" the cloud of electrons that form the outer surface of atoms,

http://www.aip.org/history/einstein/atoms.htm

Atoms are built from...

- Protons
- Electrons
- Neutrons

- But what holds them together?

Fundamental forces

Strong nuclear force

Strong but short range ($\sim 10^{-15}$ m)

Electrostatic (electromagnetic) forces

Intermediate and midrange ($\sim 10^{-10}$ m)

Gravity

Weak but long range (light years!)

Strong nuclear force

- Used as “glue” between protons and neutrons in the nucleus
- Protons repel each other, but the strong nuclear force overwhelms the electrostatic repulsion
- Beyond 83 protons (bismuth), all nuclei become unstable

Electrostatic Forces...

- Electrostatic forces are dominant once particles are more than 10^{-15} m apart
- Protons and electrons are more than 10^{-15} m apart
- **ELECTROSTATIC INTERACTIONS ARE THE DRIVING FORCE BEHIND CHEMISTRY!**

Charge behaviors..

- Like charges repel
  - + repels + - repels -
- Unlike charges attract
  - + attracts -
- Neutral charges are indifferent
  - 0 ignores + and - and 0

The US Office of Naval Research just unveiled its new rail-gun that uses charge repulsion to accelerate a sliding metal conductor between two rails and launch a 28-pound HVP up to 5,600 mph!

The Atomic Nucleus

- Protons and neutrons are packed into a HIGH density nucleus

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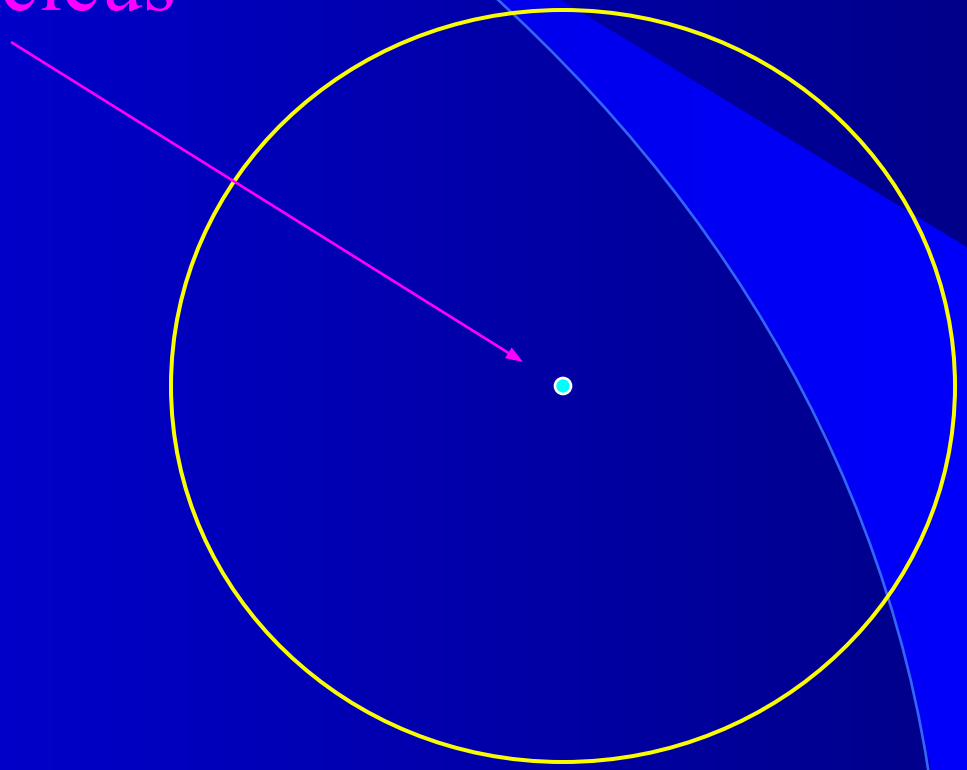


The Atomic Nucleus

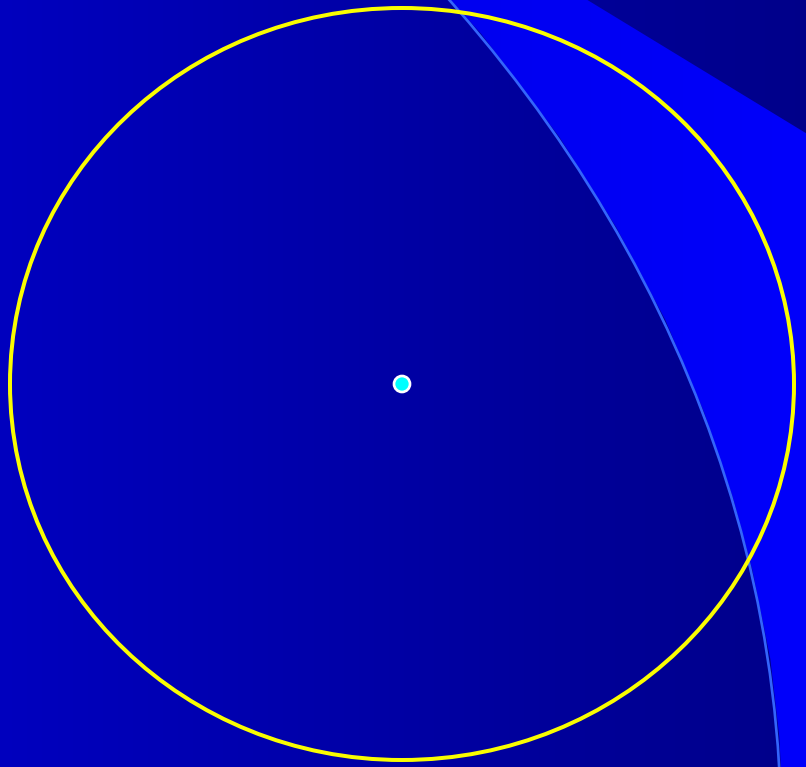
- Protons and neutrons are collectively called nucleons
- Strong nuclear force holds nucleus together
- Neutrons can be viewed as “proton glue”

Nuclear Density

- Incredibly dense: 1.8×10^{14} g/cm^3
- A paper clip with this density would weigh 10,000,000 tons!
- Neutrons stars have this density
- As they rapidly spin they give off radio waves and are known as pulsars

The electron cloud

- Electrons move through the space surrounding the nucleus in unknown trajectories



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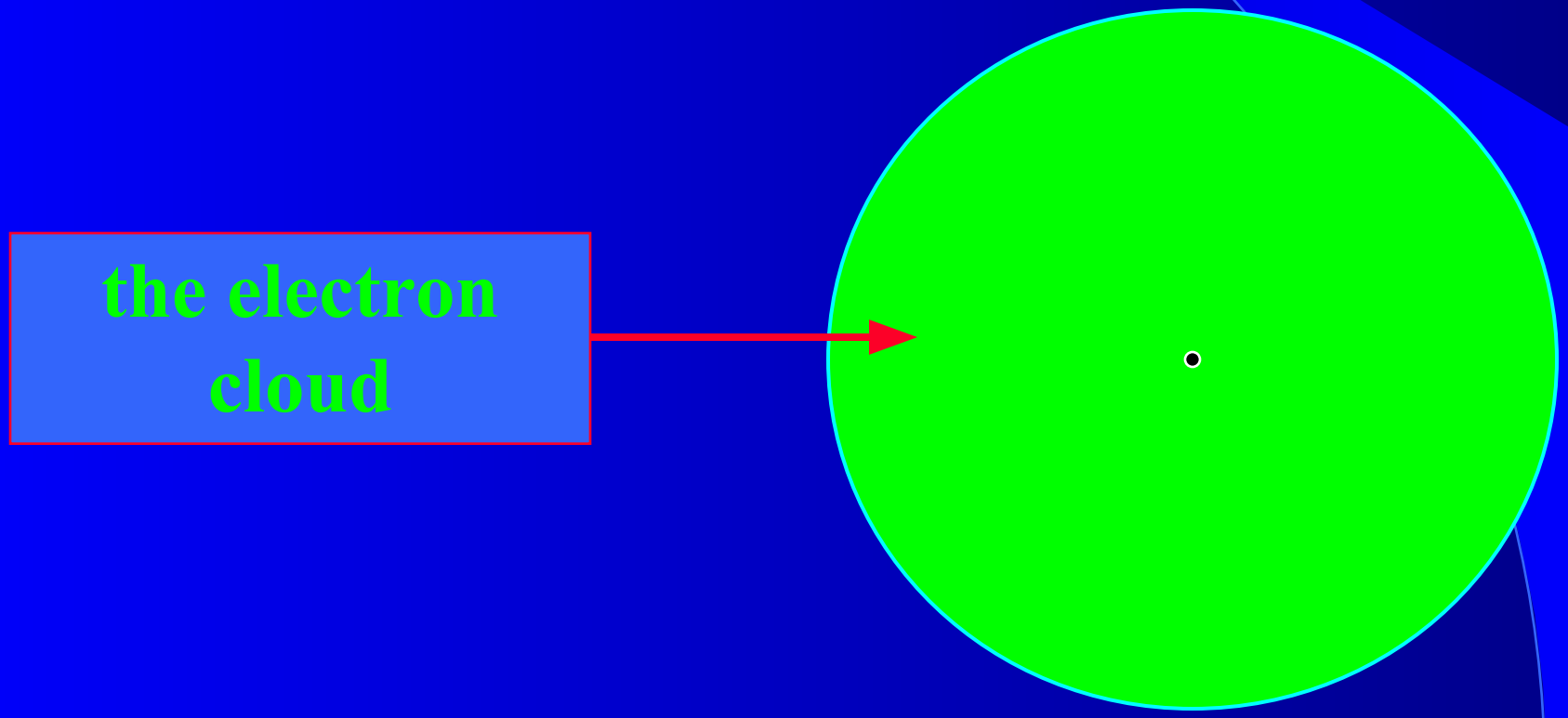

