Introduction to Mineral Processing

Amir Eskanlou, Ph.D.

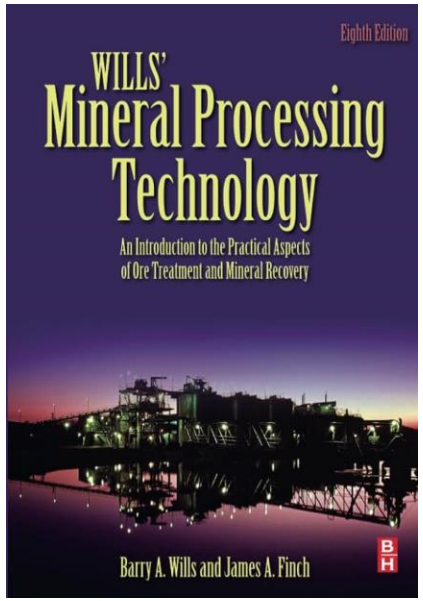
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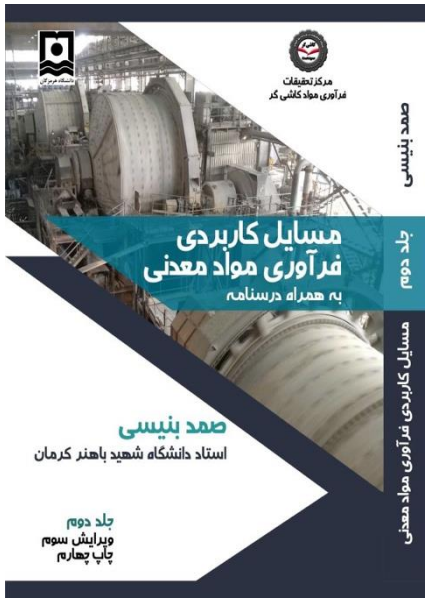
MINERAL-X

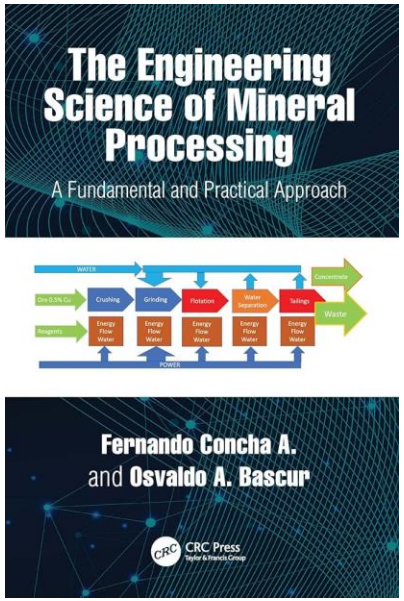


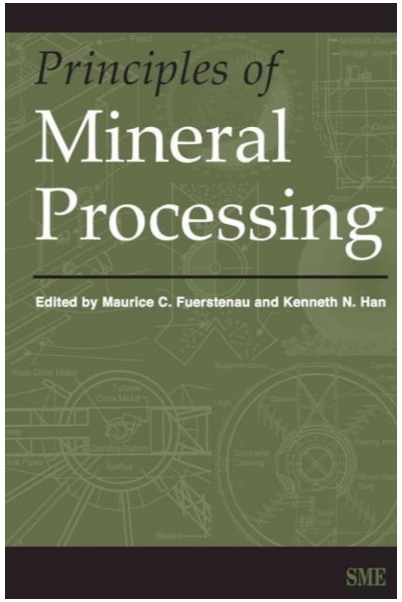
Kamoa-Kakula Copper, DRC

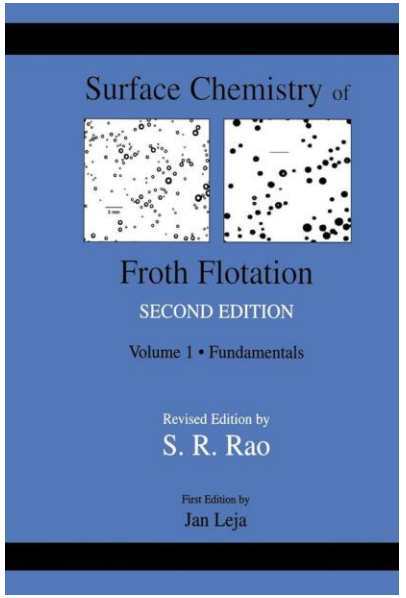
References

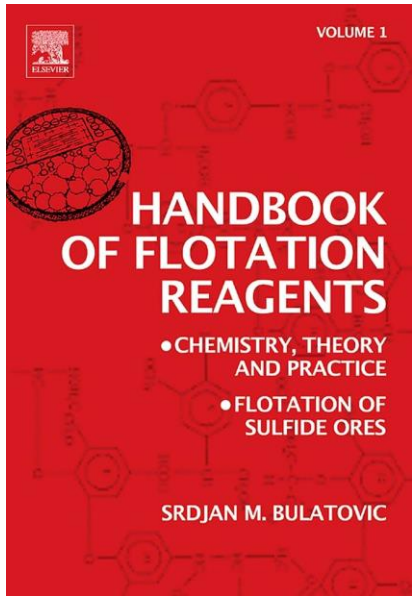

Eighth Edition
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Mineral Processing
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An Introduction to the Practical Aspects
of Ore Treatment and Mineral Recovery
Barry A. Wills and James A. Finch
B
H

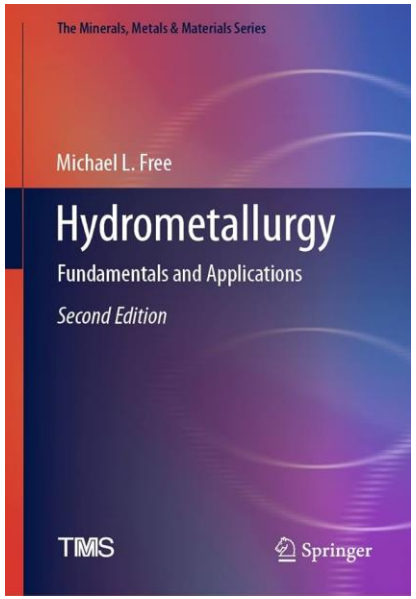

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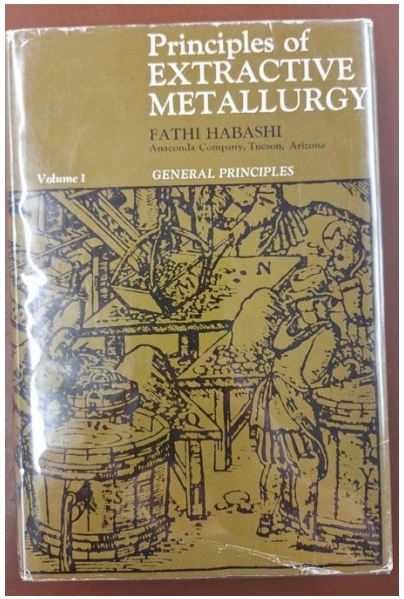

The Engineering
Science of Mineral
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A Fundamental and Practical Approach
Fernando Concha A.
and Osvaldo A. Bascur
CRC Press

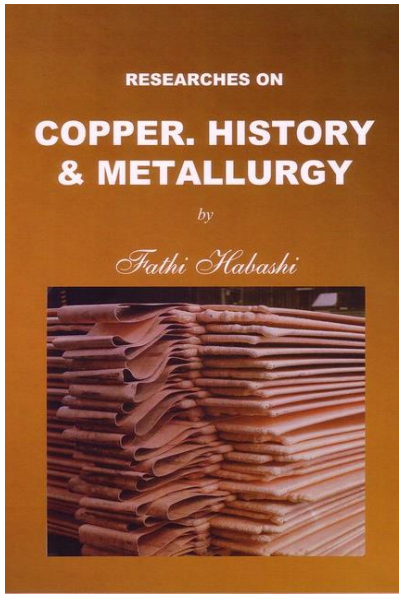

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COPPER. HISTORY
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by
Fathi Habashi

Introduction

The average newborn infant will need a lifetime supply of:

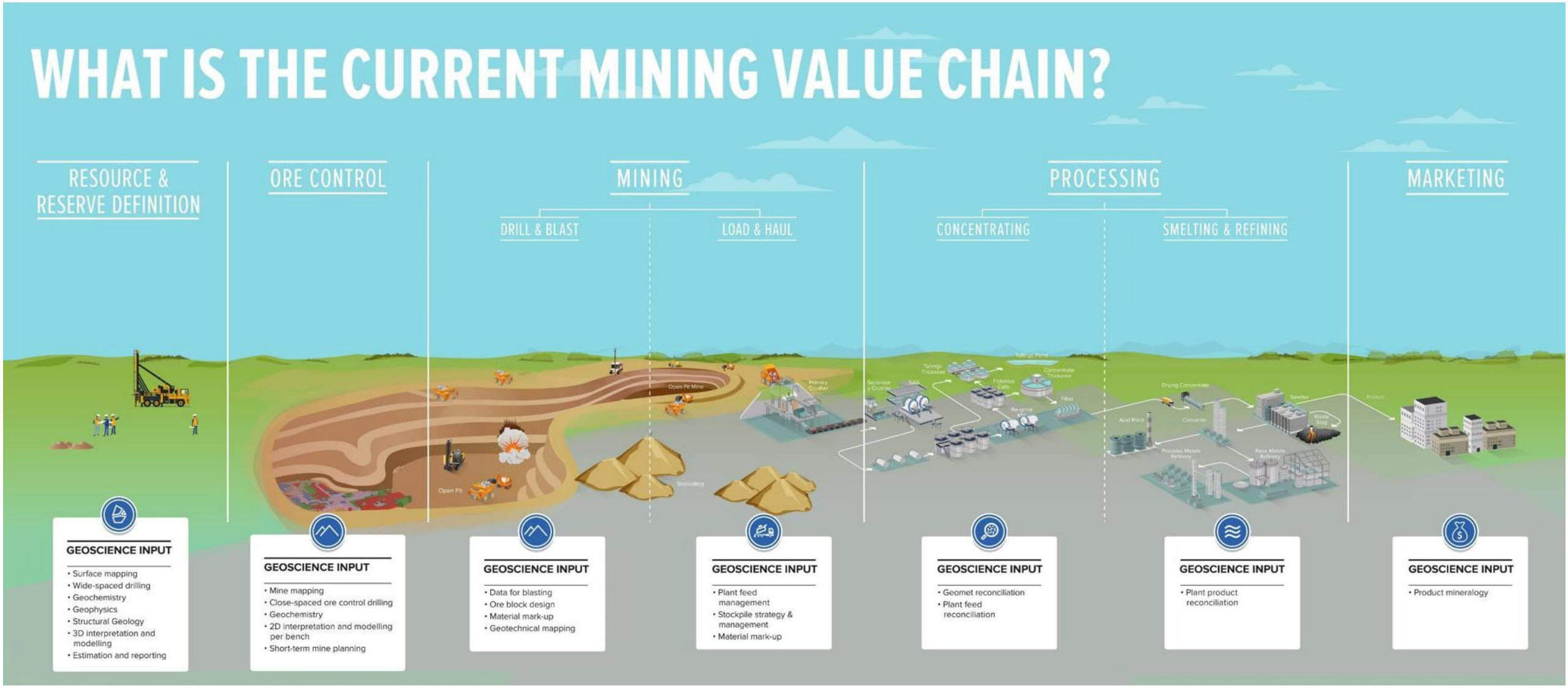


- 871 pounds of lead
- 502 pounds of zinc
- 950 pounds of copper
- 2,692 pounds of aluminum
- 21,645 pounds of iron ore
- 11,614 pounds of clays
- 30,091 pounds of salt
- 1,420,000 pounds of stone, sand, gravel, and cement

USGS
science for a changing world


If it's not GROWN,
IT MUST BE MINED
Through the Ages
STONE AGE
COPPER AGE
FLINT, OBSIDIAN
Societies have grown hand-in-hand with the use of minerals from the

WHAT IS THE CURRENT MINING VALUE CHAIN?



https://x.com/StrayosAI

Mineral: a naturally occurring inorganic solid with a definite chemical composition and crystalline structure.



Chalcopyrite

Chemical formula: $CuFeS_2$
Specific gravity: 4.1– 4.3 g/cm³
Crystal system: Tetragonal

Rock: A natural aggregate of different minerals (sometimes just one mineral dominates).



Chalcopyrite, Quartz, Pyrite, Pyrrhotite, Magnetite

Deposit: a natural concentration of minerals in the Earth crust that can be mined for profit.



Escondida (BHP), the largest open pit copper mine in the world.

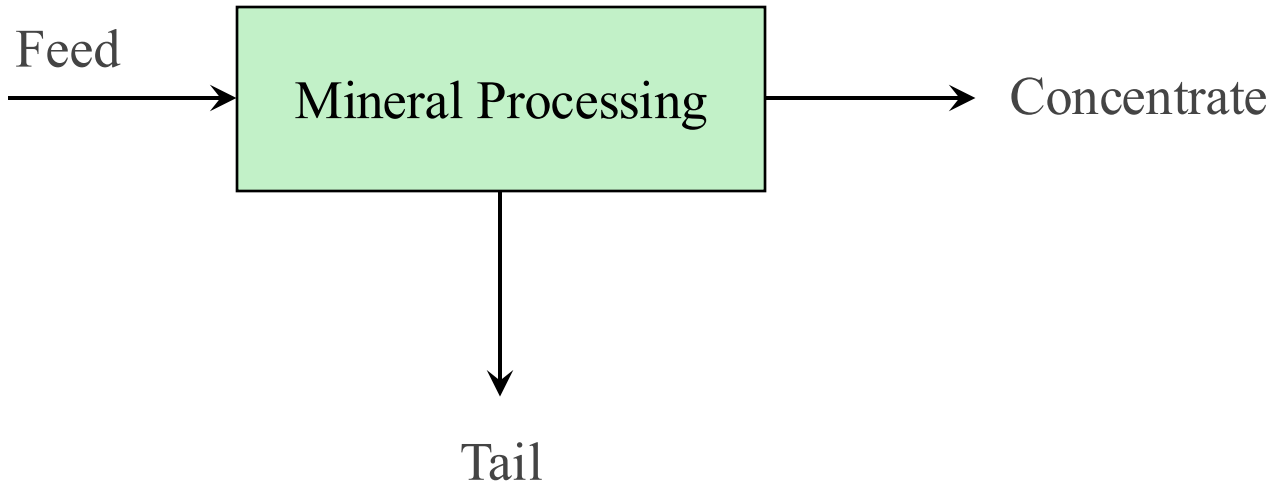
Osvaldo Bascur

Ore: a mineral deposit that is in demand and can be mined economically, i.e. its contained value [grade, market price] exceeds extraction and processing costs.

Gangue: the unwanted or worthless material in an ore, also called waste rock.

Grade: the percentage of valuable metal contained in an ore.

Mineral Processing Technology











Role of Mineral Processing

Mineral processing (ore dressing) can reduce the volume of material sent for smelting by using primarily physical methods. This reduces transportation cost, smelting cost, and metal losses.

Major Operations in Mineral Processing:

1. Liberation (freeing valuable minerals from gangue)
2. Concentration (upgrading the ore)

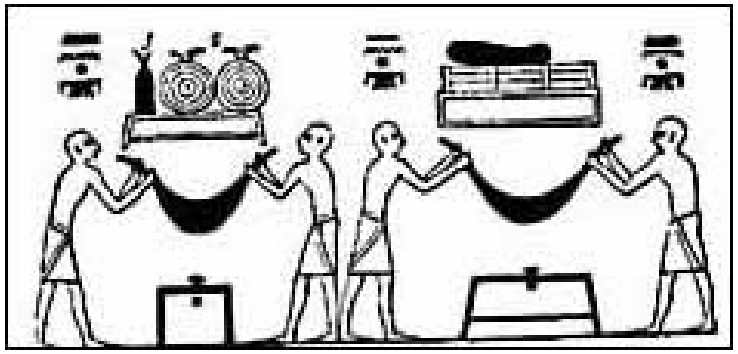
A Brief History

"In tombs of the First Dynasty, which may be dated to at least 3000 B.C., objects, or parts of objects, have been found, either made wholly of gold or embellished in part with gold."

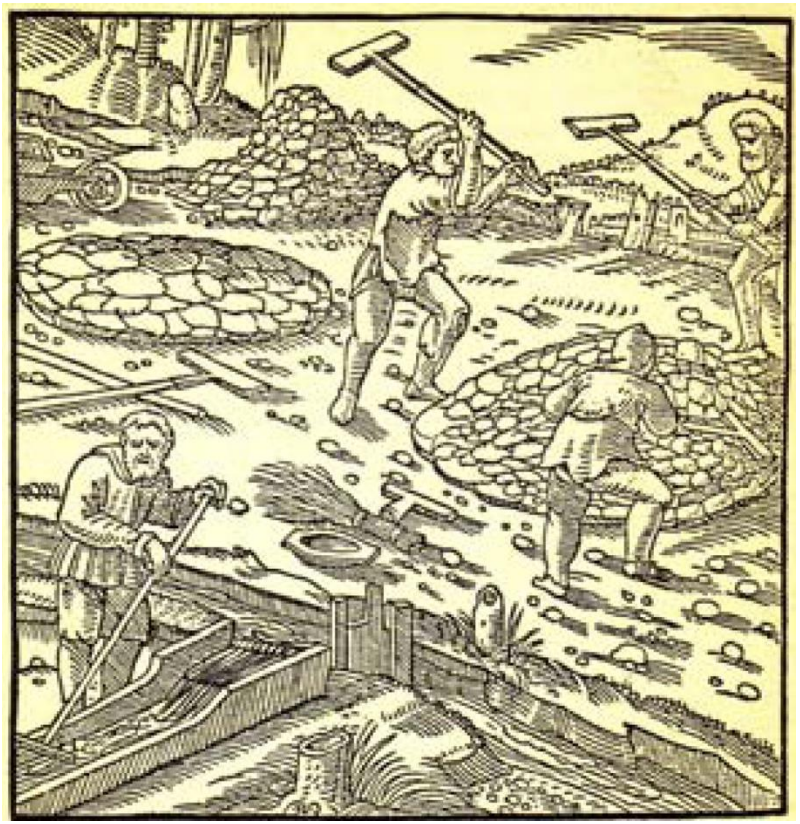




Smelting of gold. Mastaba of Mereruka, Saqqara Necropolis. Ancient Egypt.



Beneficiation of gold by washing. An ancient Egyptian wall painting



Crushing by pounding with bats in Agricola's time

"…to economize the consumption of wood it would be necessary to remove as much as possible of the gangue minerals from the charge to the furnace."

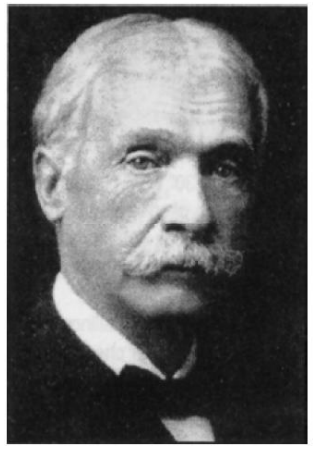
A short history of mineral processing, Fathi Habashi, Laval University, Quebec, Canada

A Brief History

"It was Peter von Rittinger at the Schemnitz School of Mines in the Austrian Empire who first taught the subject of mineral dressing and wrote specialized books on this topic."



Peter von Rittinger
(1811-1872)



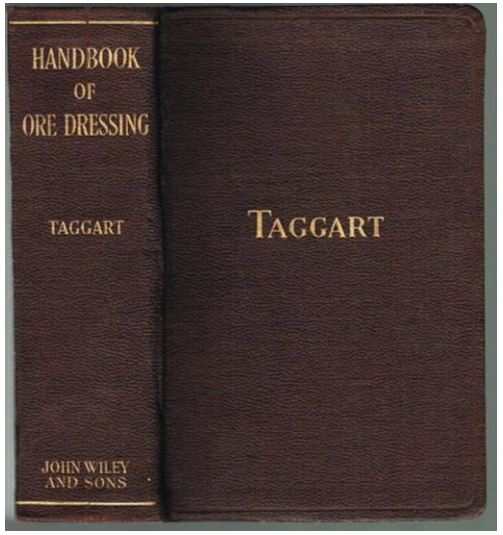
Robert H. Richards
(1844-1945)

"Robert H. Richards in USA was the first to organized a mineral dressing laboratory at MIT and published a series of books on the subject that started in 1903."

"the first chair in mineral dressing was founded in 1919 at Columbia School of Mines and was occupied by Arthur F. Taggart who authored Handbook of Ore Dressing in 1927."



Antoine M. Gaudin (1900-1974)



"Antoine M. Gaudin joined in 1939, who also taught mineral dressing at Columbia, Utah, and Montana before joining MIT."

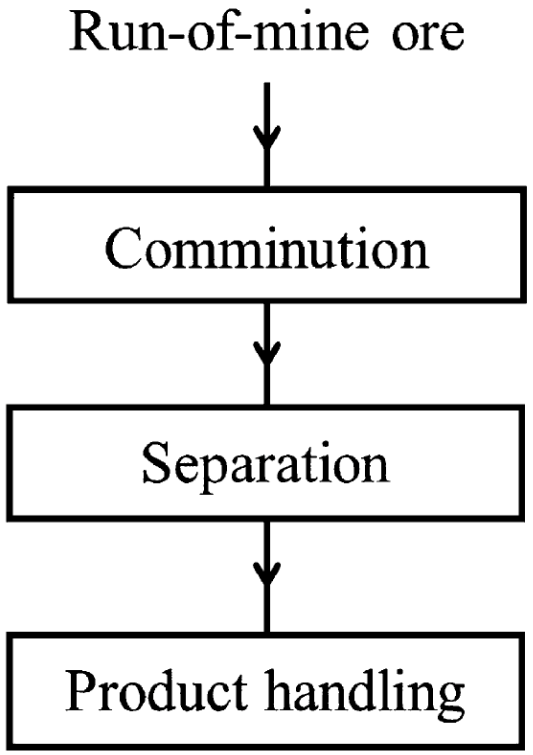
A short history of mineral processing, Fathi Habashi, Laval University, Quebec, Canada

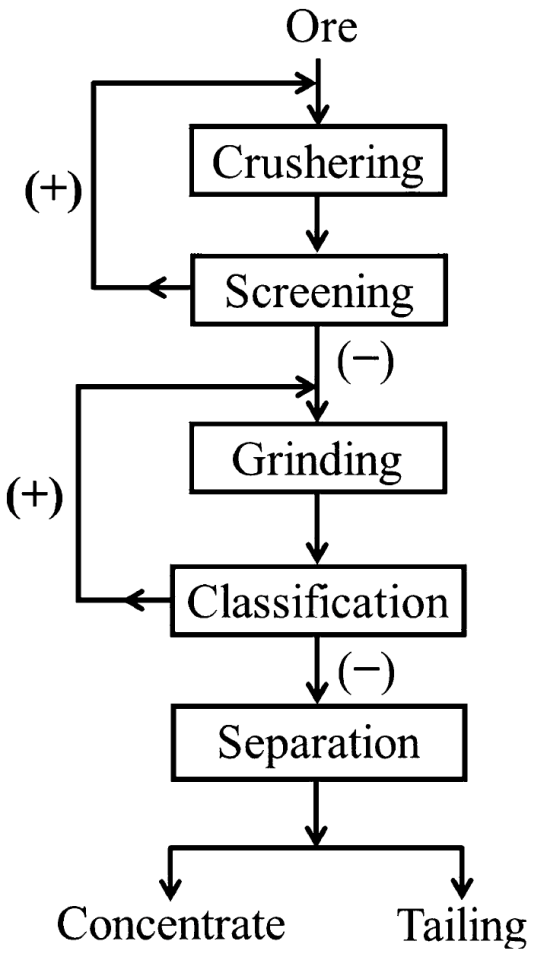


Kamoa-Kakula Copper, DRC
https://www.ivanhoemines.com/

Process Flow:

The general scheme of combined operations in a processing plant is typically as follows.



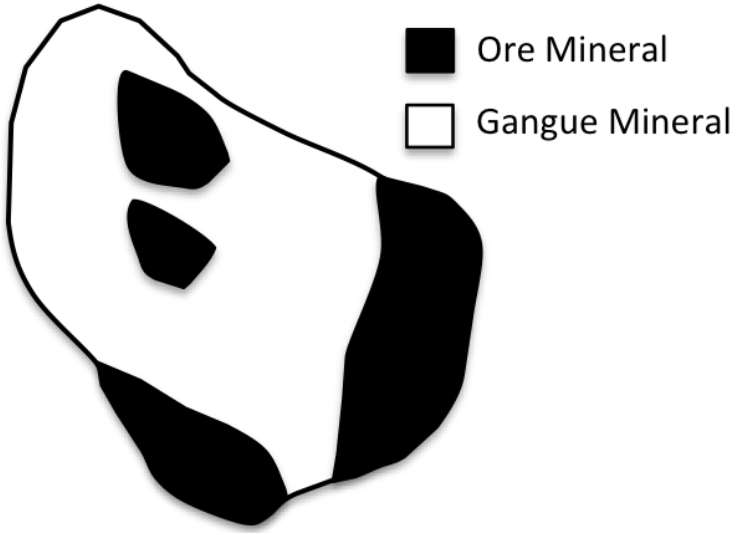


Comminution

... reducing rock size from large chunks into smaller particles by crushing and grinding.

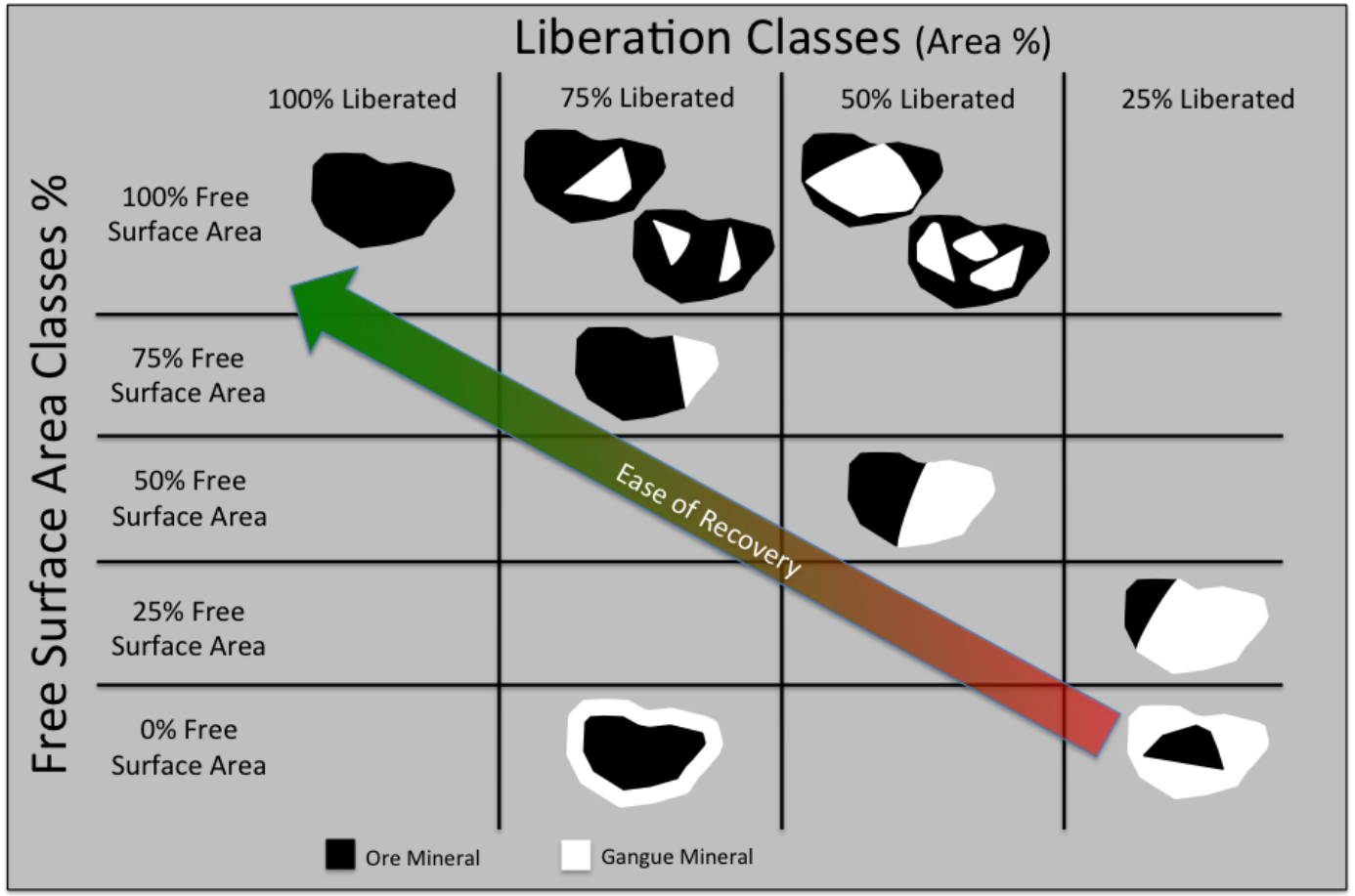
Liberation

After mining, the next step is to free valuable minerals from waste rock.



Degree of Liberation

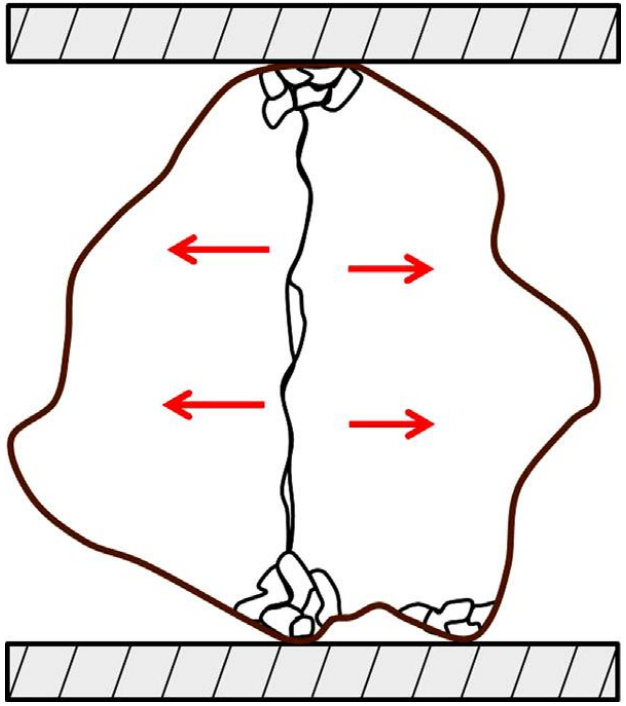
The percentage of the total valuable mineral that exists in a free (unlocked) state.

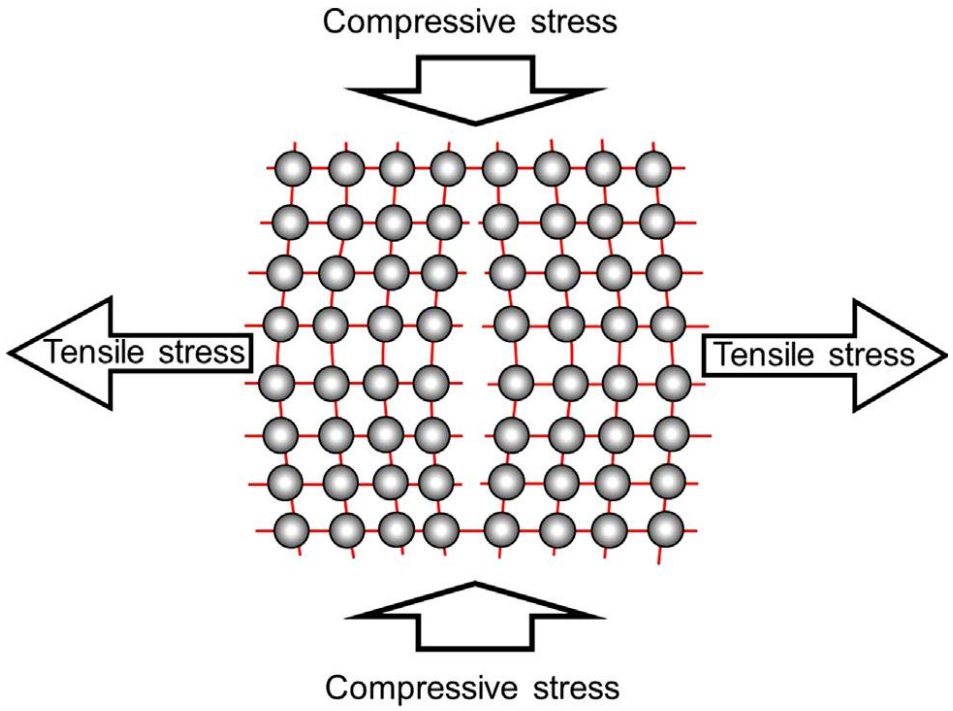


Particles classified by liberation and free surface area.