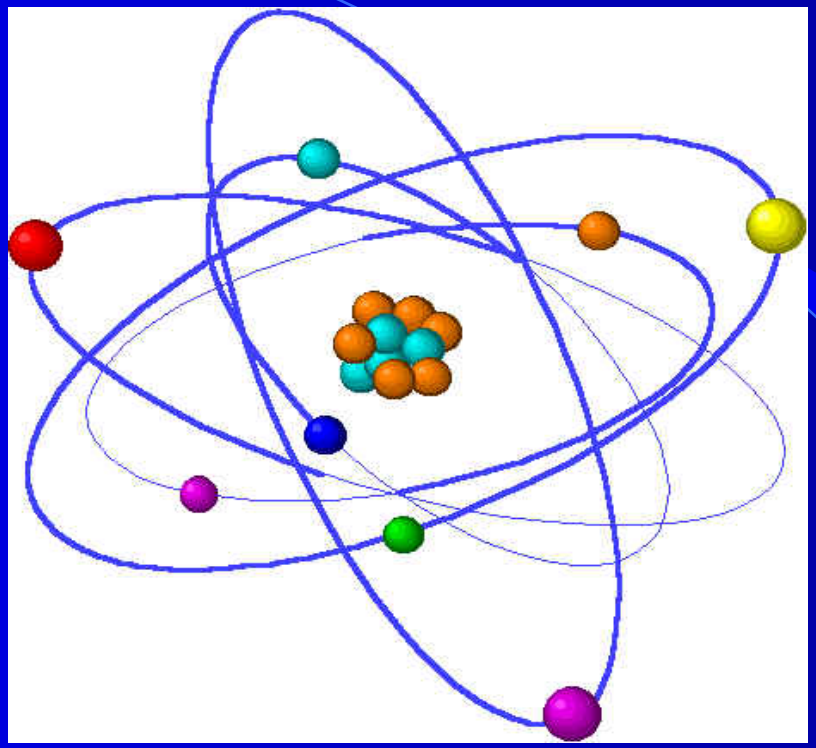

An inaccurate diagram of an atom!

http://sciencecabin.com/there-are-three-parts-of-the-atoms/

The electron cloud

- Atoms are mostly empty space
- Nuclear diameter: 10^{-15} m
- Electron cloud diameter: 10^{-10} m
- If the nucleus is pea-sized,
- the electron cloud is as big as a domed football stadium!

Subatomic Particles

Table : Subatomic Particles

Particle	Symbol	amu's	grams	Charge

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Electron	e^-	0.0005486	9.110×10^{-28}	-1
Neutron	n	1.0087	1.675×10^{-24}	0

Atomic Mass Units (amu)

- Masses of atoms and subatomic particles are so small that they are often expressed on a relative scale
- 1 amu = 1/12 the mass of a carbon-12 atom
- $= 1.6605 \times 10^{-24}$ g
- = 1 dalton (biochemistry)

Atomic Number, Z

- Atom type determined by number of protons in nucleus
- # of protons = atomic number
- = Z
- Atomic numbers are integers that increase through the periodic table

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Neutral Atoms

- When an atom is uncharged (electrically neutral)…
- # of protons = # of electrons
- # of p^+ = # of e^-
- Z = # of e^-

Consider a neutral copper atom...

- Number of protons: $Z = ?$

Consider a neutral copper atom...

- Number of protons: $Z = 29$

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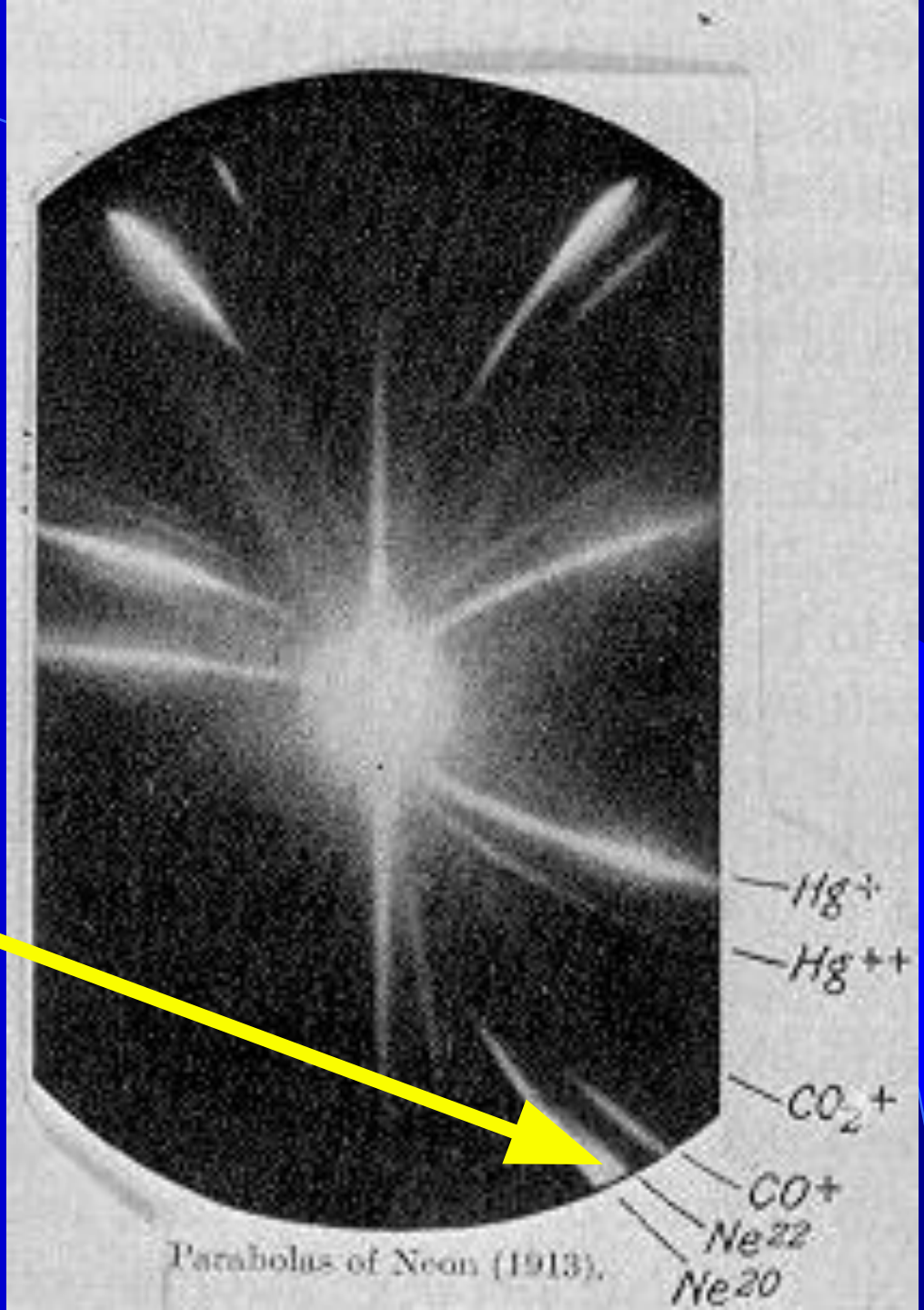
Mass Number, A

- When weighing chemicals, need to account for neutrons, too.
- # of neutrons is not fixed for an atom type

The first evidence of different masses appeared at the bottom right corner of this J. J. Thomson photographic plate. Two of the patches are both from neon: neon of mass 20 and neon of mass 22.



Parabolas of Neon (1913).

Mass Number, A

- When weighing chemicals, need to account for neutrons, too.
- # of neutrons is not fixed for an atom type
- For a specific atom…
- # of protons + # of neutrons = mass number
- Z + # of n = A

Carbon-12

- The most common type of carbon atom
- 6 protons
- 6 neutrons
- **6 p^+ + 6 n = 12 (mass number)**

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- **6 p^+ + 6 n = 12 (mass number)**
- NOTE: electrons ignored -- too light

Lets try another...

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- What's in a neutral nickel-60 atom?

How many protons in a neutral Ni-60 atom?

1. 60
2. 0
3. 59
4. 28

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Lets try another...

- What's in a neutral nickel-60 atom?
- Protons = ?

# of protons = atomic number

Lets try another...

- What's in a neutral nickel-60 atom?
- Protons = 28
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How many electrons in a neutral Ni-60 atom?

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Lets try another...

- What's in a neutral nickel-60 atom?
- Protons = 28
- Electrons = ?

In a neutral atom

# of protons = # of electrons

Lets try another...

- What's in a neutral nickel-60 atom?
- Protons = 28
- Electrons = 28

How many neutrons in a neutral Ni-60 atom?

1. 60
2. 32
3. 58
4. 28

How many neutrons in a neutral Ni-60 atom?

1. 60
2. 32
3. 58
4. 28

Lets try another...

- What's in a neutral nickel-60 atom?
- Protons = 28
- Electrons = 28
- Neutrons = ?

Mass number is...

# of protons + # of neutrons

Lets try another...

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- Electrons = 28
- Neutrons = 60 - 28

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- Shorthand notation: 28 p^+, 28 e^-, 32 n

Ions

- Not all atoms are electrically neutral
- A charged atom (or molecule) is called an ion
- Ion charge = # of p^+'s - # of e^-'s

What's the charge of an atom that has 16 protons and 18 electrons?

1. -2
2. -1
3. 0
4. +2

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With 16 p^+'s, it can only be a sulfur atom

Aha! It's a sulfide ion, S^{2-}

Ions

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- A charged atom is called an ion
- Ion charge = # of p^+'s
- What's the charge of an
  16 protons and 18 electr
- Ion charge = 16

  = -2

The ion charge is written as a superscript to the right, with the charge sign listed last

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- This imparts a negative charge
- e.g., Cl^- ion
- 17 protons
- 18 electrons
- 1 excess e^-

How to remember which is which

- C a t ion
- See a + ion

- A n ion
- A negative ion

Hydrogen isotopes

- Most hydrogen atoms have a nucleus with just 1 proton
- hydrogen-1
- protium
- About 15 of every 100,000 hydrogen atoms has a neutron as well
- hydrogen-2
- deuterium (D) or heavy hydrogen

Deuterium and Harold Urey

- The neutron was theoretically predicted to exist by Chadwick around 1930
- Harold C. Urey (UM chemistry alum/faculty!) proved the existence of neutrons by isolating deuterium
- Awarded 1934 Nobel prize
- He isolated deuterium through fractional distillation of liquid hydrogen
- Chemists use deuterium all the time in the form of heavy water, D_2O

Harold Clayton Urey was born in Walkerton, Indiana, on April 29, 1893, as the son of the Rev. Samuel Clayton Urey and Cora Rebecca Reinsehl, and grandson of pioneers who settled in Indiana. His early education in rural schools led to his graduation from high school in 1911 after which he taught for three years in country schools.