Spencer, S and Sutherland, D - 2000

Principles of Comminution



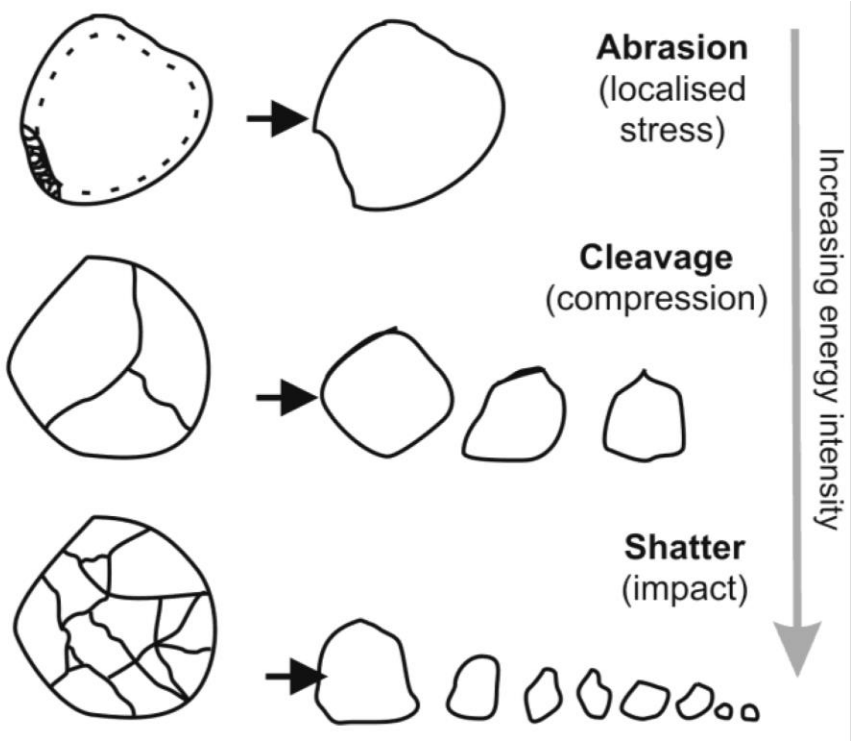




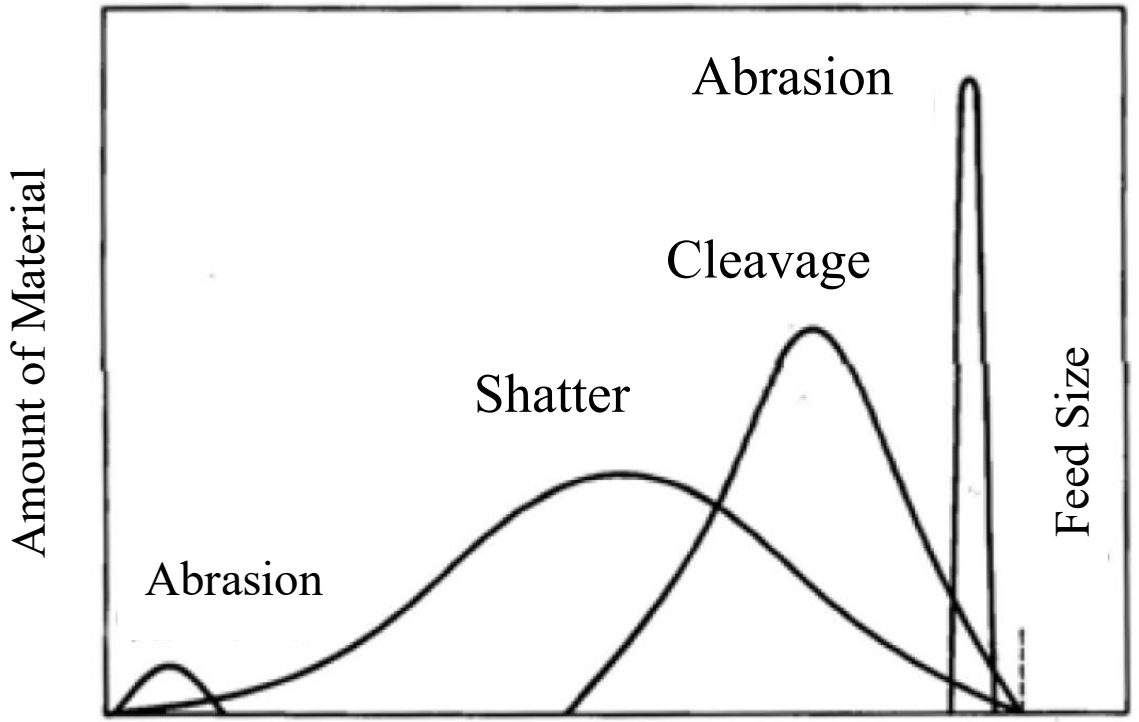
- Minerals are crystalline solids with atoms arranged in a 3D lattice.
- Bond type and strength (chemical/physical) determine structure.
- Intermolecular bonds act only at very short distances and break under tensile stress.
- Stress distribution in rocks is uneven, even under uniform loading.
- Distribution depends on mineral mechanical properties and especially on existing fractures.

Fracture Mechanisms

- **Cleavage** – caused by point loading.
- **Shatter** – caused by high loading rate and high stress.
- **Abrasion** – caused by particle–particle impacts, producing very fine particles (fines).



Bowers et al., 1996. Processing plant principles.



Theory of Comminution

Comminution theories examine the relationship between input energy and the size of particles produced.



Bond's Law

- The input work is proportional to the length of new cracks formed.
- Surface area is inversely proportional to particle diameter, and the crack length is assumed proportional to one dimension of the surface.
- The required energy is inversely proportional to the square root of the particle diameter.

Bond's Work Index:

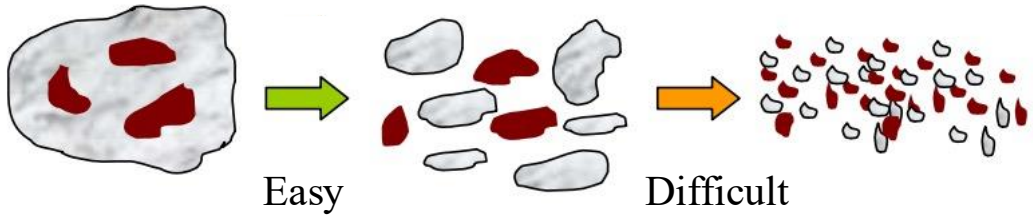
$$W = W_i\left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right)$$

F: Feed size (μm) at which 80% passes.

P: Product size (μm) at which 80% passes.

W_i (work index): The resistance of a material to crushing and grinding. Defined as the energy (kWh/ton) required to reduce material from infinite size to 80% passing 100 μm.

W: Input work (kWh/ton).



An Example Problem:

What amount of energy is required to grind particles from a feed size of 3 mm (F_{80} = 3000 µm) to a product size of 75 µm (P_{80} = 75 µm), given that the Work Index Wi = 14 kWh/t for this sample?



Energy?



3000 µm

75 µm

Solution:

Bond's equation:

$$W = W_i \left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}} \right)$$

Substitute values:

$$W = 14 \left(\frac{10}{\sqrt{75}} - \frac{10}{\sqrt{3000}} \right)$$

$$W = 13.6 \, \frac{\text{kWh}}{t}$$

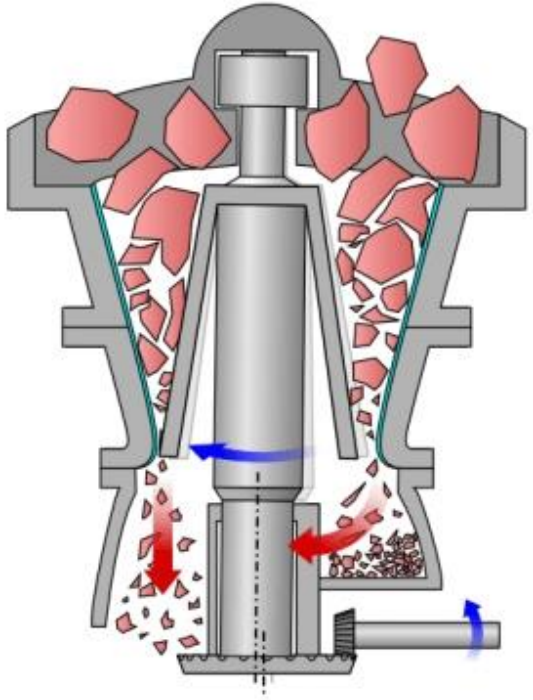
Convert to horsepower-hours per ton:

$$13.6 \, \frac{\text{kWh}}{t} \times \frac{1.341 \, HP}{1 \, kW} = 18.24 \, \frac{HP \cdot h}{t}$$

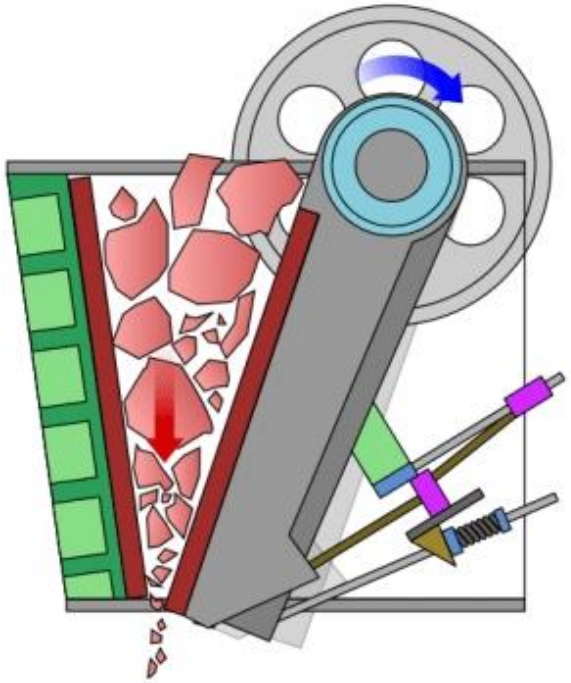
Crushers

Input size: 500 mm – 1500 mm

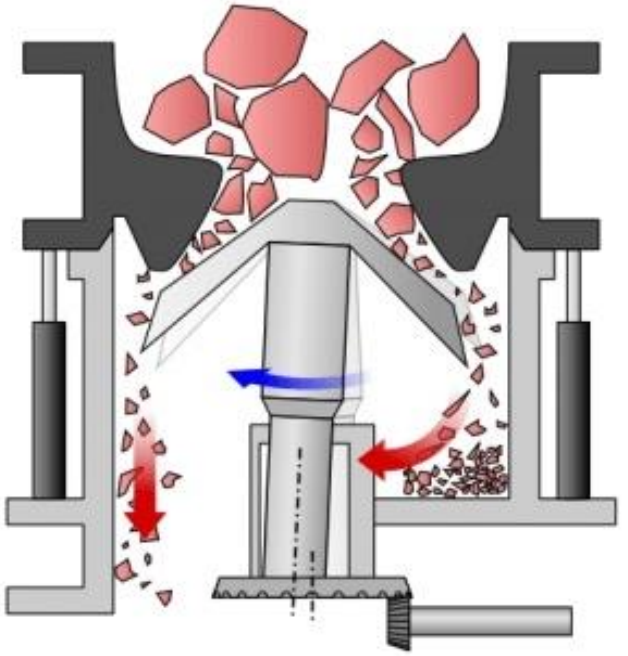
Output size: 100 mm – 300 mm



Gyratory Crusher



Jaw Crusher



Cone Crusher

Primary

Secondary

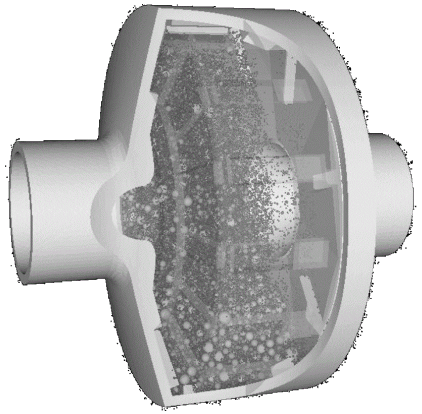
Mills

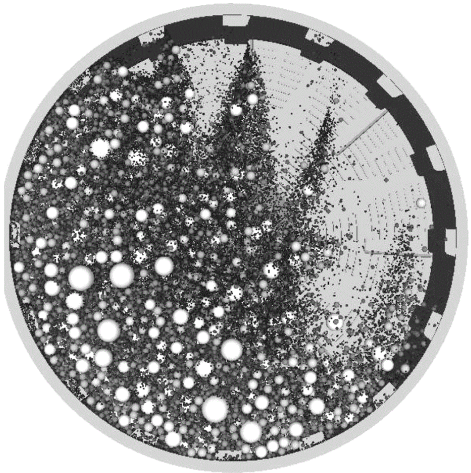
AG/ SAG Mill



Ball Mill

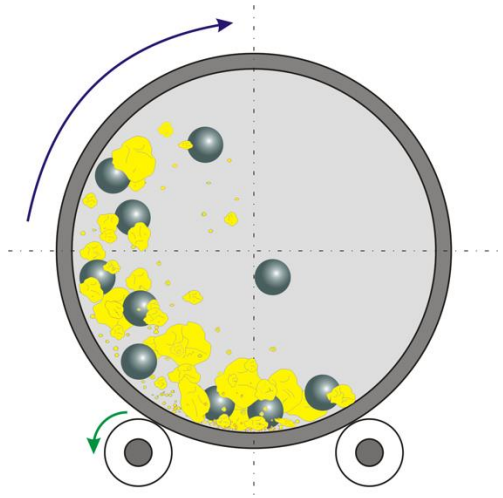








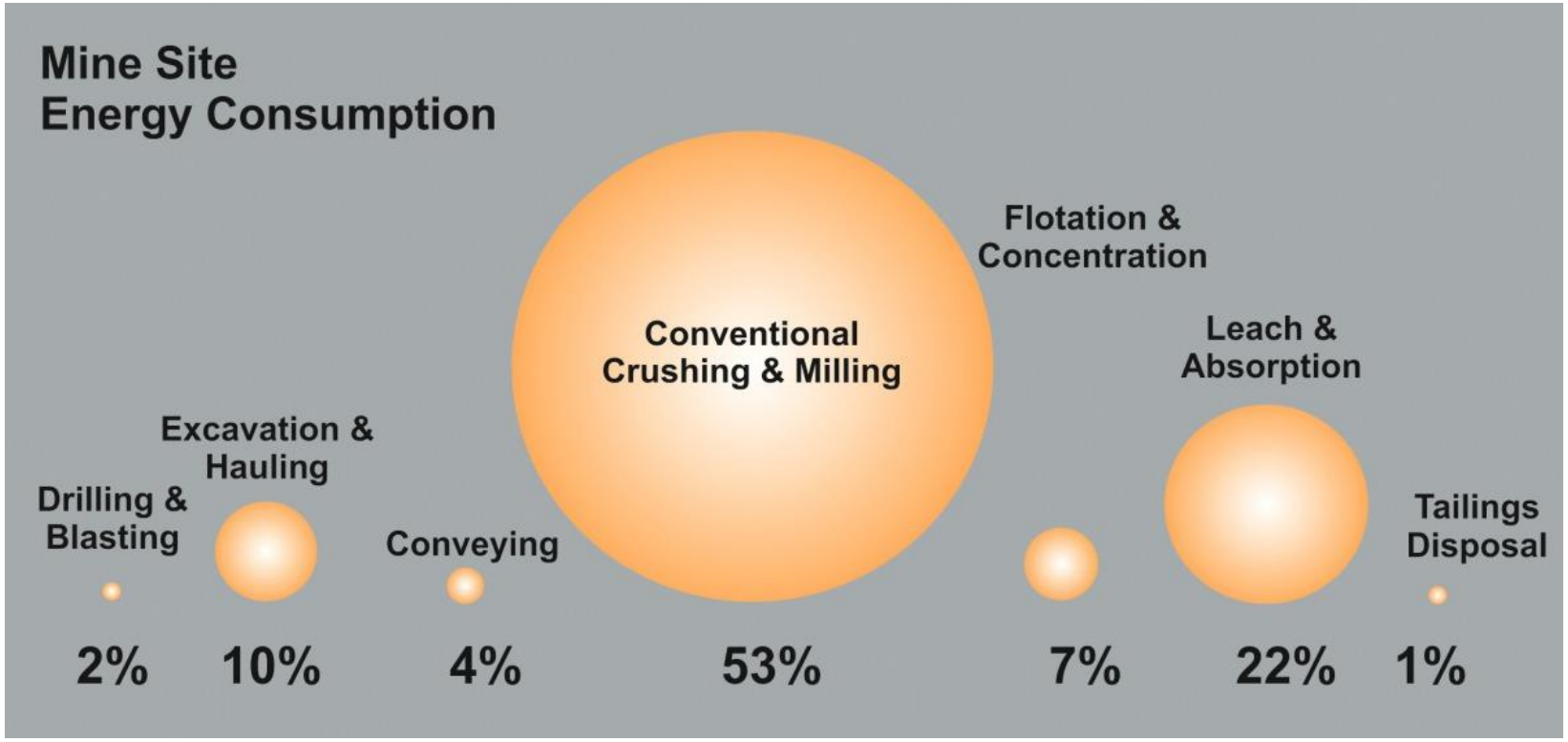
Media

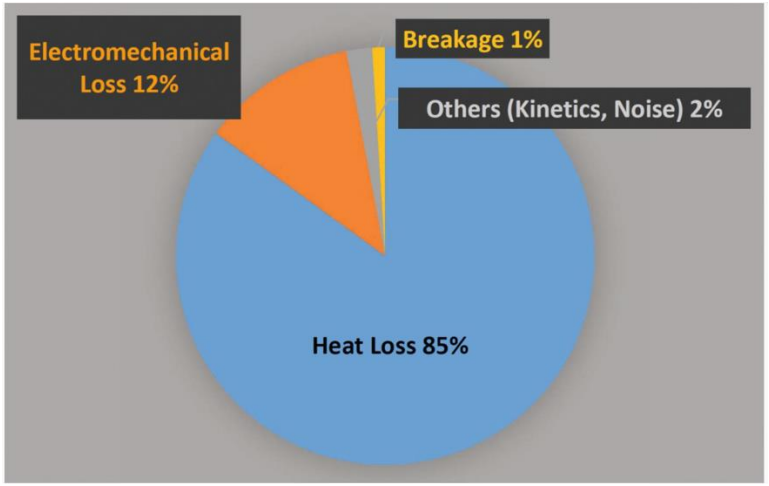


www.911metallurgist.com/

Energy consumption is a huge issue!

It is estimated that only about 1% of the comminution energy is actually used for particle breakage.

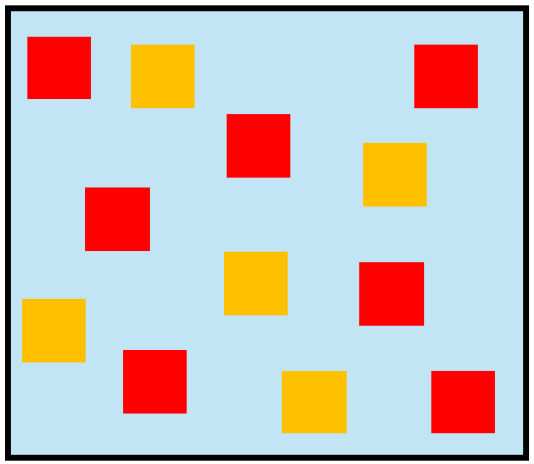




~80% for REE ore in Mountain Pass (MP Materials)

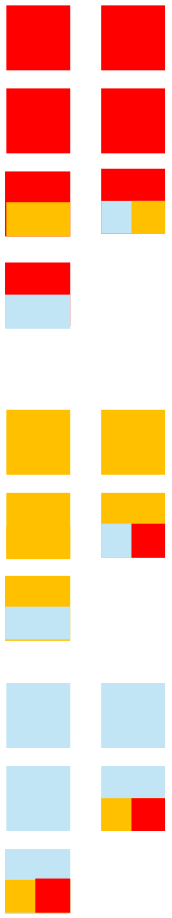
https://www.at-minerals.com/

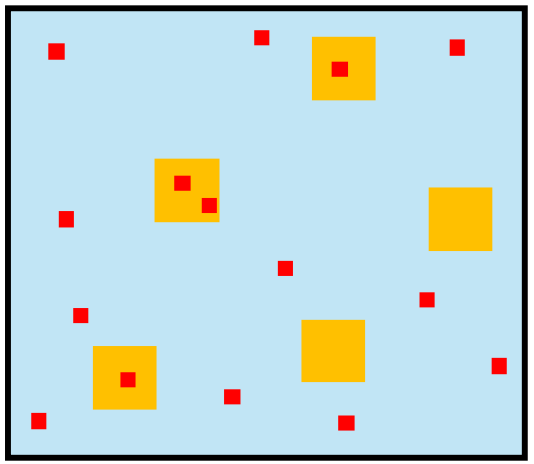
Ore Grade Matters!



High Grade Ore

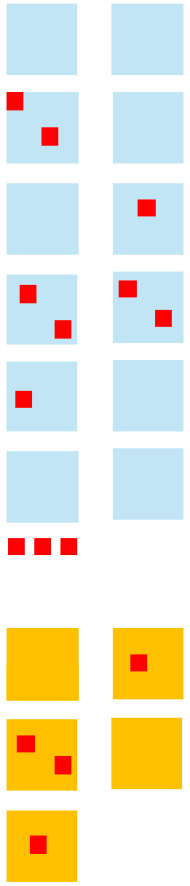
Grinding Product





Low Grade Ore

Grinding Product



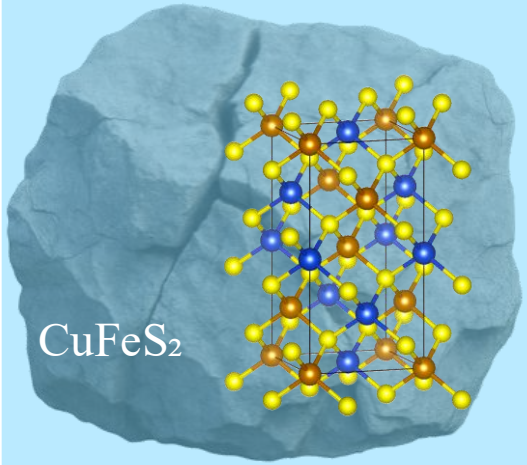
More Grinding Needed

Wet Grinding

The energy required for comminution decreases in the presence of water, and even more with surface-active chemicals, since water adsorption weakens the bond strength at crack tips.

Electrochemical (Galvanic) Interaction

Cathodic Reaction

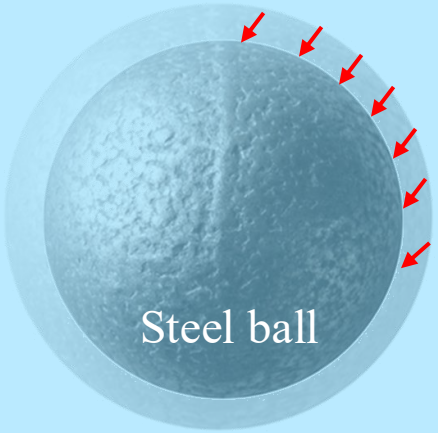


$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

$$CuFeS_2 + 4O_2 \rightarrow Cu^{2+} + Fe^{2+} + 2SO_4^{2-}$$

$$CuFeS_2 + 4Fe^{3+} \rightarrow Cu^{2+} + 5Fe^{2+} + 2S^0$$

$Fe(OH)_3$, $Cu(OH)_2$, and elemental S^0 can deposit on mineral surfaces.



Anodic Reaction

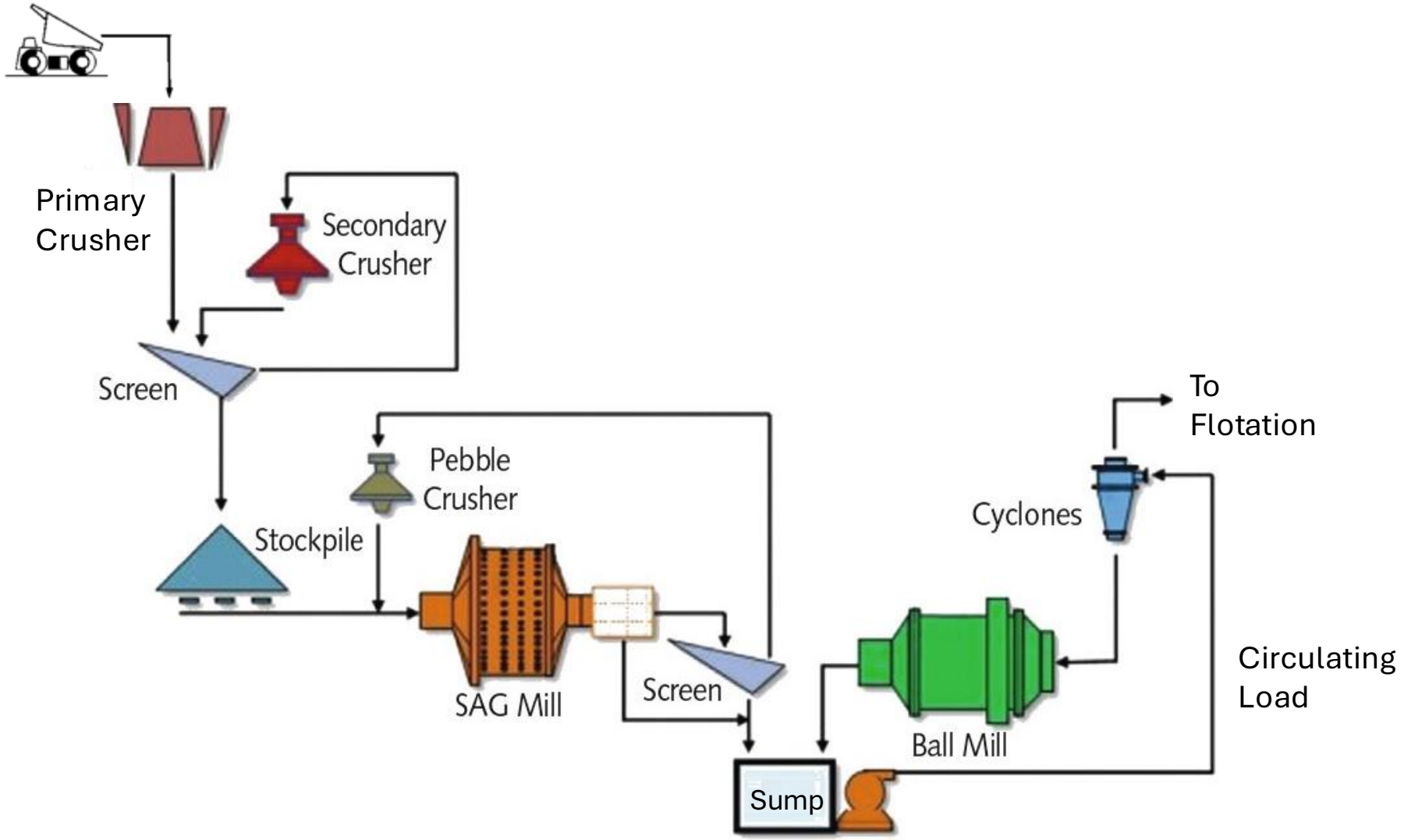
$$Fe \rightarrow Fe^{2+} + 2e^- \quad \text{Corrosion}$$

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$$

This lowers slurry pH, increasing lime consumption for pH control.



Comminution Circuit

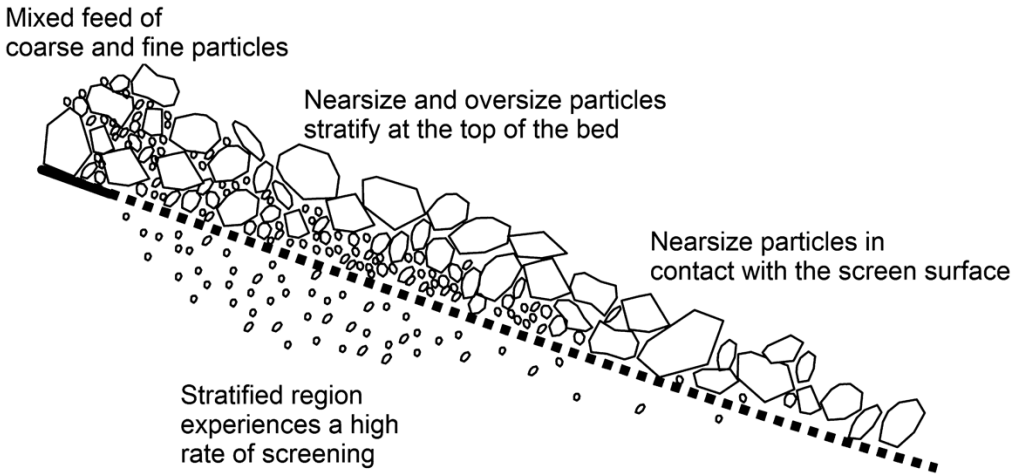


Sizing & Classification

... separating mineral particles using the difference in their size.

Screening







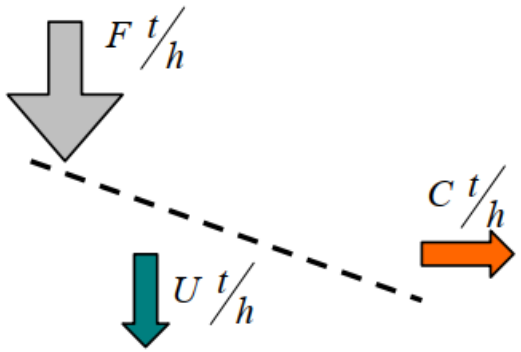
Similar to how we do it in our kitchen!

Screen Efficiency

Two key factors determine screening efficiency:

- The amount of undersize material (finer than the aperture) that remains on the screen.
- The amount of oversize material (coarser than the aperture) that passes through the screen.

The quantity of misclassified material is the main indicator of screening efficiency.