In 1914 he entered the University of Montana and received his Bachelor of Science degree in Zoology in 1917. He spent two years as a research chemist in industry before returning to Montana as an instructor in Chemistry. In 1921 he entered the University of California to work under Professor Lewis and he was awarded the degree of Ph.D. in Chemistry in 1923. He spent the following year in Copenhagen at Professor Niel Bohr's Institute for Theoretical Physics as American-Scandinavian Foundation Fellow to Denmark and on his return to the United States he became an Associate in Chemistry at Johns Hopkins University. In 1929 he was appointed Associate Professor in Chemistry at Columbia University and he became Professor in 1934.

Professor's Urey's early researches concerned the entropy of diatomic gases and problems of atomic structure, absorption spectra and the structure of molecules. In 1931 he devised a method for the concentration of any possible heavy hydrogen isotopes by the fractional distillation of liquid hydrogen: this led to the discovery of deuterium.

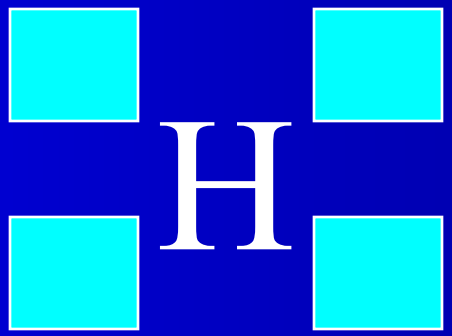
Hydrogen isotopes (Cont'd.)

- Nuclear reactions create a third isotope with two neutrons in the nucleus
- hydrogen-3
- tritium
- This is a radioisotope in that it decays and gives off harmful radiation

Isotope notation...

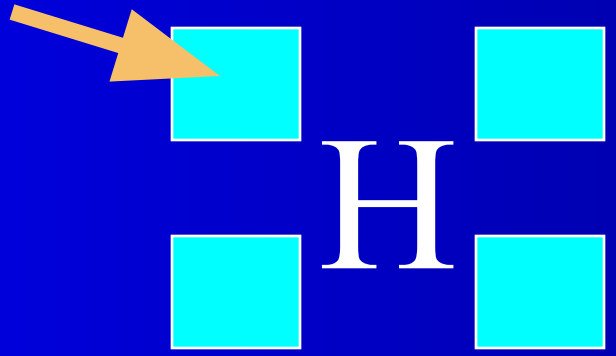
Isotope notation...

All four positions around a symbol can hold information



Isotope notation...

Mass number, A



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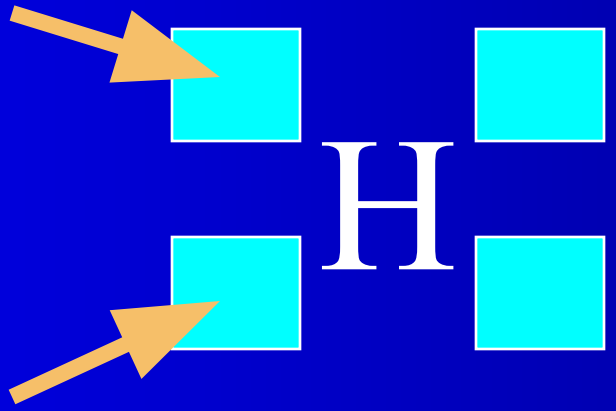
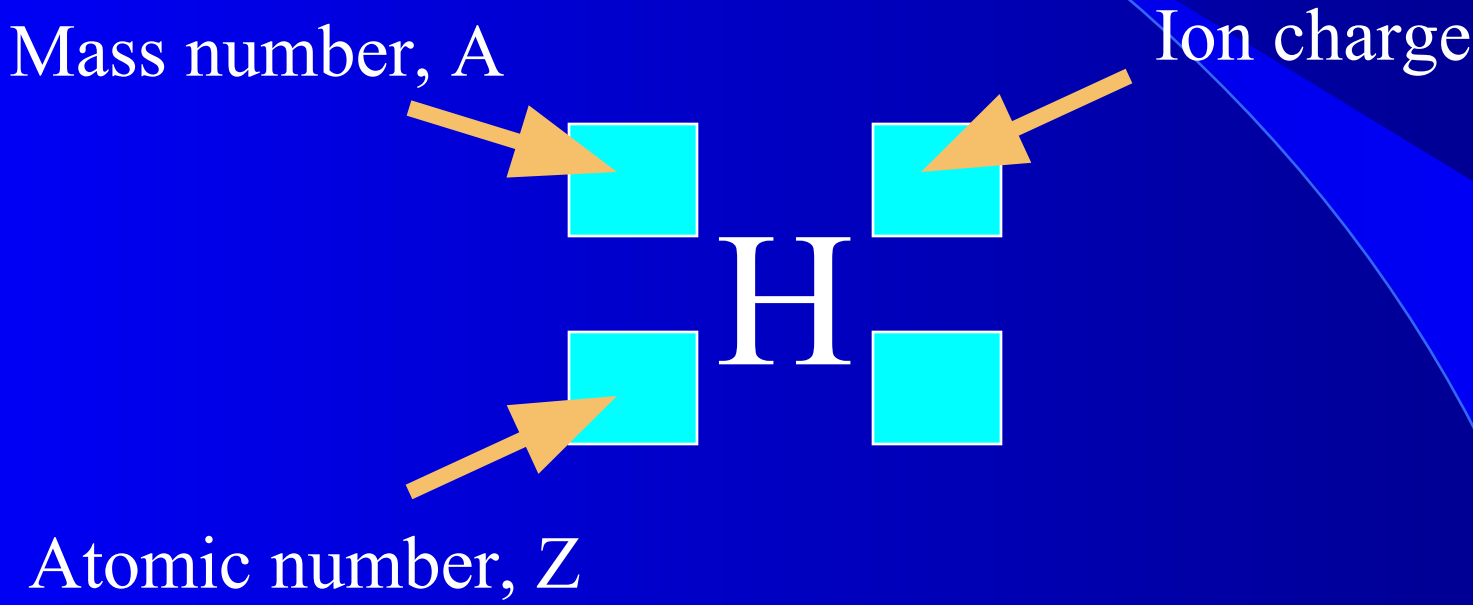


Atomic number, Z

Isotope notation...



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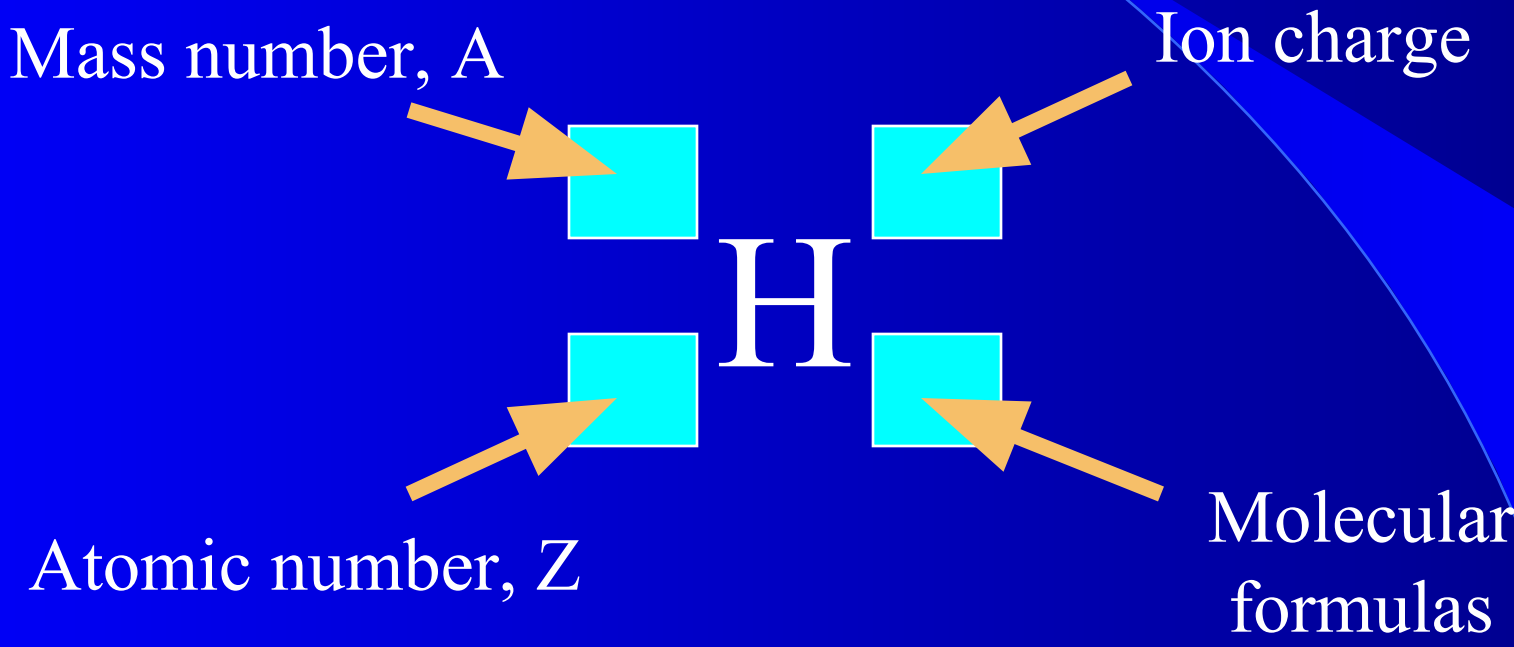

Isotope notation...

Consider a +1 ion of a deuterium atom

$$H$$

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A deuterium atom has 1 proton in its nucleus

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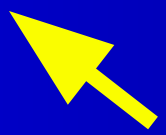

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Isotope notation...

Consider a +1 ion of a deuterium atom

$$_{1}H$$

Isotope notation...

Consider a +1 ion of a deuterium atom

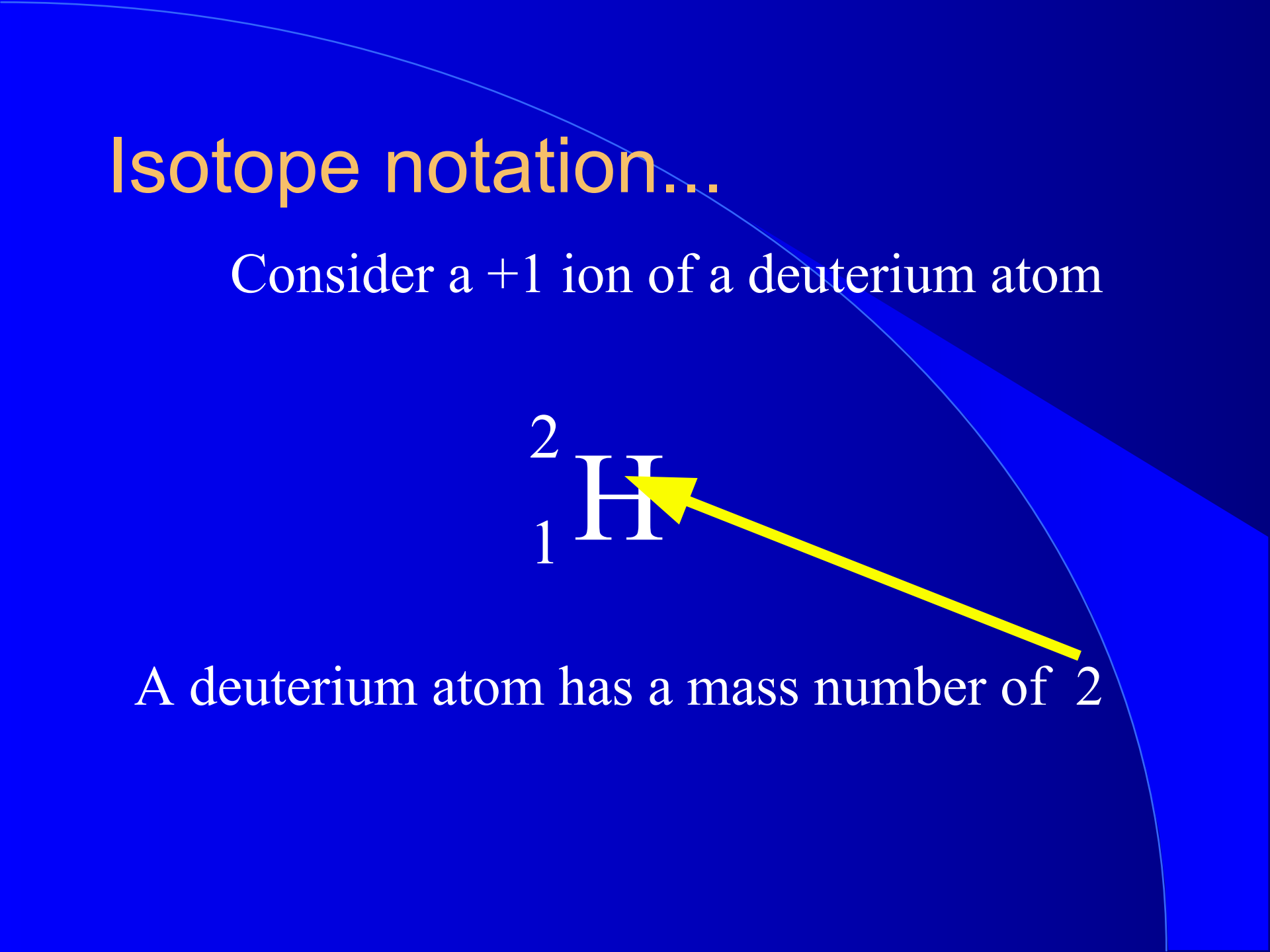
$$_{1}H$$

A deuterium atom has a mass number of 2

Isotope notation...

Consider a +1 ion of a deuterium atom

$$^{2}_{1}H$$



A deuterium atom has a mass number of 2

Isotope notation...

Consider a +1 ion of a deuterium atom

$$^{2}_{1}H$$

Isotope notation...

Consider a +1 ion of a deuterium atom

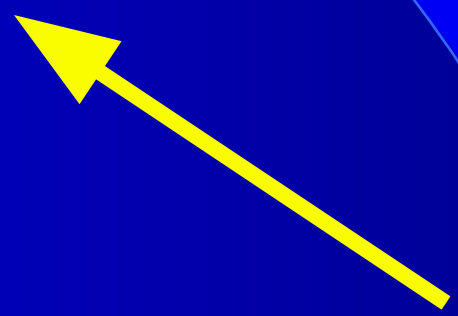
$$^{2}_{1}H$$

A deuterium cation has a charge of +1

Isotope notation...

Consider a +1 ion of a deuterium atom

$$^{2}_{1}H^{+}$$



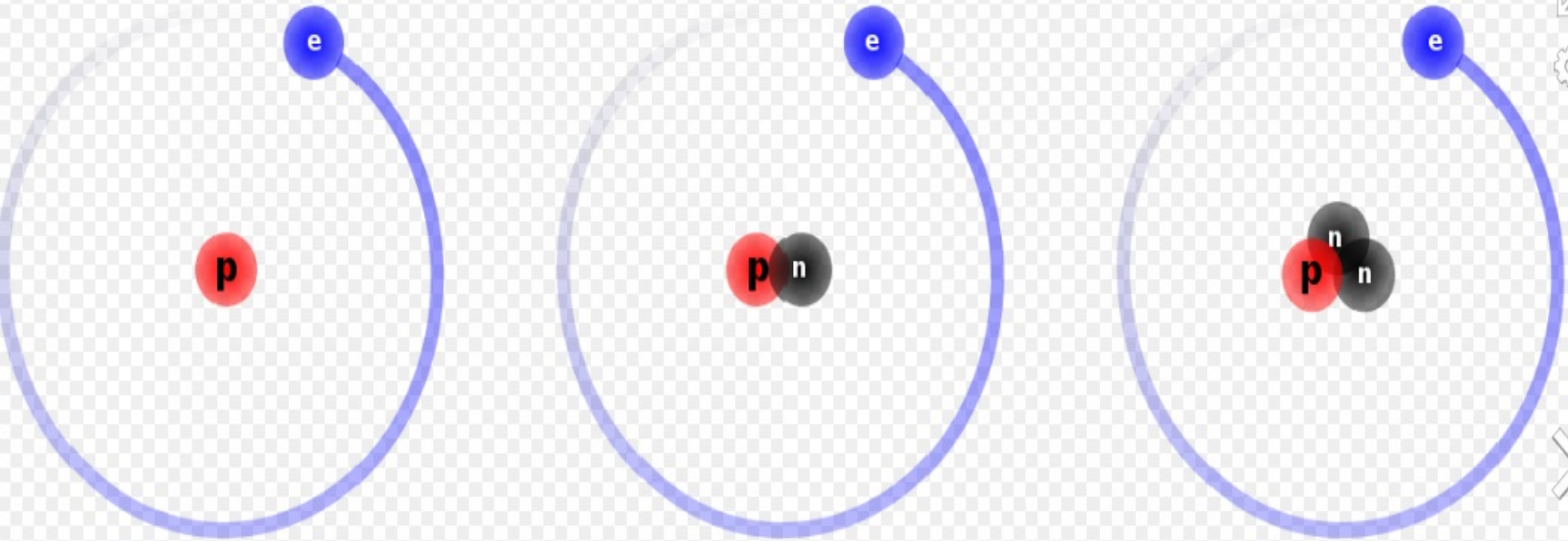
A deuterium cation has a charge of +1

Isotope notation...

Consider a +1 ion of a deuterium atom

$$^{2}_{1}H^{+}$$

Isotopes of Hydrogen



$^{1}_{1}H$ $^{2}_{1}H$ $^{3}_{1}H$

Protium **Deuterium** **Tritium**

Atomic Weights

- Atoms of the same type that differ in neutron count are called isotopes
- Most elements in nature occur as a mixture of several isotopes
- Isotopes DON'T make much difference in a chemical sense
- Isotopes DO make a difference in weighing out samples

Weighted Averages

- Masses listed on periodic table are weighted averages of natural isotopic abundances
- Chlorine comes in two common forms
- 75.53% is chlorine-35
- 24.47% is chlorine-37
- Exact masses are
- Chlorine-35 34.97
- Chlorine-37 36.96

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The average MUST be somewhere between 35 and 37!

Example calculation

Example calculation

Contribution from Cl-35

Example calculation

Contribution from Cl-35 + Contribution from Cl-37

Example calculation

Contribution from Cl-35 + Contribution from Cl-37

$$\frac{75.53}{100}(34.97)$$

Example calculation

Contribution from Cl-35 + Contribution from Cl-37

$$\frac{75.53}{100}(34.97) + \frac{24.47}{100}(36.96)$$

Example calculation

Contribution from Cl-35 + Contribution from Cl-37

$$\frac{75.53}{100}(34.97) + \frac{24.47}{100}(36.96)$$

$$(0.7553 \times 34.97) + (0.2447 \times 36.96)$$

Example calculation

Contribution from Cl-35 + Contribution from Cl-37

$$\frac{75.53}{100}(34.97) + \frac{24.47}{100}(36.96)$$

$$(0.7553 \times 34.97) + (0.2447 \times 36.96)$$

$$26.41 + 9.04$$

Example calculation

Contribution from Cl-35 + Contribution from Cl-37

$\frac{75.53}{100}(34.97)$ + $\frac{24.47}{100}(36.96)$

(0.7553 x 34.97) + (0.2447 x 36.96)

26.41 + 9.04

Note that contribution from Cl-35

Example calculation

Contribution from Cl-35 + Contribution from Cl-37

$$\frac{75.53}{100}(34.97) + \frac{24.47}{100}(36.96)$$

$$(0.7553 \times 34.97) + (0.2447 \times 36.96)$$

$$26.41 + 9.04$$

Note that contribution from Cl-35 is about 3 times that from Cl-37

Example calculation

Contribution from Cl-35 + Contribution from Cl-37

$\frac{75.53}{100}(34.97) + \frac{24.47}{100}(36.96)$

$(0.7553 \times 34.97) + (0.2447 \times 36.96)$

$26.41 + 9.04$

$= 35.45$

Example calculation

Contribution from Cl-35 + Contribution from Cl-37

$\frac{75.53}{100}(34.97)$ + $\frac{24.47}{100}(36.96)$

(0.7553 x 34.97) + (0.2447 x 36.96)

26.41 + 9.04

Weighted average appears on periodic table → = 35.45

Weighted Averages

- Masses listed on periodic table are weighted averages of natural isotopic abundances
- Magnesium comes in three common forms
- 78.70% is magnesium-24
- 10.13% is magnesium-25
- 11.17% is magnesium-26
- Exact masses are
- magnesium-24 23.98504
- magnesium-25 24.98584
- magnesium-26 25.98259

Weighted Averages

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The average MUST be somewhere between 24 and 26!