- Overall mass balance:

$$F = C + U$$

- Mass balance of oversize (coarse material):

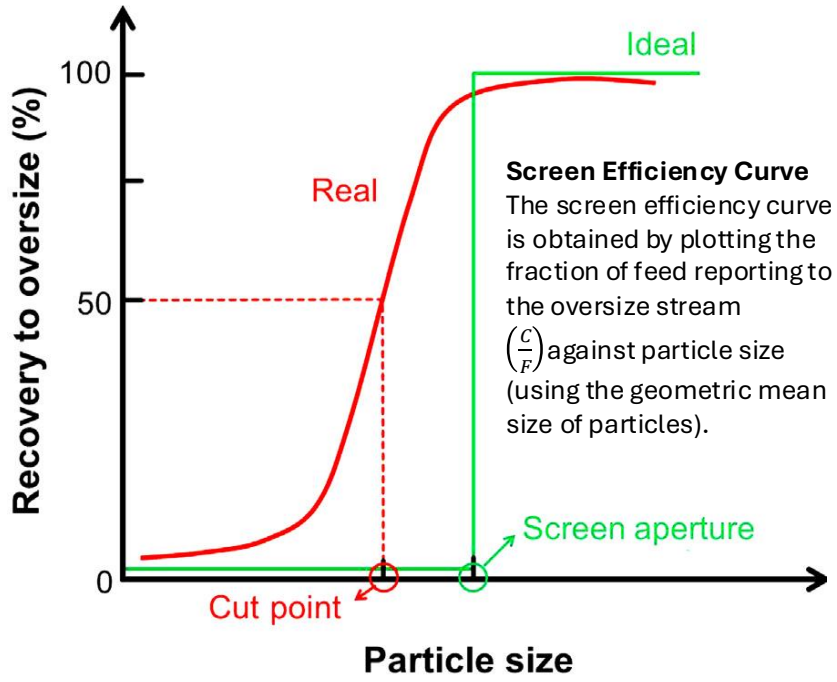
$$Ff = Cc + Uu$$

- Mass balance of undersize (fine material):

$$F(1-f) = C(1-c) + U(1-u)$$

F = feed
C = oversize stream (on screen)
U = undersize stream (through screen)
f = fraction of feed larger than aperture
c = fraction of oversize larger than aperture
u = fraction of undersize larger than aperture

$$E = \frac{c-f}{c(1-f)} \times 100$$

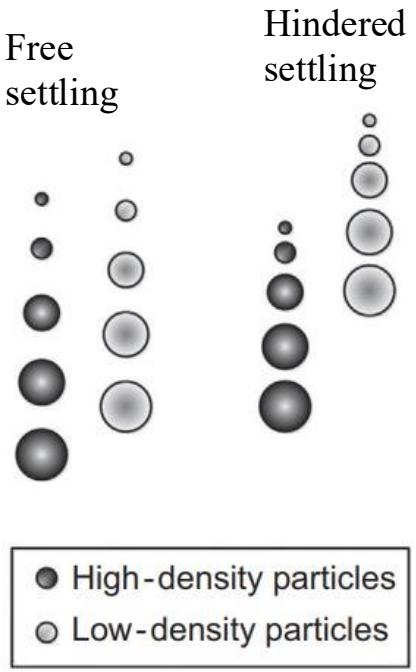


Classification

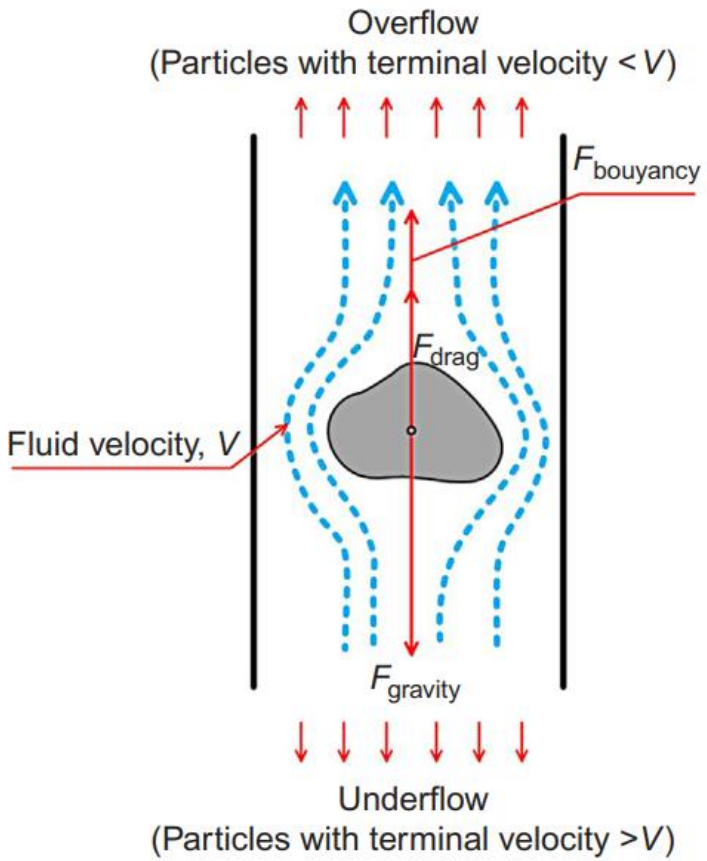
- Screening is inefficient for fine particles; classification in water is commonly used.
- Classification separates particles by their settling velocity in a fluid.
- Settling velocity depends on size, density, and shape.

Principles of Classification

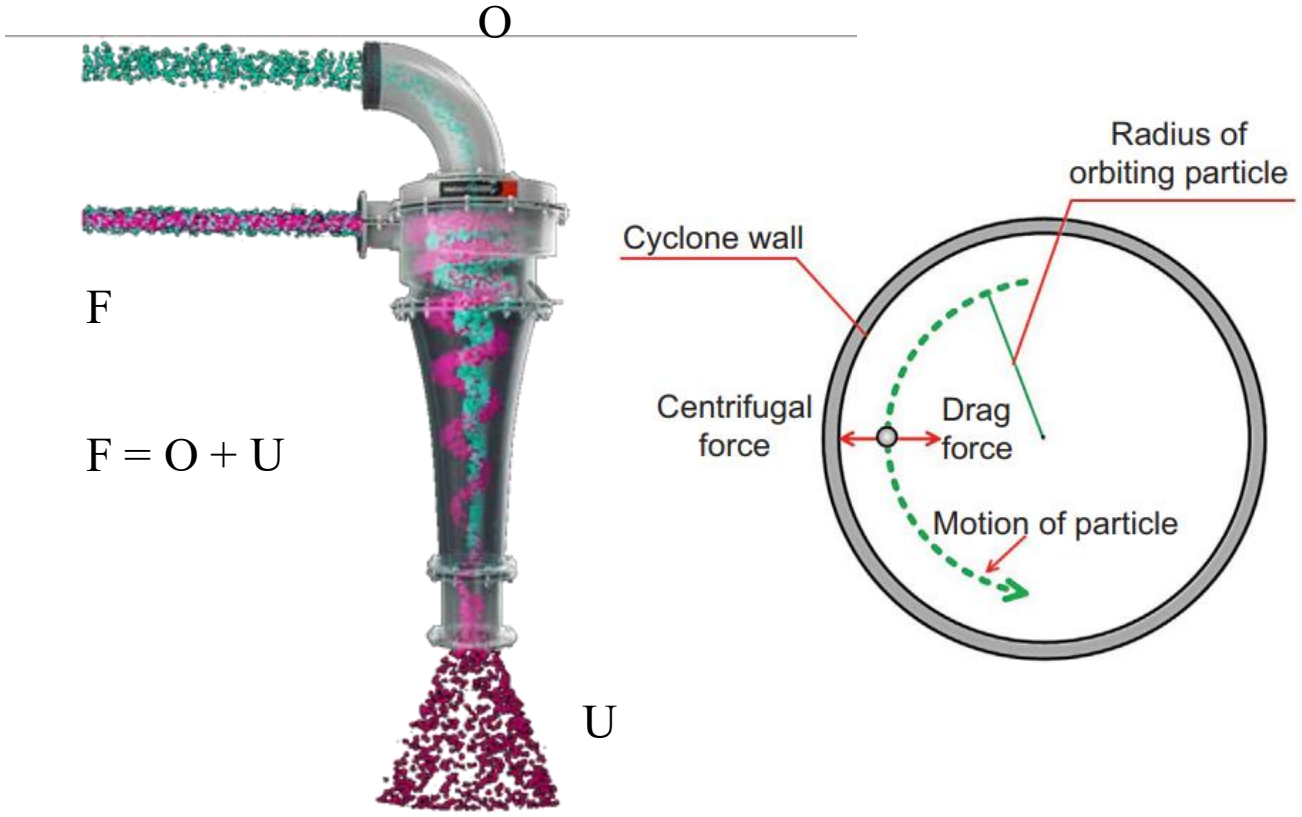
- In a vacuum, falling bodies accelerate equally regardless of size or density.
- In a viscous medium (air or water), resistance to motion increases with velocity.
- When gravity, fluid resistance, and buoyancy balance, the particle reaches terminal velocity and falls at a constant speed.