Example calculation

Contribution from Mg-24 + Contribution from Mg-25

+ Contribution from Mg-26

Example calculation

Contribution from Mg-24 + Contribution from Mg-25 + Contribution from Mg-26

$$\frac{78.70}{100}(23.98504) + \frac{10.13}{100}(24.98584) + \frac{11.17}{100}(25.98259)$$

Example calculation

Contribution from Mg-24 + Contribution from Mg-25

+ Contribution from Mg-26

$$\frac{78.70}{100}(23.98504) + \frac{10.13}{100}(24.98584) + \frac{11.17}{100}(25.98259)$$

$$0.7870\,(23.98504) + 0.1013\,(24.98584) + 0.1117\,(25.98259)$$

Example calculation

Contribution from Mg-24 + Contribution from Mg-25

+ Contribution from Mg-26

0.7870 (23.98504) + 0.1013 (24.98584)

+ 0.1117 (25.98259)

Example calculation

Contribution from Mg-24 + Contribution from Mg-25 + Contribution from Mg-26

$0.7870\ (23.98504) + 0.1013\ (24.98584) + 0.1117\ (25.98259)$

$= 18.87623 + 2.53107 + 2.90226$

Example calculation

Contribution from Mg-24 + Contribution from Mg-25

+ Contribution from Mg-26

$$0.7870\,(23.98504) + 0.1013\,(24.98584)$$

$$+ 0.1117\,(25.98259)$$

$$= 18.87623 + 2.53107 + 2.90226$$

$$= 24.30955$$

Example calculation

Contribution from Mg-24 + Contribution from Mg-25

+ Contribution from Mg-26

$0.7870\ (23.98504) + 0.1013\ (24.98584)$

$+ 0.1117\ (25.98259)$

$= 18.87623 + 2.53107 + 2.90226$

$= 24.30955$

$= 24.31$ (4 sig figs allowed)

The Periodic Table

- As more elements were discovered, researchers noted “triplets” that had similar chemical properties
- Lithium, sodium, and potassium react vigorously with water
- Chlorine, bromine, and iodine are all pungent nonmetals

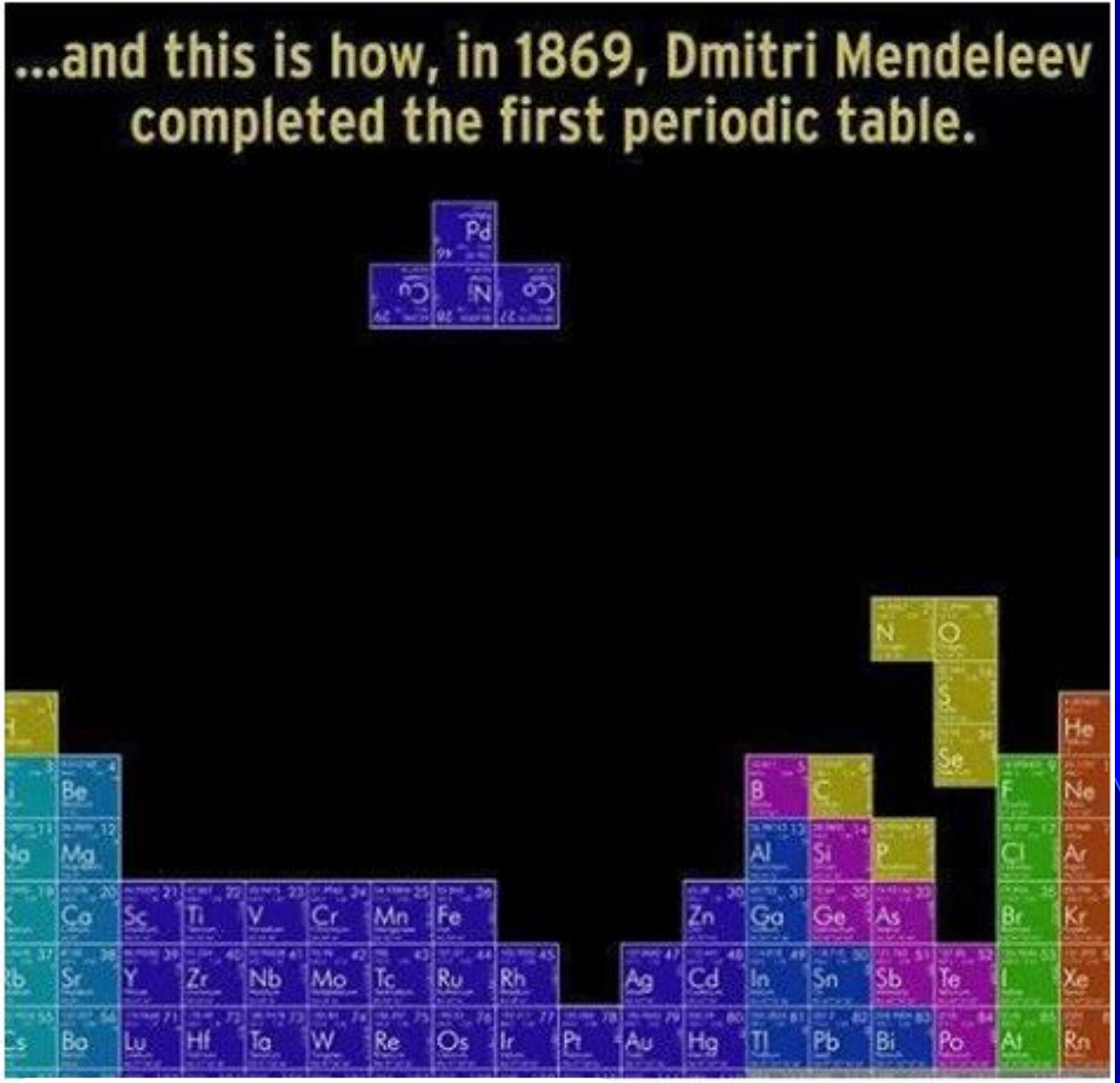
Dmitri Mendeleev

- Let chemical character dictate placement rather than atomic weight
- Co (53.9882 amu) before Ni (58.6934 amu)
  - Te (127.60) before I (126.9045 amu)
- His positioning in 1869 anticipated quantum theory by 60 years

An early version of Mendeleev's periodic table

Group / Period	I	II	III	IV	V	VI	VII	VIII
1	H=1							
2	Li=7	Be=9.4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27.3	Si=28	P=31	S=32	Cl=35.5	
4	K=39	Ca=40	?=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56,Co=59 Ni=59
5	Cu=63	Zn=65	?=68	?=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	?=100	Ru=104,Rh=104 Pd=106
7	Ag=108	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140				
9								
10			?Er=178	?La=180	Ta=182	W=184		Os=195,Ir=197 Pt=198
11	Au=199	Hg=200	Tl=204	Pb=207	Bi=208			
12				Th=231		U=240		

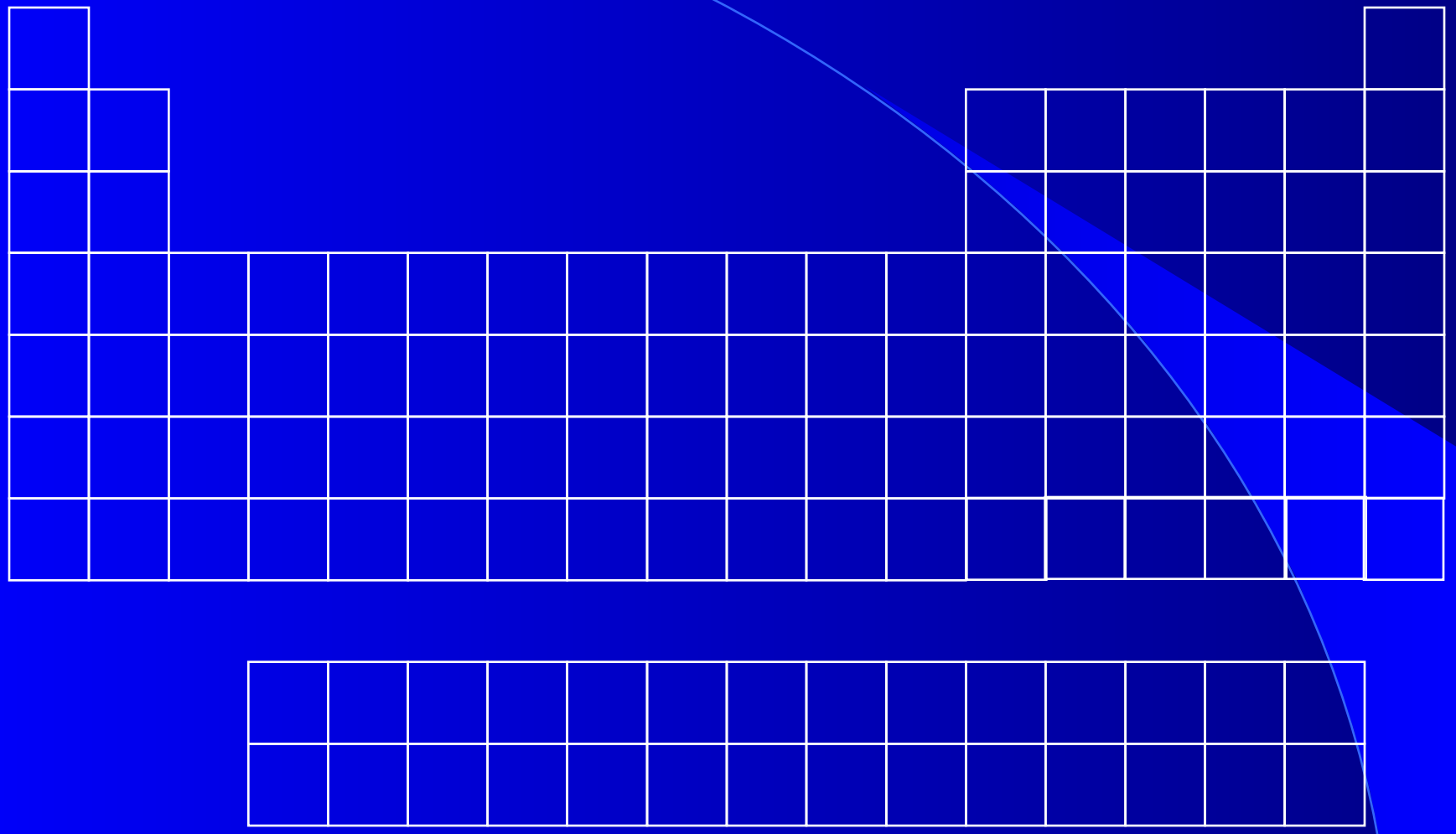
Here it is commemorated in stone on the side of a Russian science building



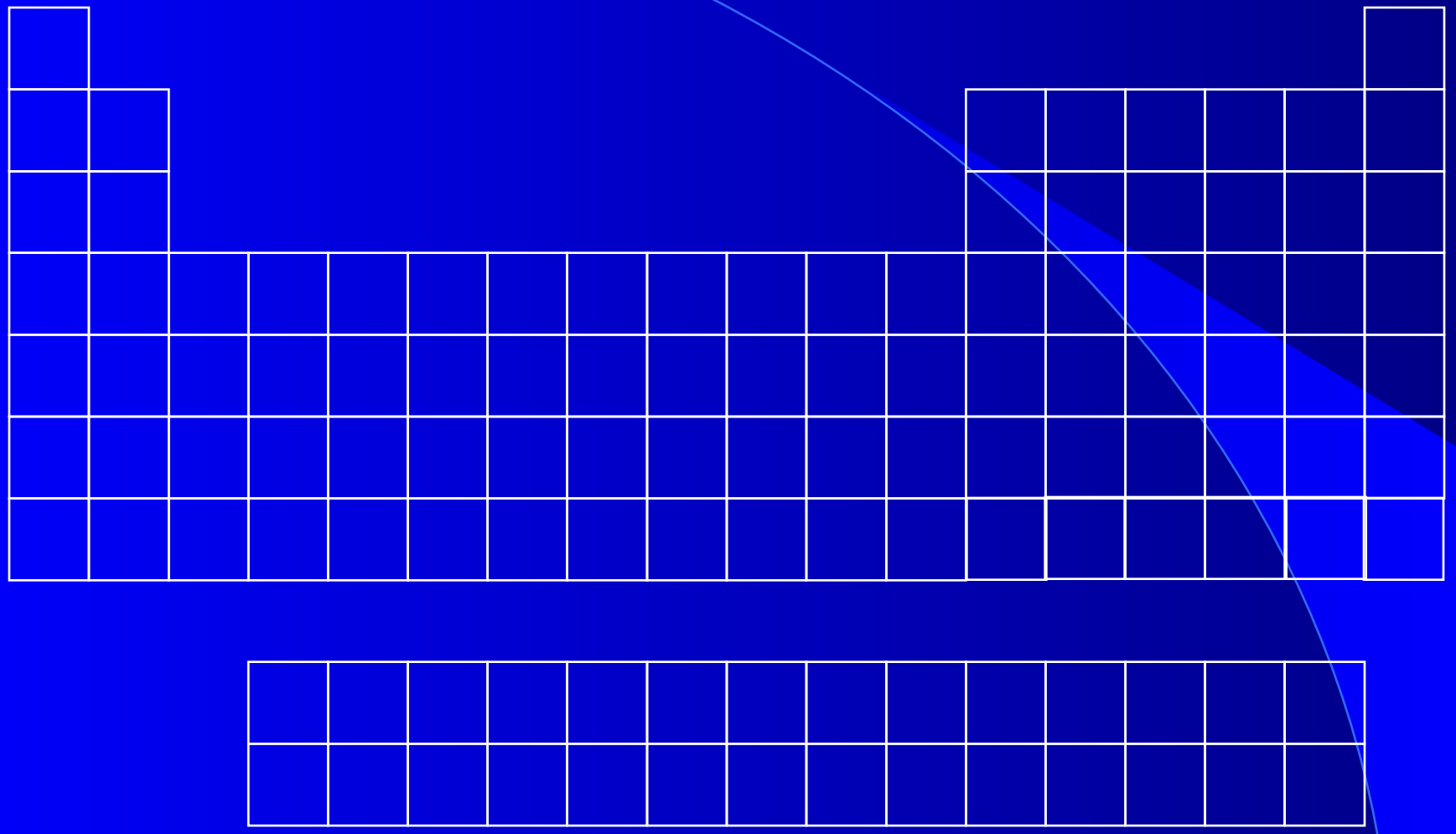
February 8th

Today is the birthday of Dmitri Mendeleev, the Russian chemist who designed the periodic table.

The Periodic Table



Each row is a period



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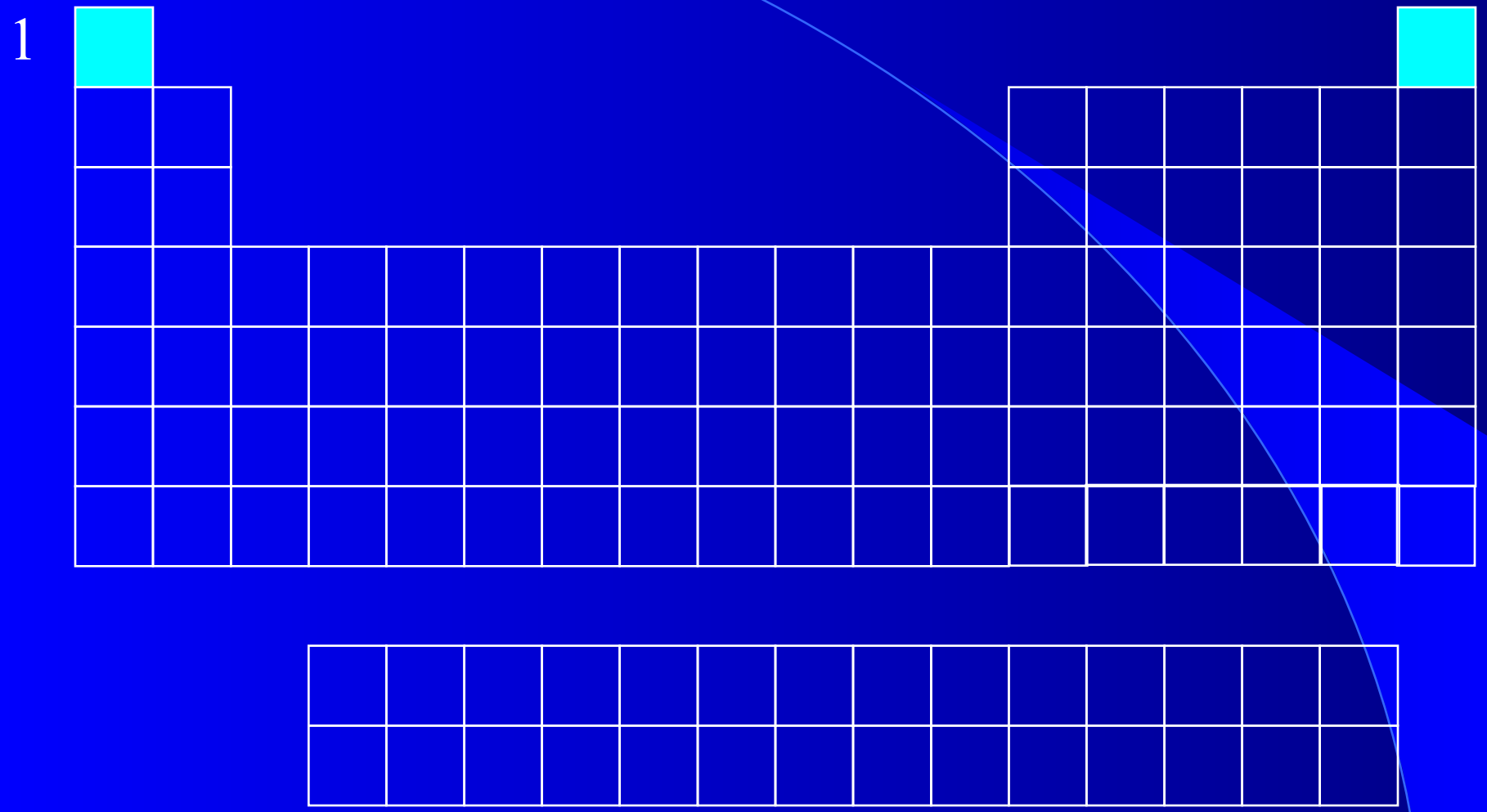