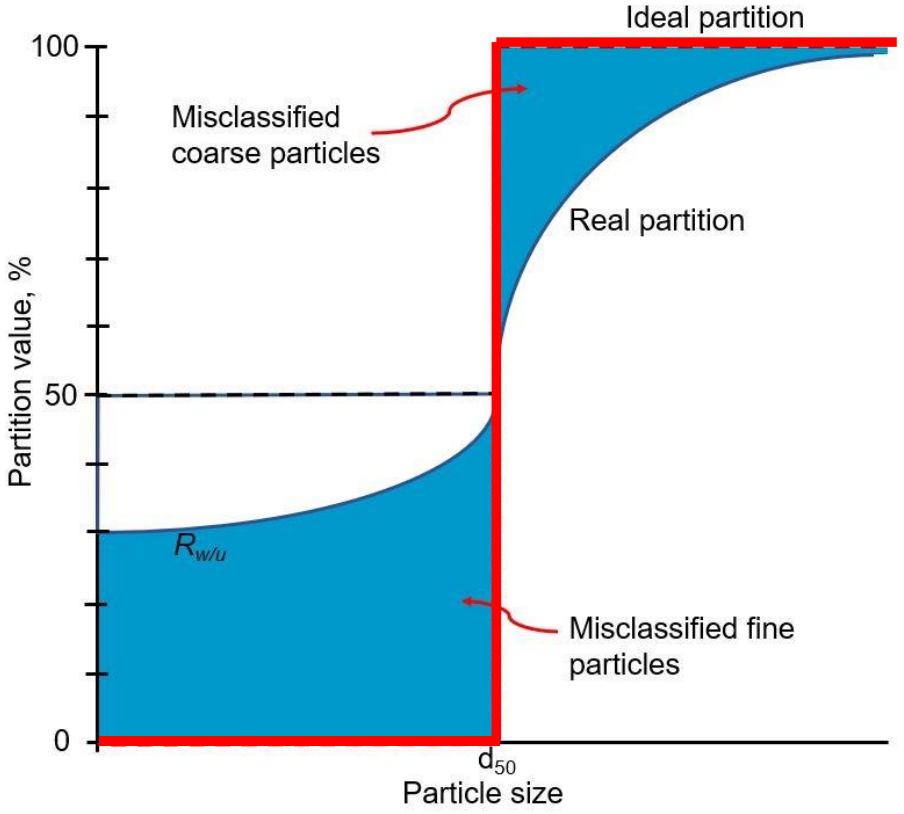
Force Balance



Hydrocyclones



https://www.metso.com



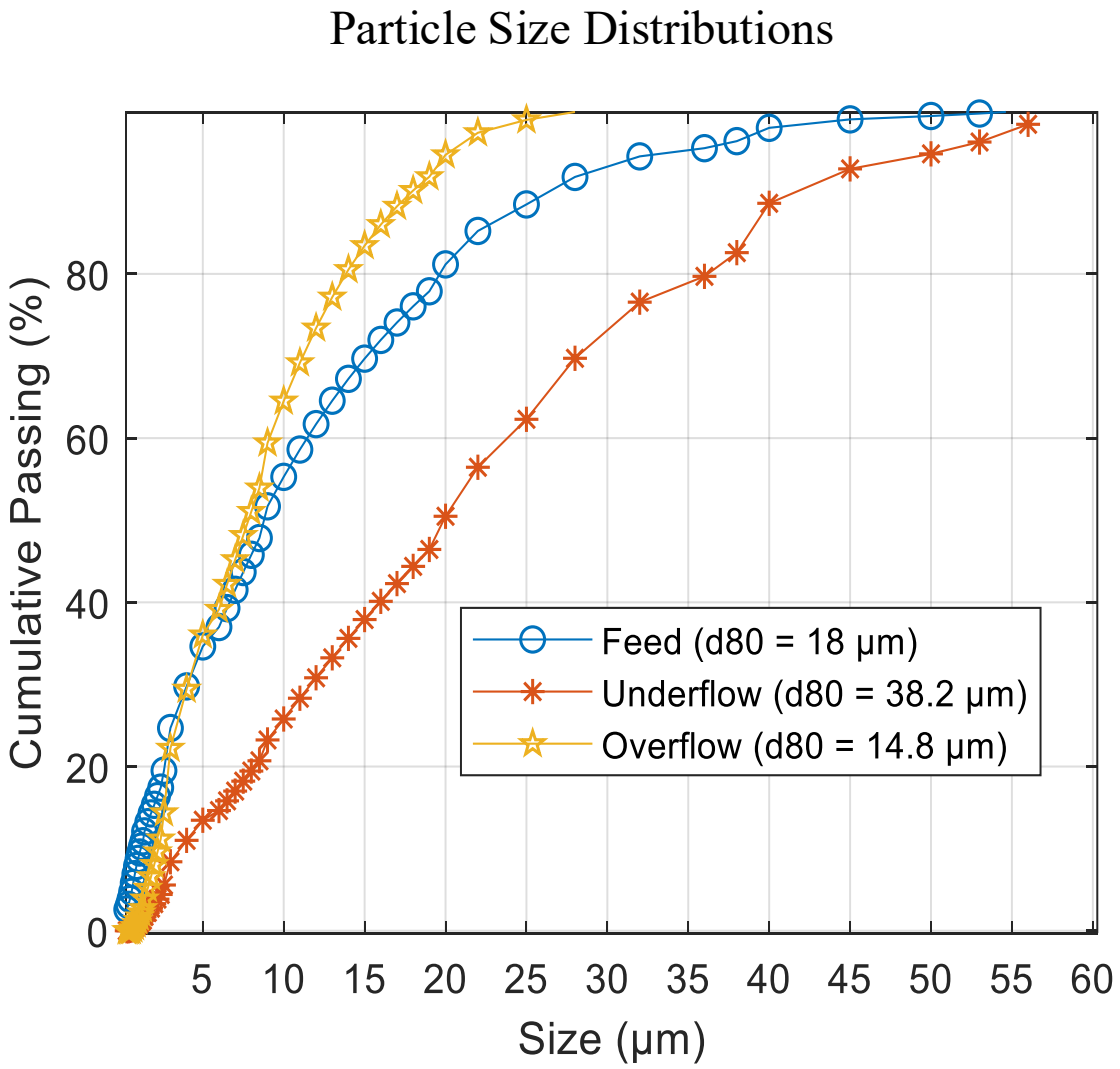
Hydrocyclone efficiency curve

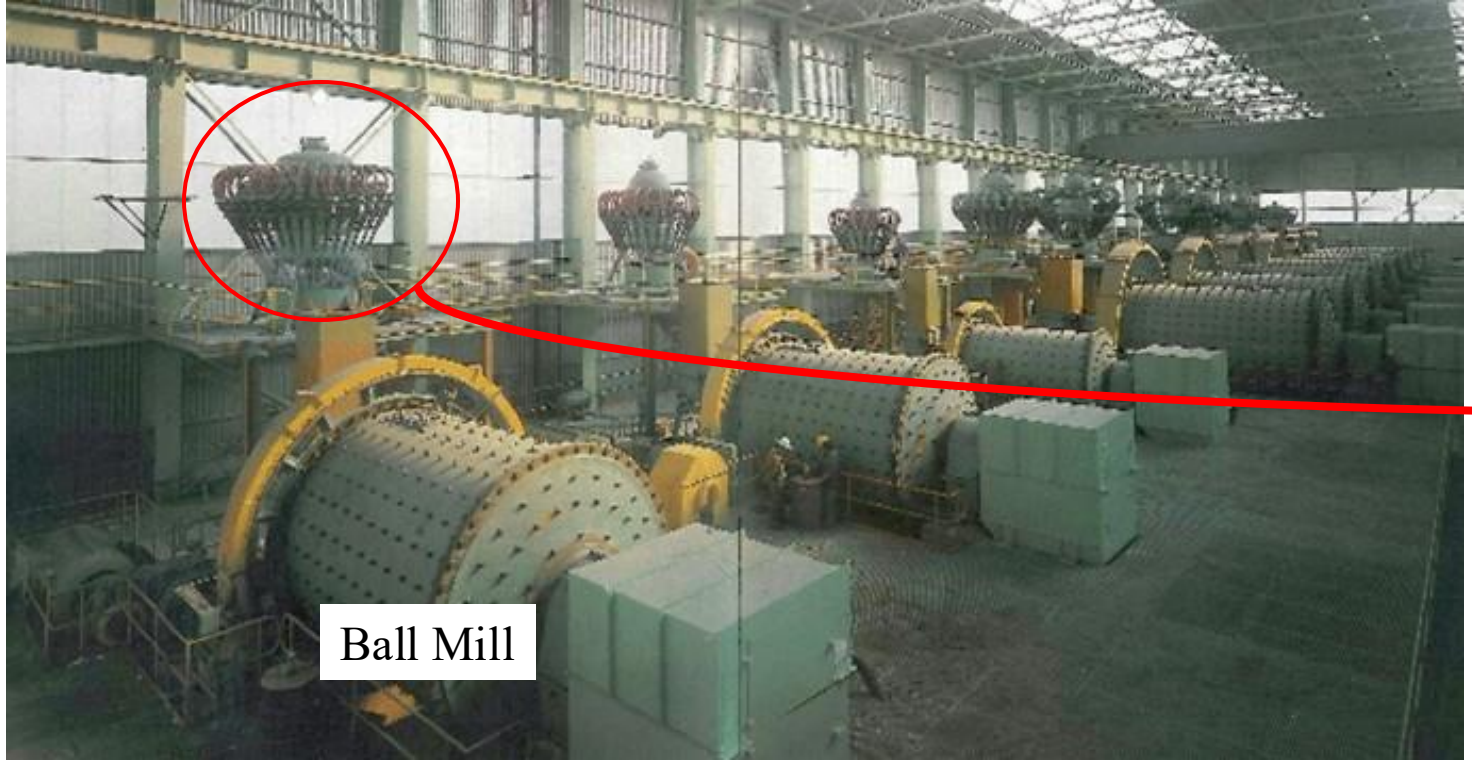
https://smi.uq.edu.au

Hydrocyclones



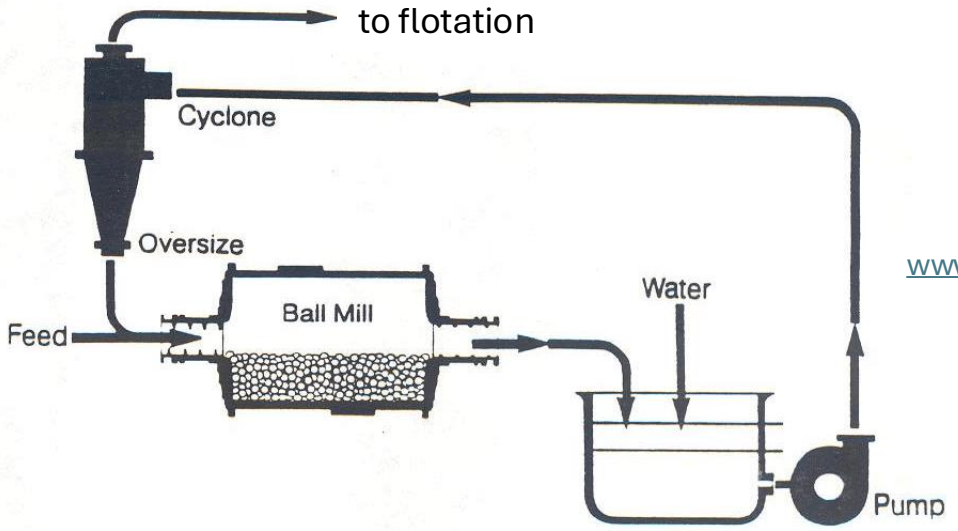
1.5-inch hydro-cyclone







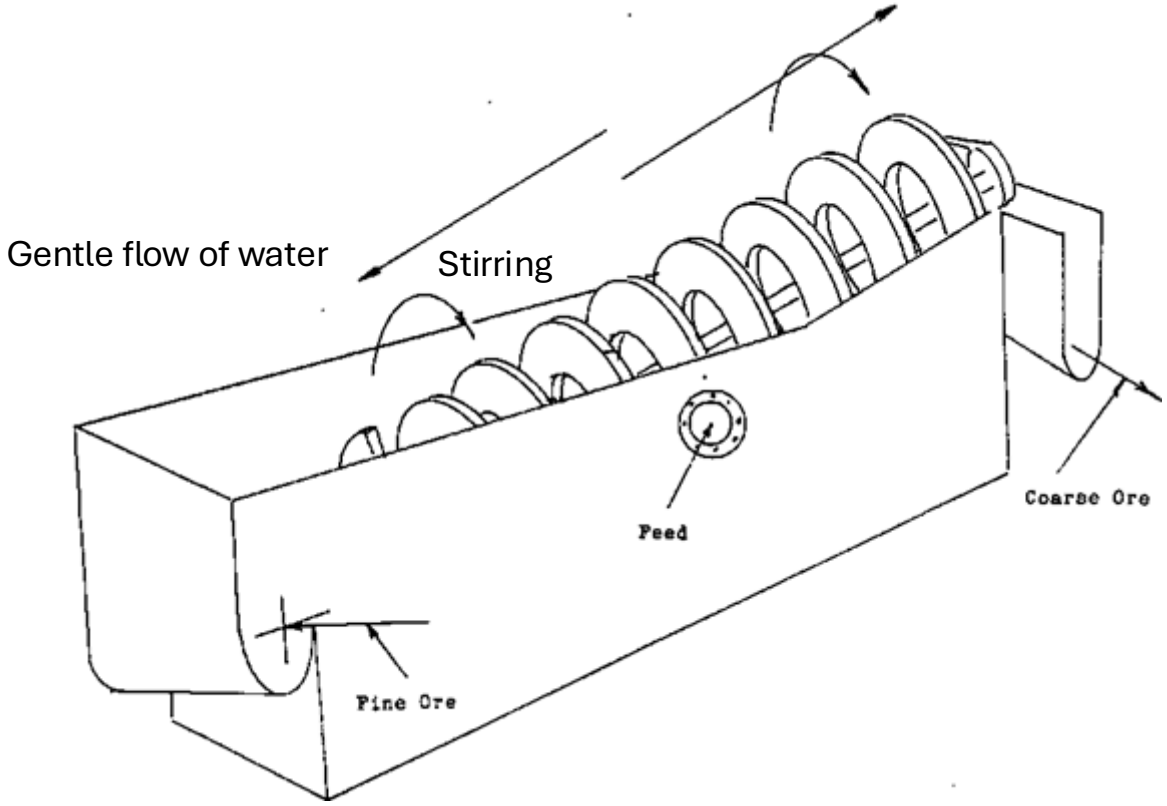
Cluster of hydrocyclones



www.911metallurgist.com

Spiral Classifiers

- Particles with low settling velocity in the fluid report to the overflow.
- Particles with high settling velocity settle at the bottom and are lifted against the water flow by the spiral.
- The spiral action releases fine particles, preventing them from being carried into the coarse (underflow) product.



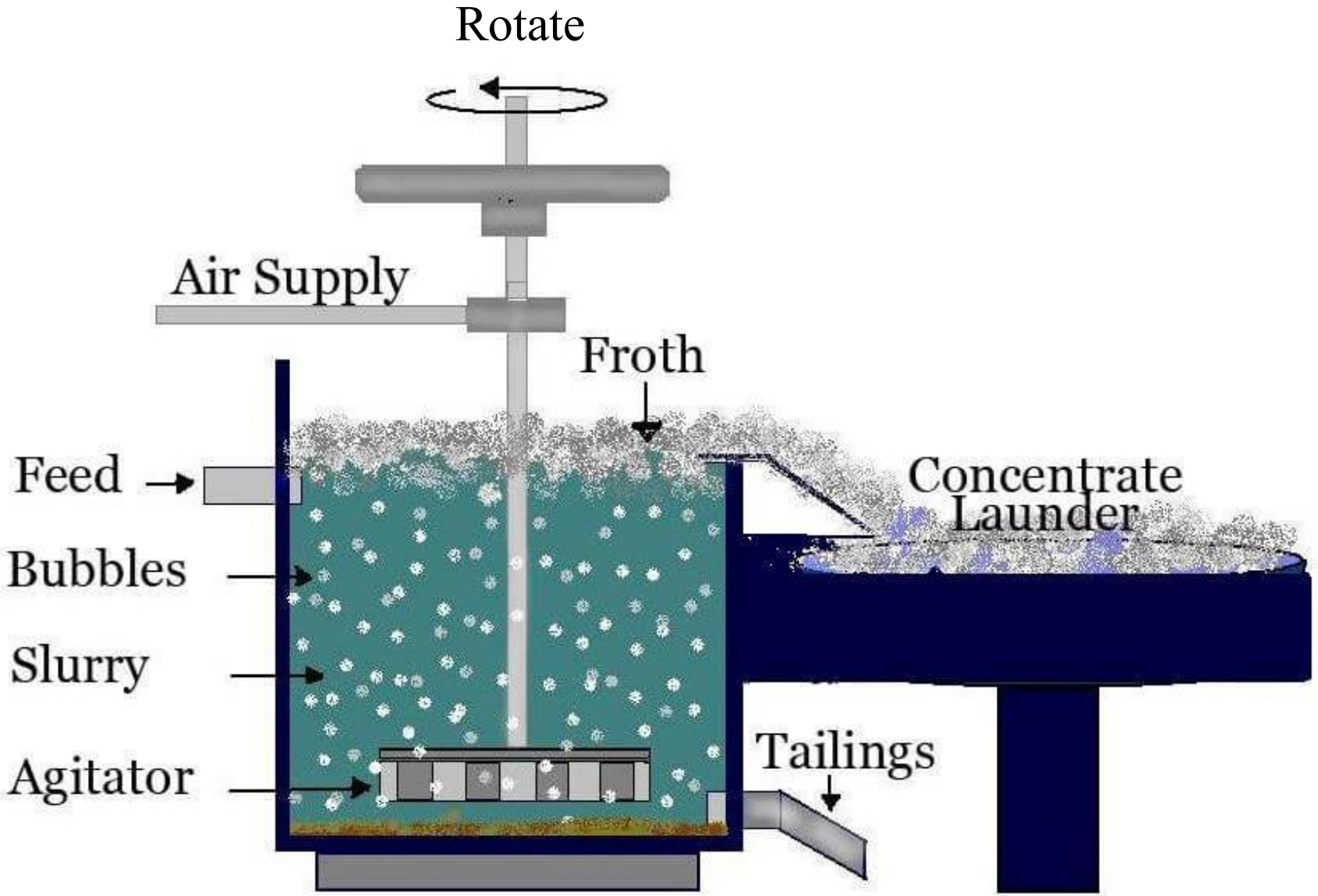


Mineral Processing course notes, Samad Banisi, Bahonar University
www.911metallurgist.com

Froth Flotation

... separating minerals using their surface wettability.

How froth flotation works

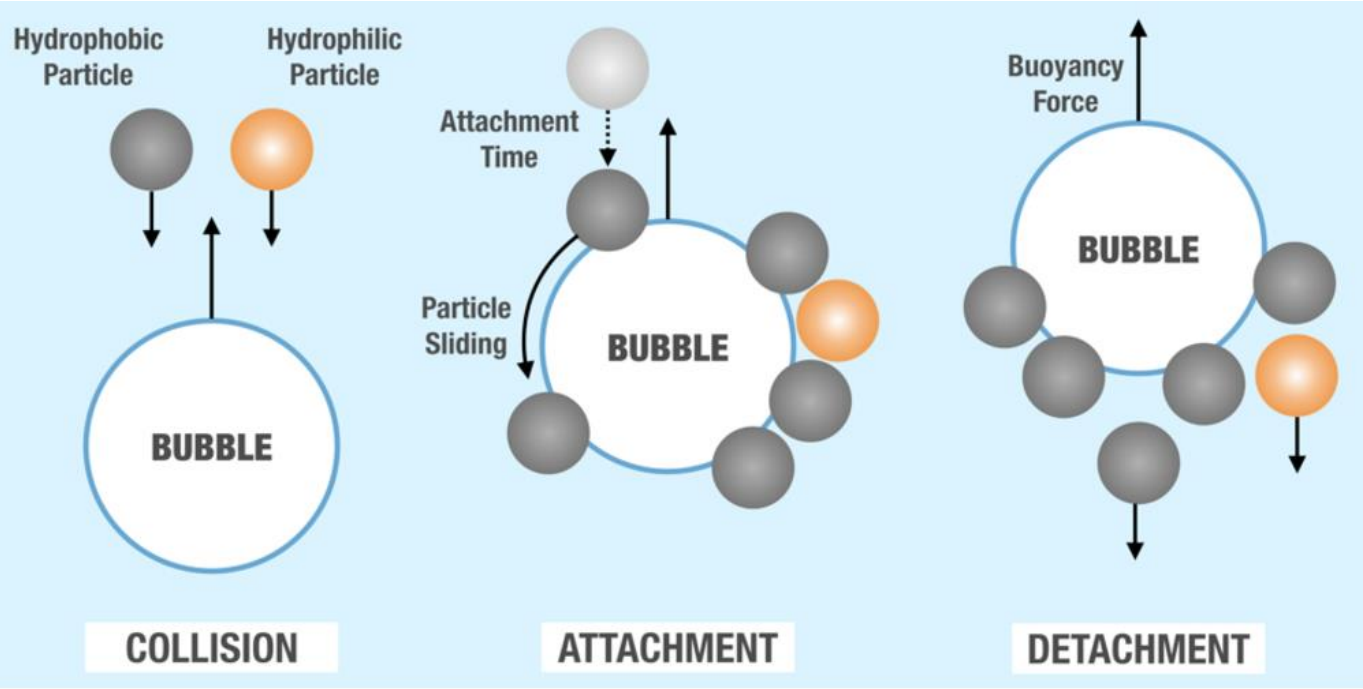


https://www.911metallurgist.com/

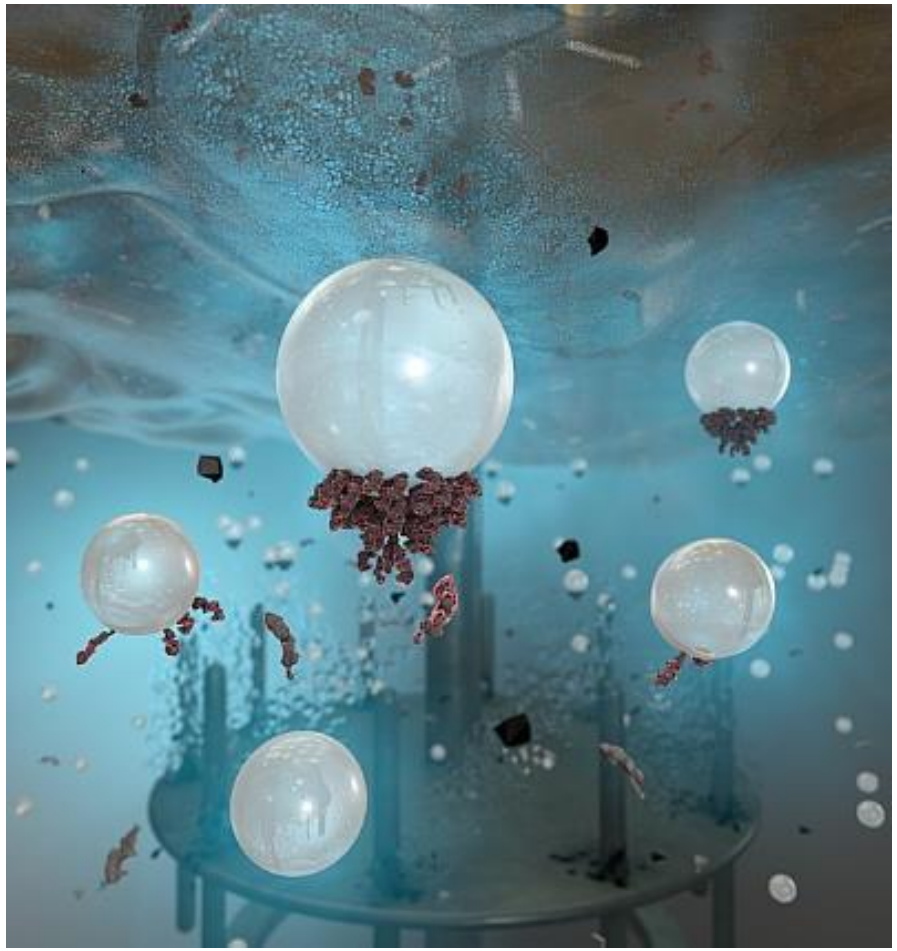
Principles of Flotation

- Flotation is usually applied to relatively fine particles (smaller than 150 μm).
- For a mineral particle to attach to an air bubble, the particle must be hydrophobic.
- For the attached particles to be carried to the concentrate, bubbles must remain stable and not break apart.
- To make particles hydrophobic, chemical reagents are used.
- To stabilize the bubbles, frothers are added.
- Most minerals are not naturally hydrophobic, so reagents must be added to make them so.
- Some naturally hydrophobic minerals include graphite, molybdenite, diamond, coal, talc, etc.