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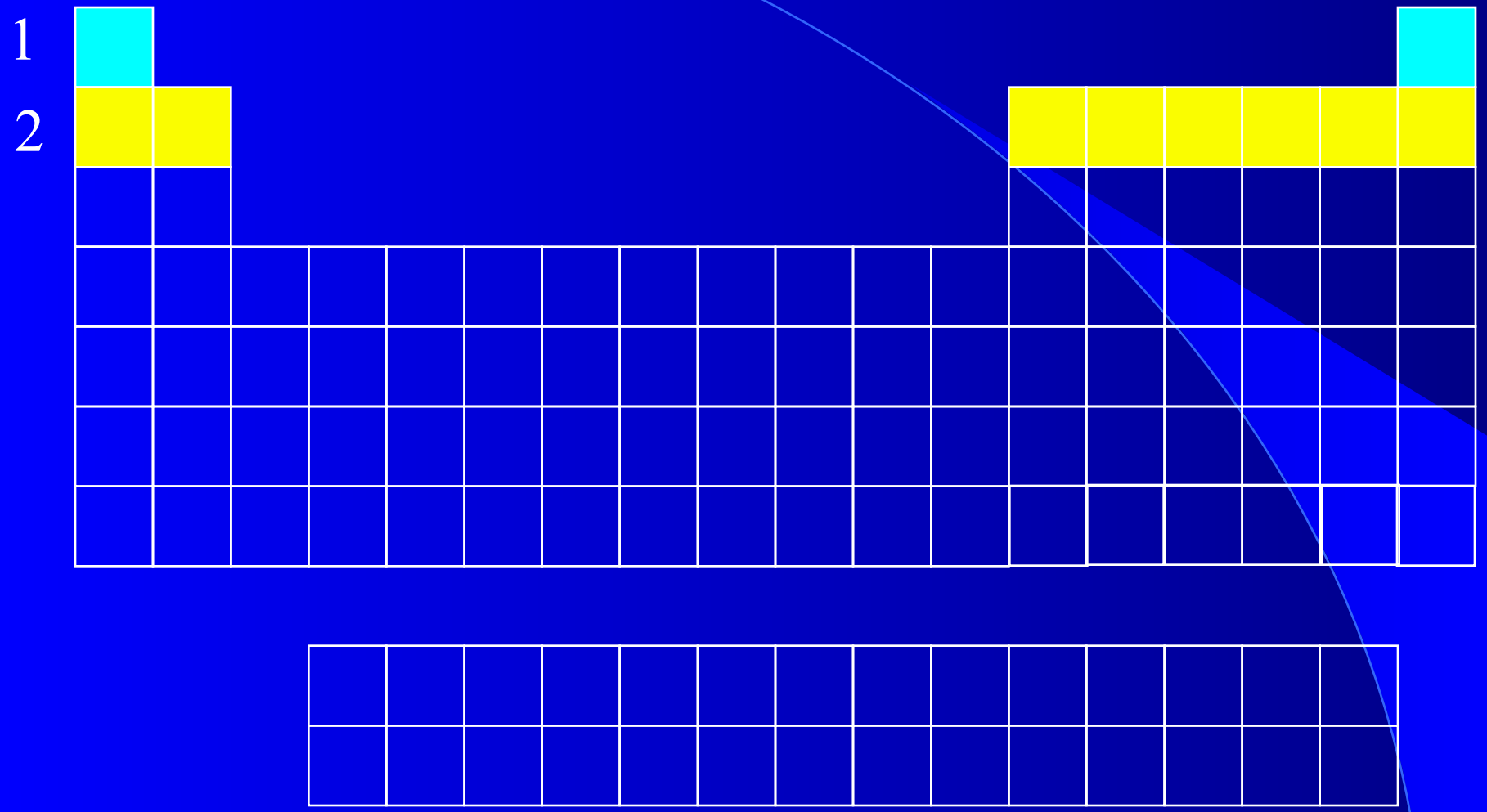

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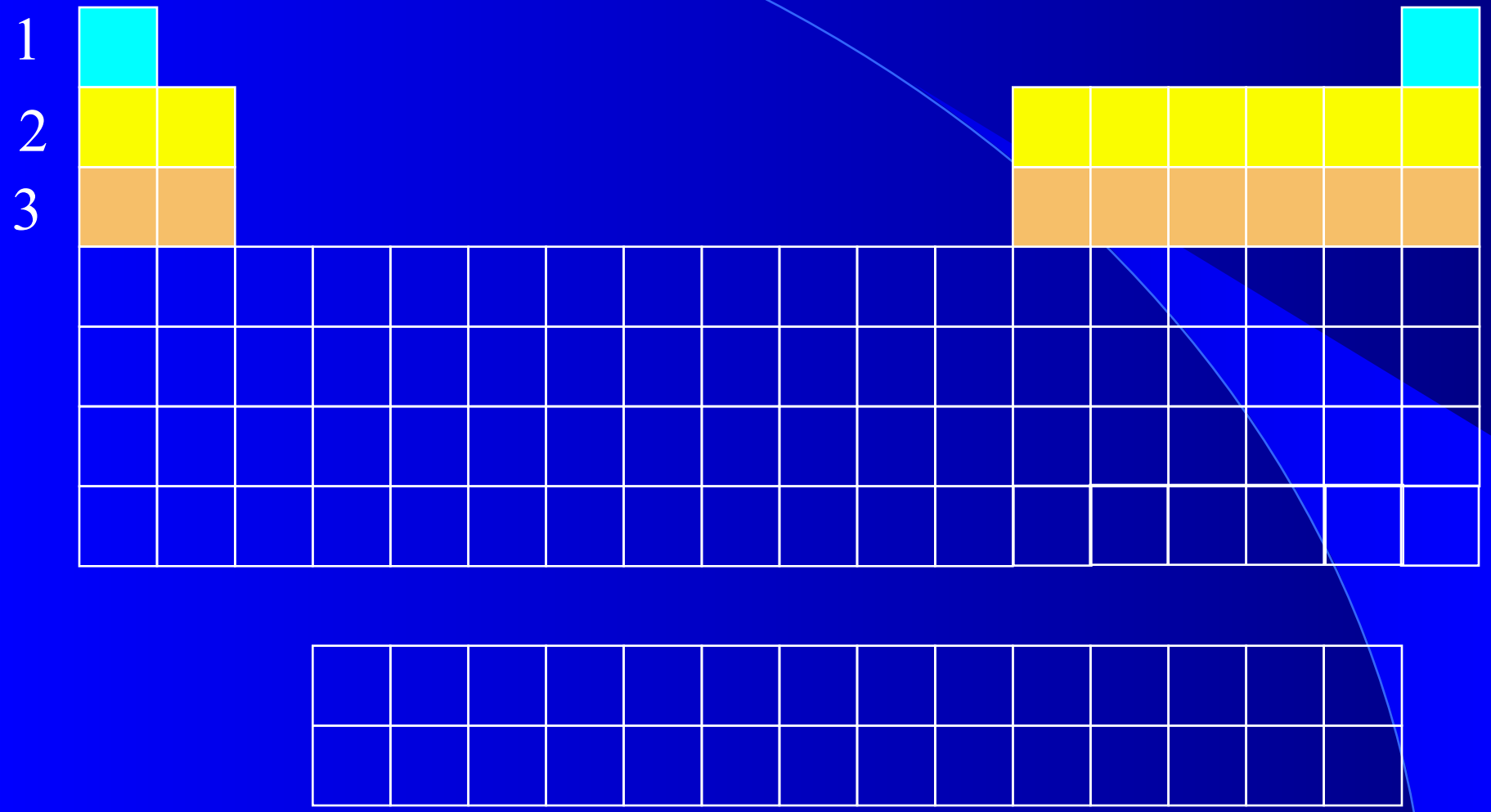

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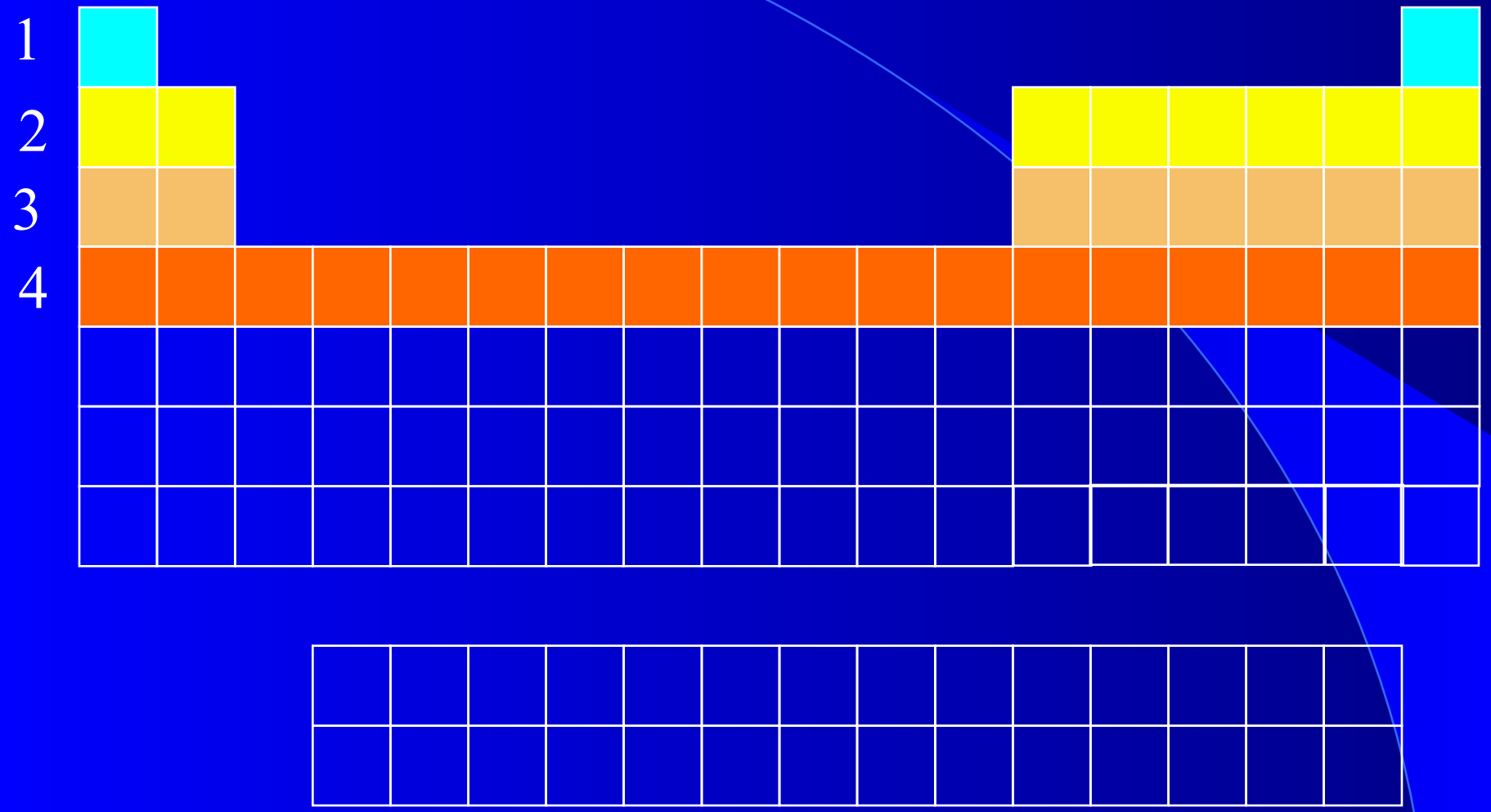