Particle collection on air bubbles



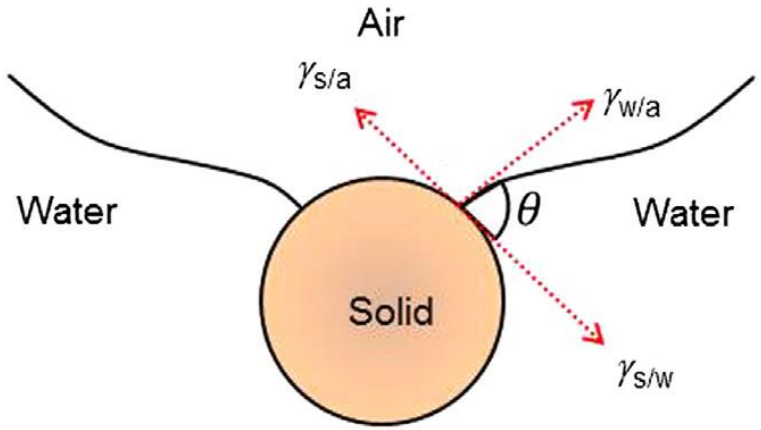
Sokolović and Mišković, 2018 - Physicochemical Problems of Mineral Processing

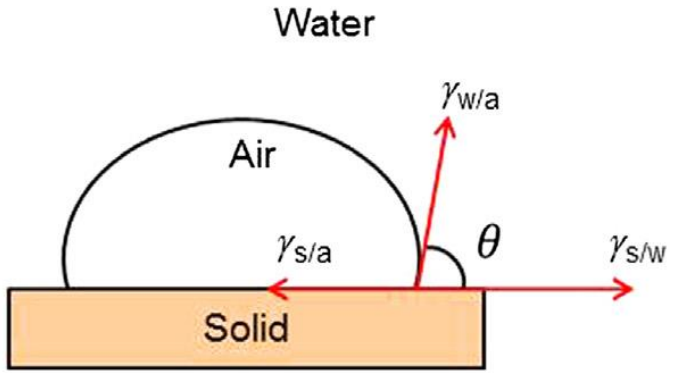


https://www.hzdr.de/db/Cms?pOid=49661&pNid=0

Hydrophobicity (wettability)







At equilibrium:

$$\gamma_{S/A} = \gamma_{S/W} + \gamma_{W/A}\cos\theta$$

Work required $(W_{S/A})$ for breaking the unit surface between particle and bubble:

$$W_{S/A} = \gamma_{W/A} \times 1 + \gamma_{S/W} \times 1 - \gamma_{S/A} \times 1$$

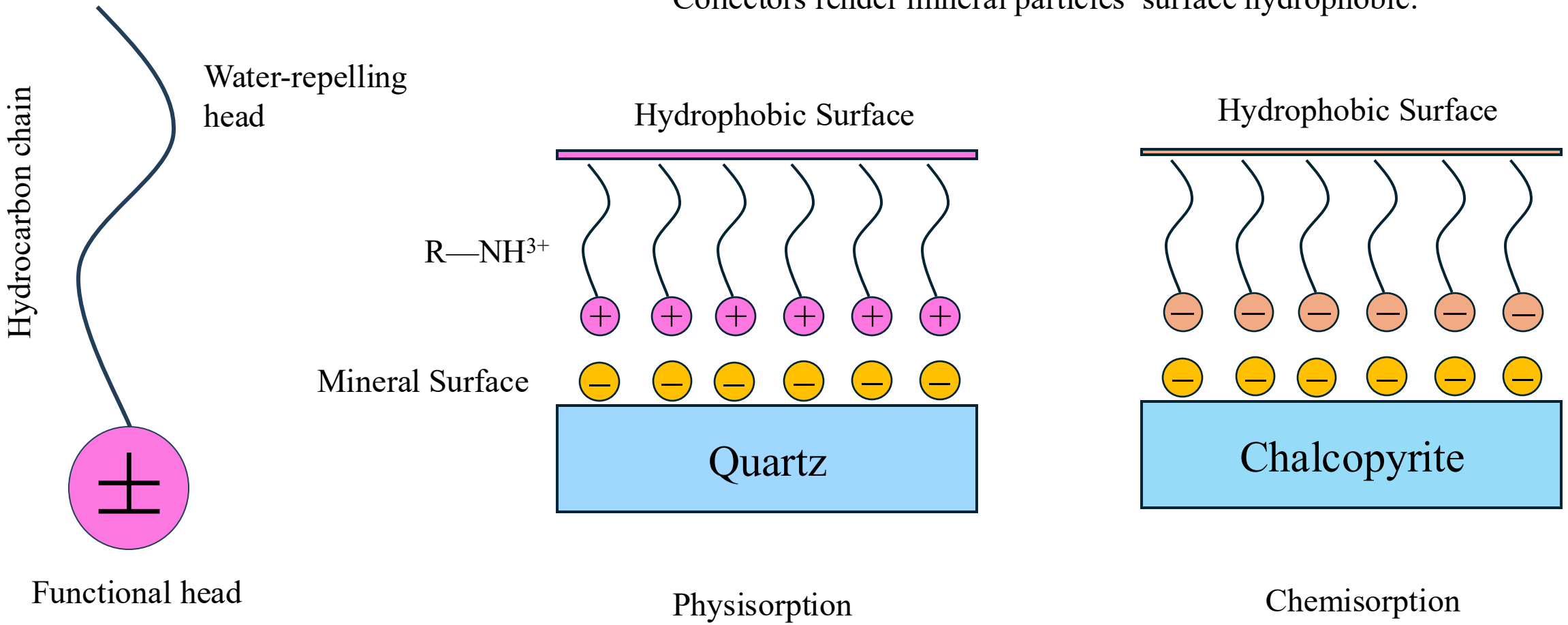
By combining the two equations above:

$$W_{S/A} = \gamma_{W/A}(1 - \cos\theta)$$

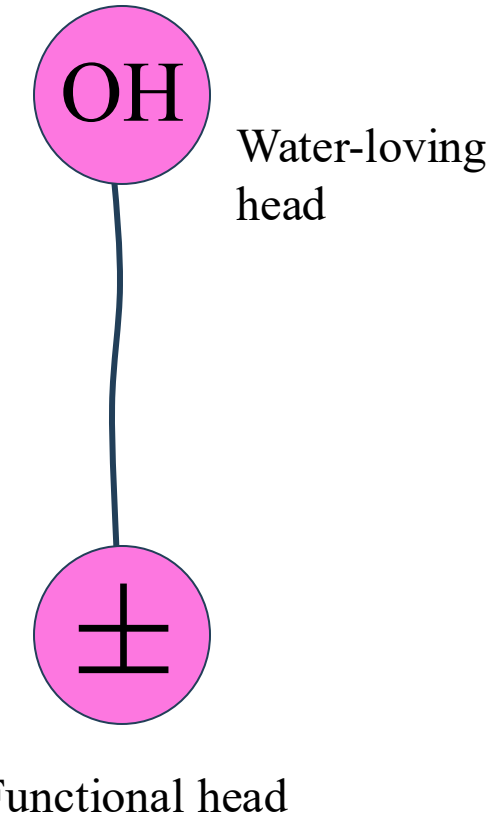
Therefore, the greater the contact angle, the more work is required to detach the particle from the bubble.

Flotation Reagents – Collectors

Collectors render mineral particles' surface hydrophobic.



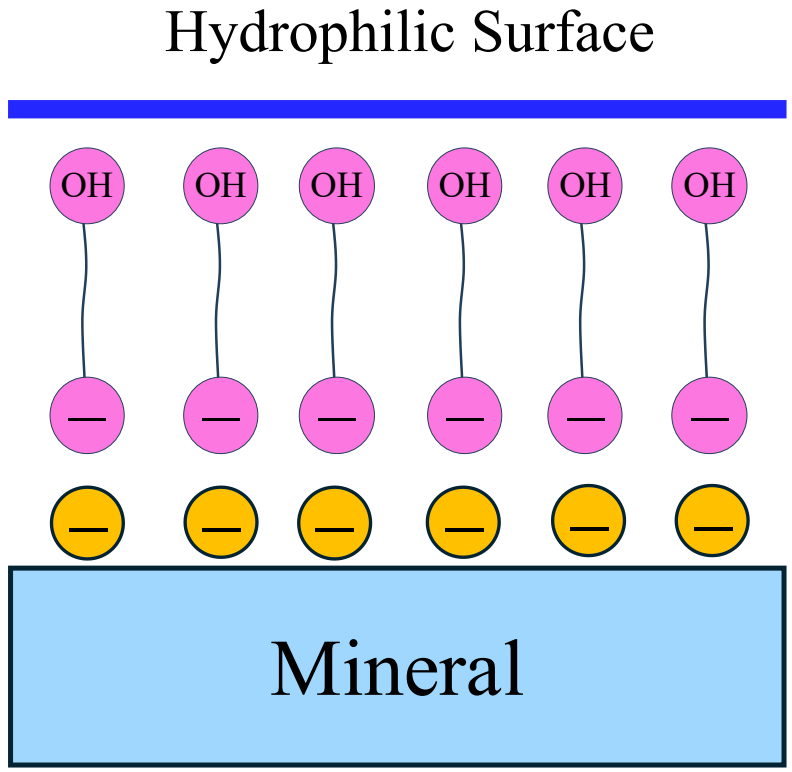
Flotation Reagents – Depressants



While making select minerals hydrophobic, We want to (if needed) keep associating minerals hydrophilic using Depressants, to enhance selectivity.

HO— $RCOO^-$

Mineral Surface

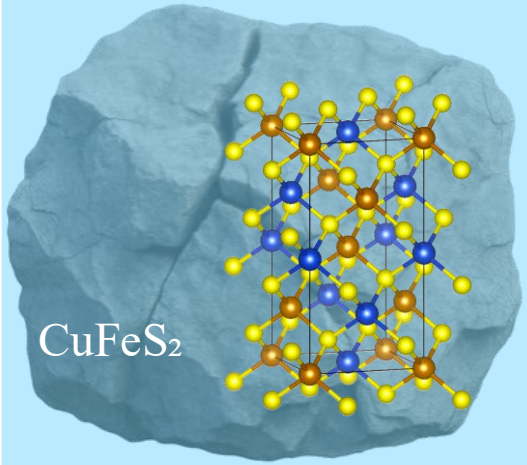


Chemistry of grinding affects froth flotation

In the presence of water and sulfide minerals, electrochemical interactions can lead to the release of metallic ions into pulp, and surface coating of particles, which eventually affect flotation.

Electrochemical (Galvanic) Interaction

Cathodic Reaction

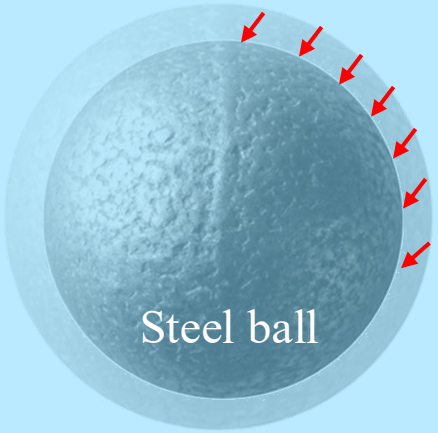


$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

$$CuFeS_2 + 4O_2 \rightarrow Cu^{2+} + Fe^{2+} + 2SO_4^{2-}$$

$$CuFeS_2 + 4Fe^{3+} \rightarrow Cu^{2+} + 5Fe^{2+} + 2S^0$$

$Fe(OH)_3$, $Cu(OH)_2$, and elemental S^0 can deposit on mineral surfaces.



Anodic Reaction

$$Fe \rightarrow Fe^{2+} + 2e^- \quad \text{Corrosion}$$

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$$

This lowers slurry pH, increasing lime consumption for pH control.

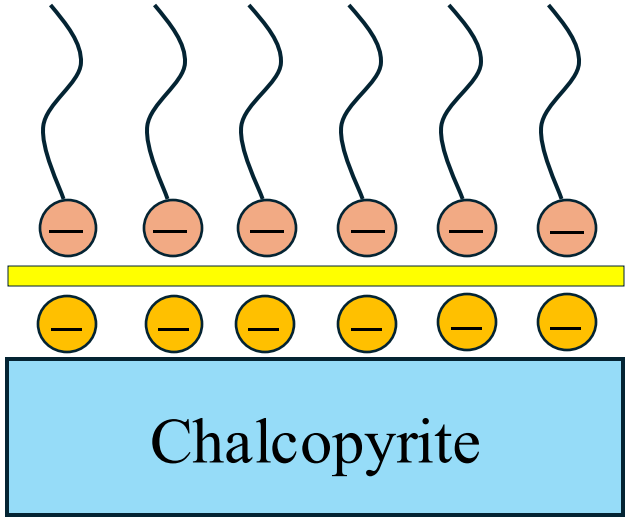
Fe3+ Cu+ S2-

Altered **surface chemistry** and **pulp chemistry** affect reagent adsorption and flotation recovery.

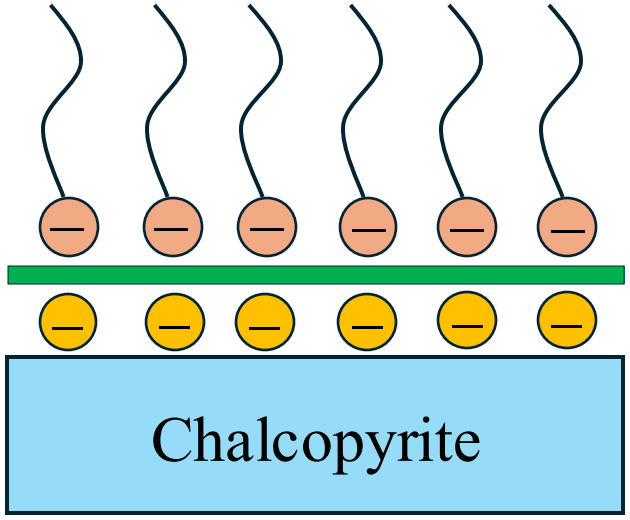
Altered mineral surface chemistry

… check your pulp chemistry, pH, and variations in grinding media loading.

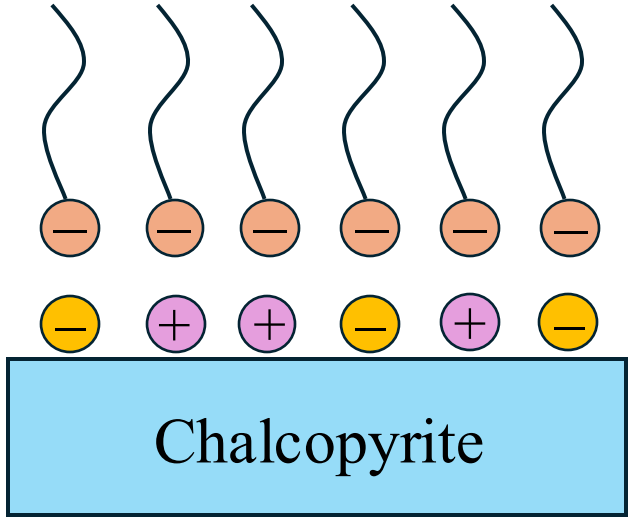
Surface passivation by elemental sulfur. No adsorption of reagents, No flotation.



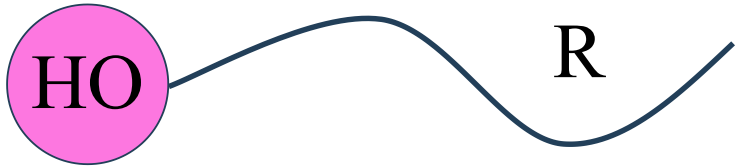
Surface coating by Fe/ Cu hydroxides. No adsorption of reagents, No flotation.



pH and adsorption of metallic ions change mineral surface groups. Inefficient flotation.