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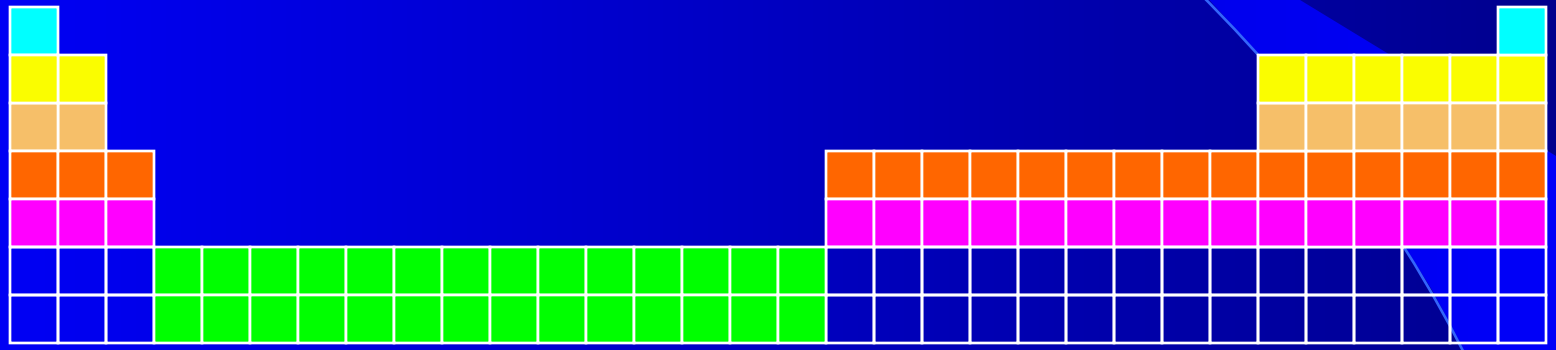
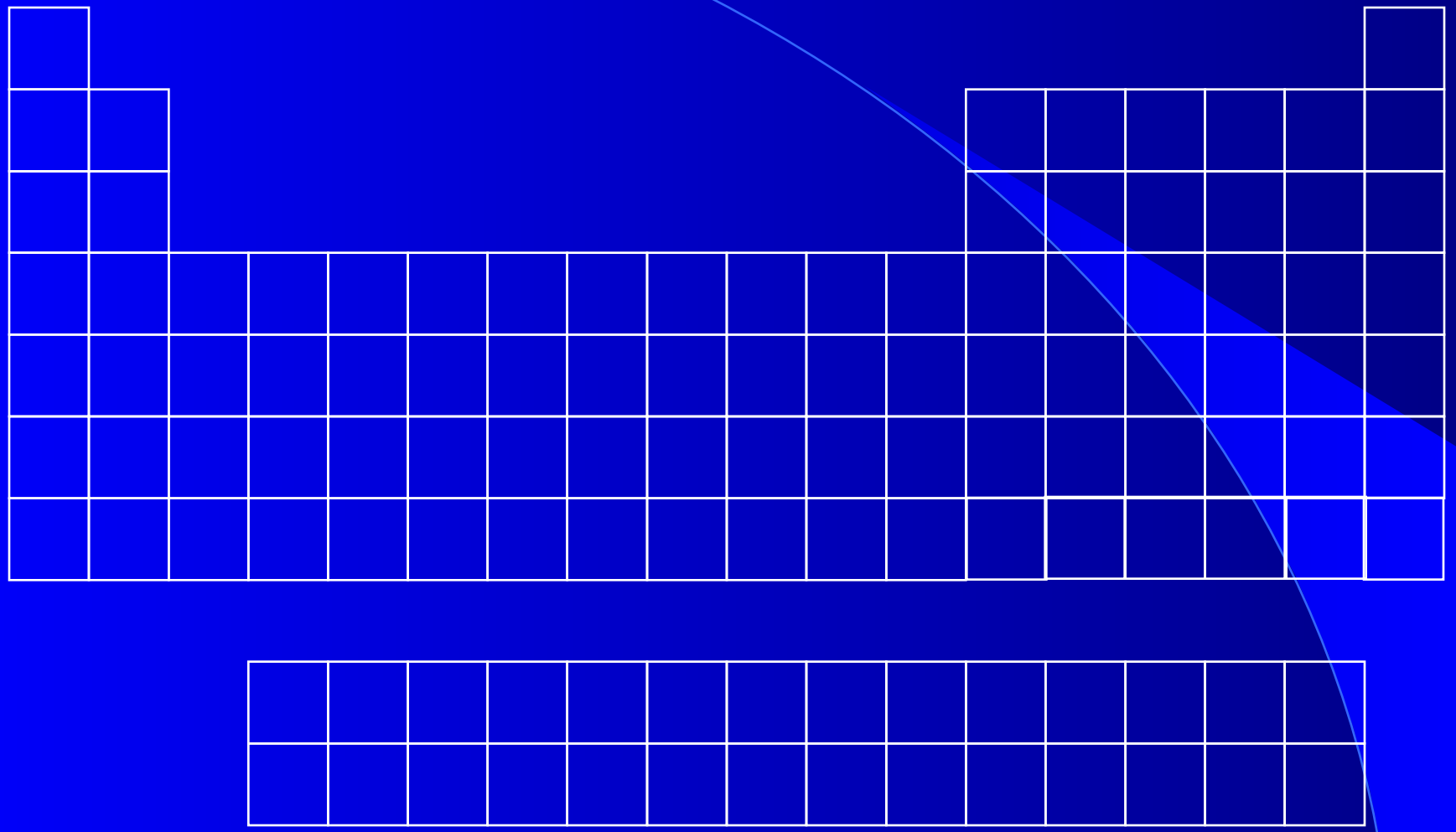
The Periodic Table

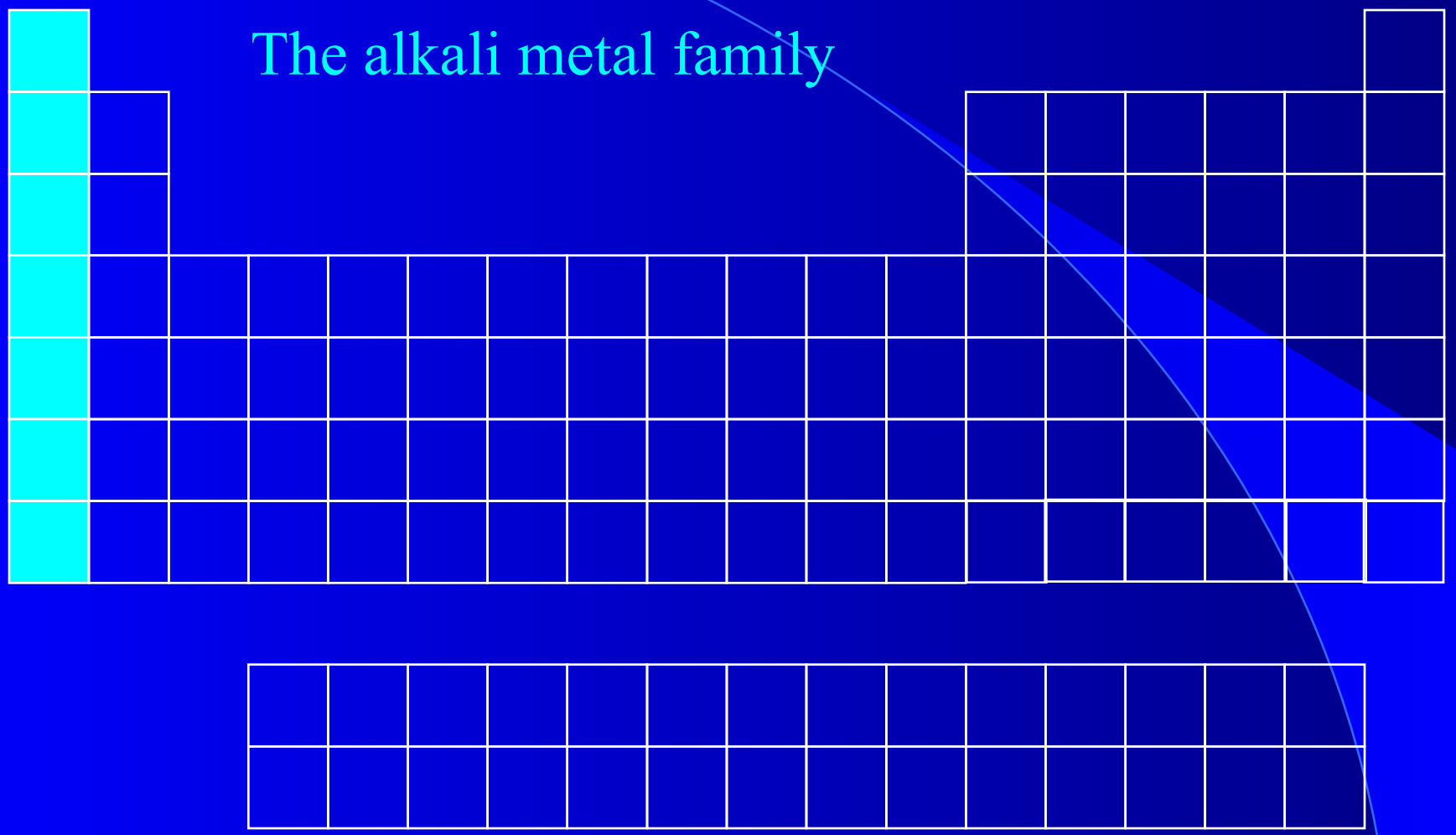


It’s not a convenient shape to print when inserted

Each column is a family



Each column is a family



Element Families

- Elements in the same family exhibit similar properties
- Alkali metals are:
- soft shiny metals
- react violently with water to produce alkaline (basic) solutions
- http://www.youtube.com/watch?v=eCk0lYB_8c0
- never found in elemental form

Lessons Learned

- Recognize the contributions of Zeno, Democritus, Dalton, Urey, Mendeleev and Pauli to our knowledge of atomic structure
- Distinguish between elements and compounds; pure substances and mixtures; heterogeneous and homogeneous mixtures
- Name and give symbols of common elements
- Know fundamental forces - strong nuclear, electrostatic, gravitational

Lessons Learned

- Explain the composition of different atoms according to the number of protons, neutrons and electrons they contain
- Know what cations and anions are. Use charge to predict electron numbers and vice versa
- Understand what isotopes are, how to write isotope notation, and how to use their natural abundances to compute average atomic masses