Flotation Reagents – Frothers

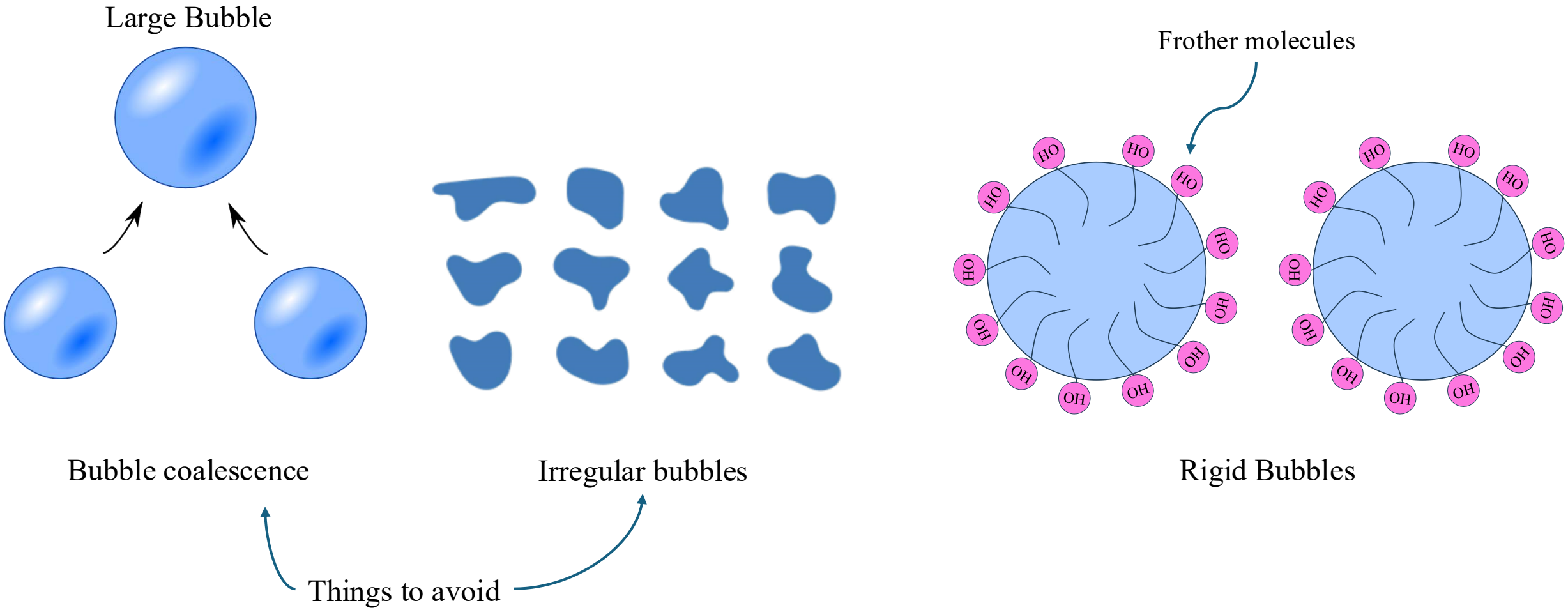


Frother behaves as soap
Flotation cell is a bubble bath

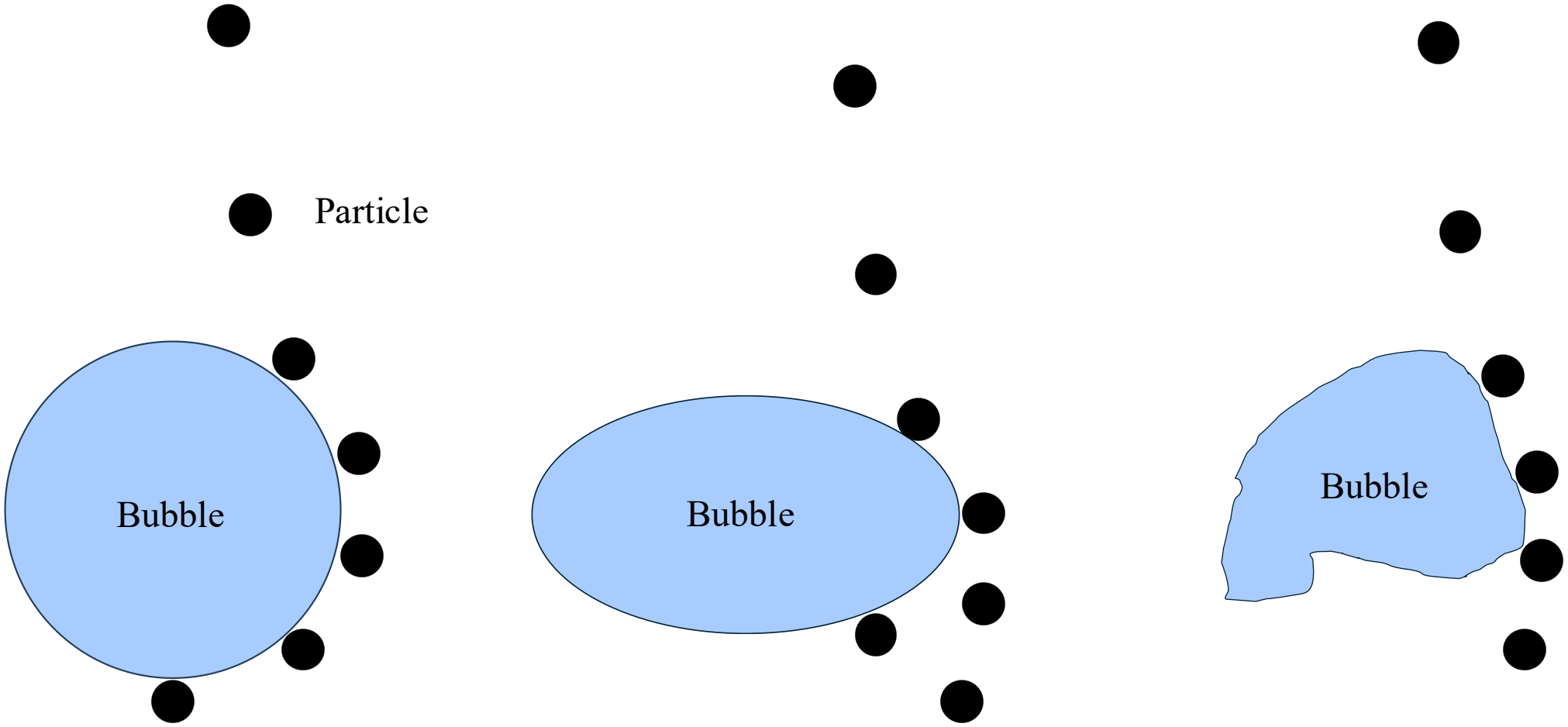




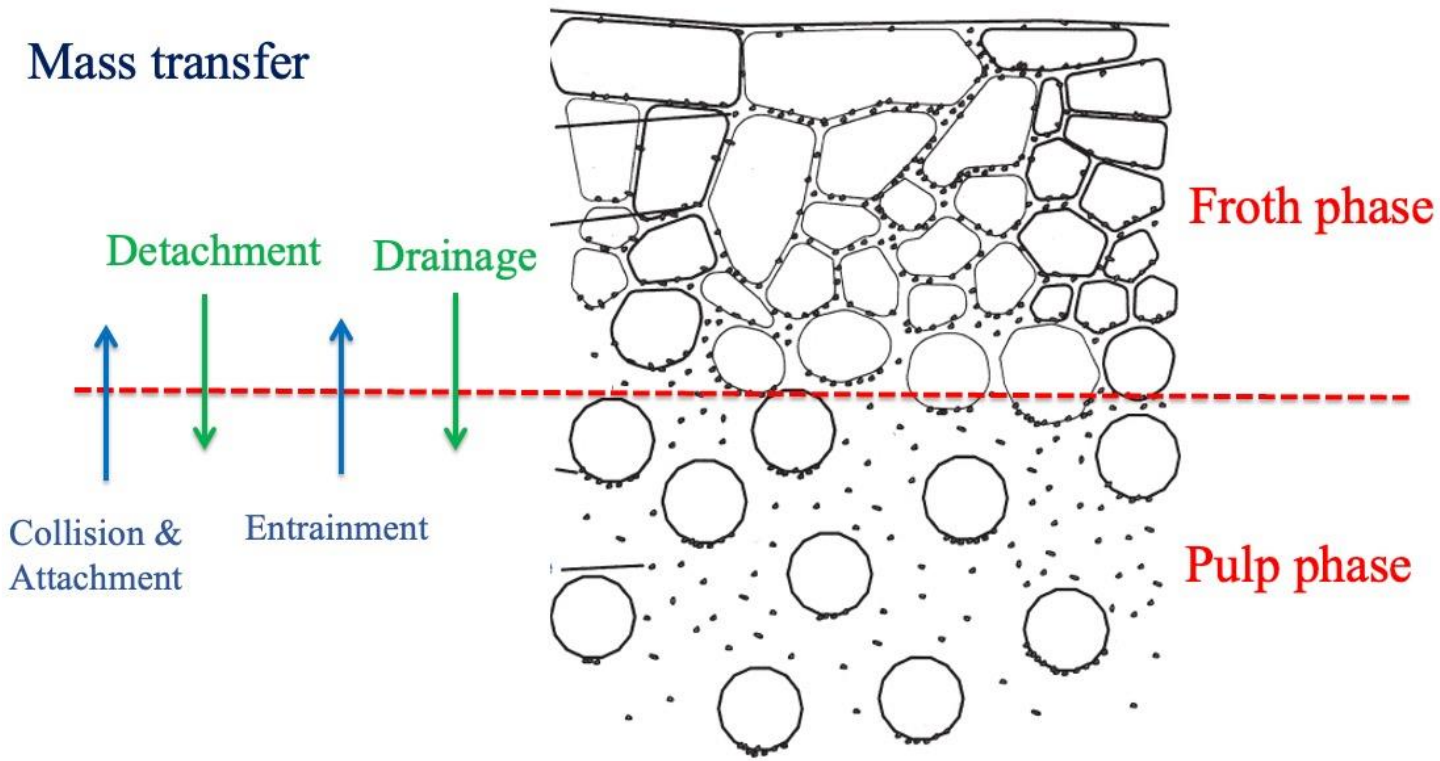
Frother helps to have small and rigid bubbles for better hydrodynamics



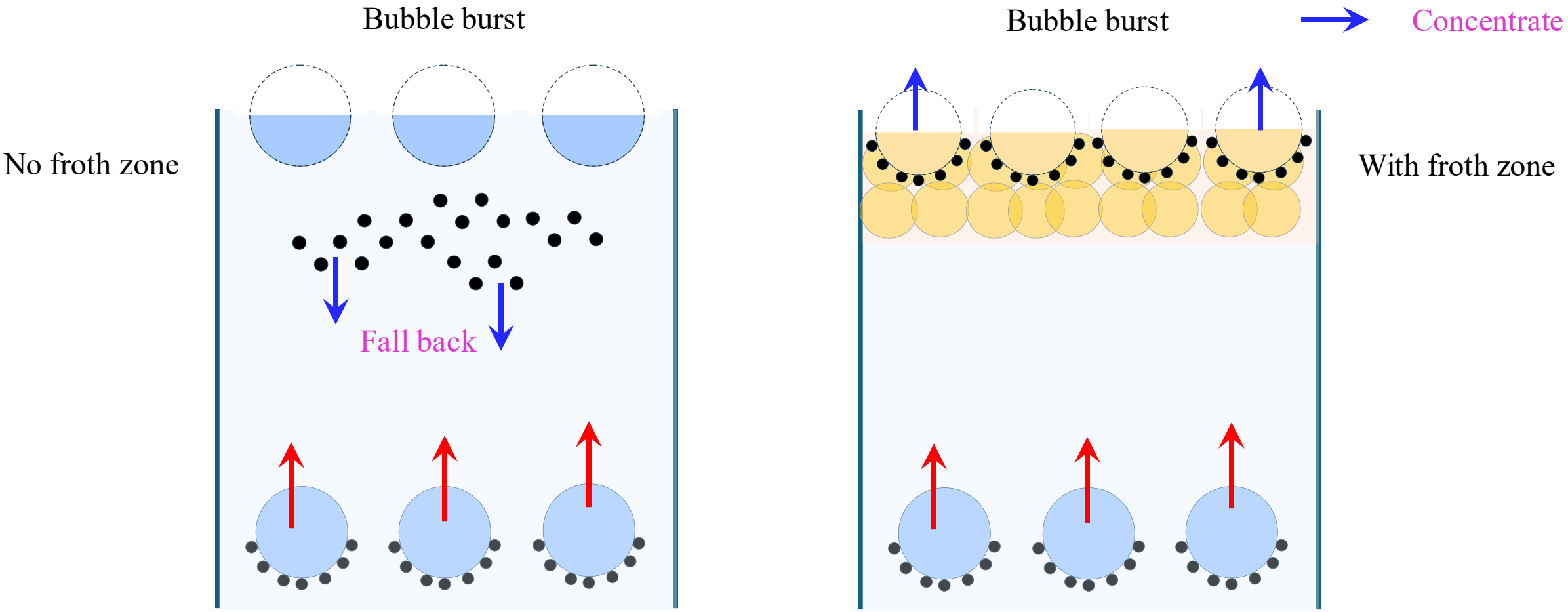
Frother helps to have spherical bubbles for more efficient collection of particles



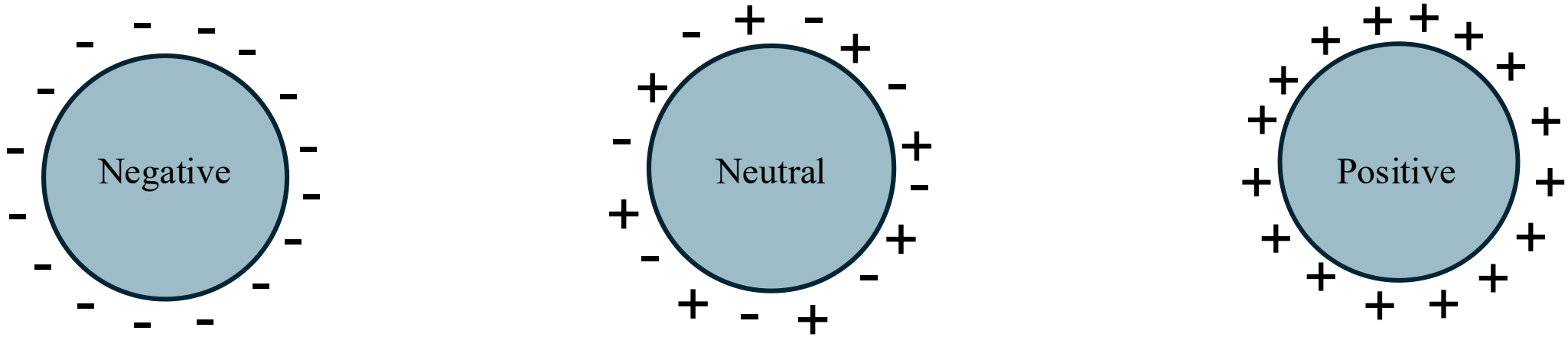
Mass transfer in mineral flotation



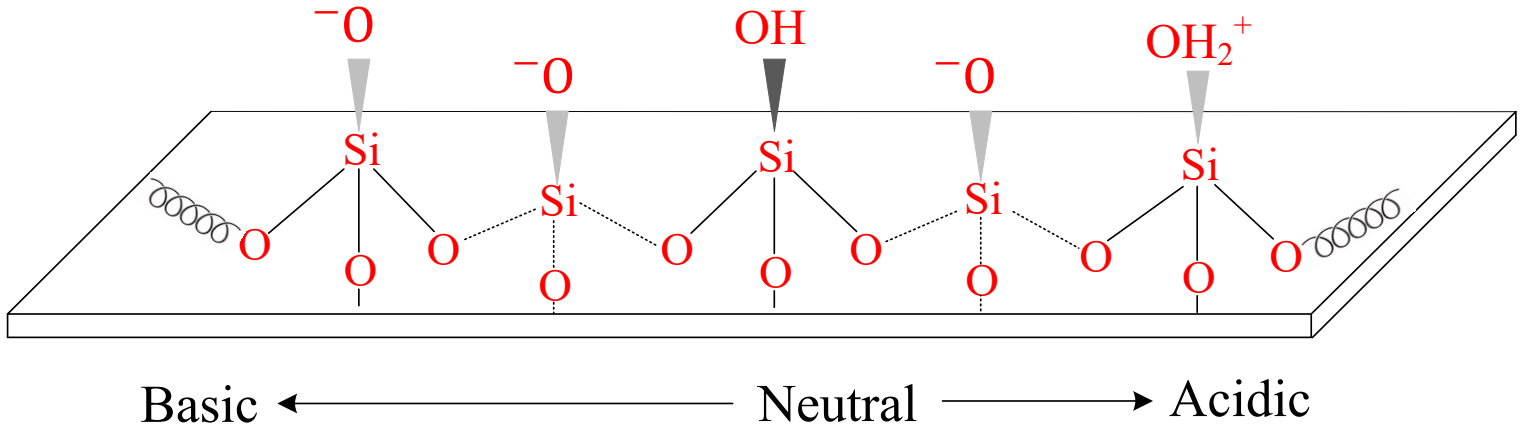
We need froth for successful mass transfer



Mineral surfaces carry electrical charges

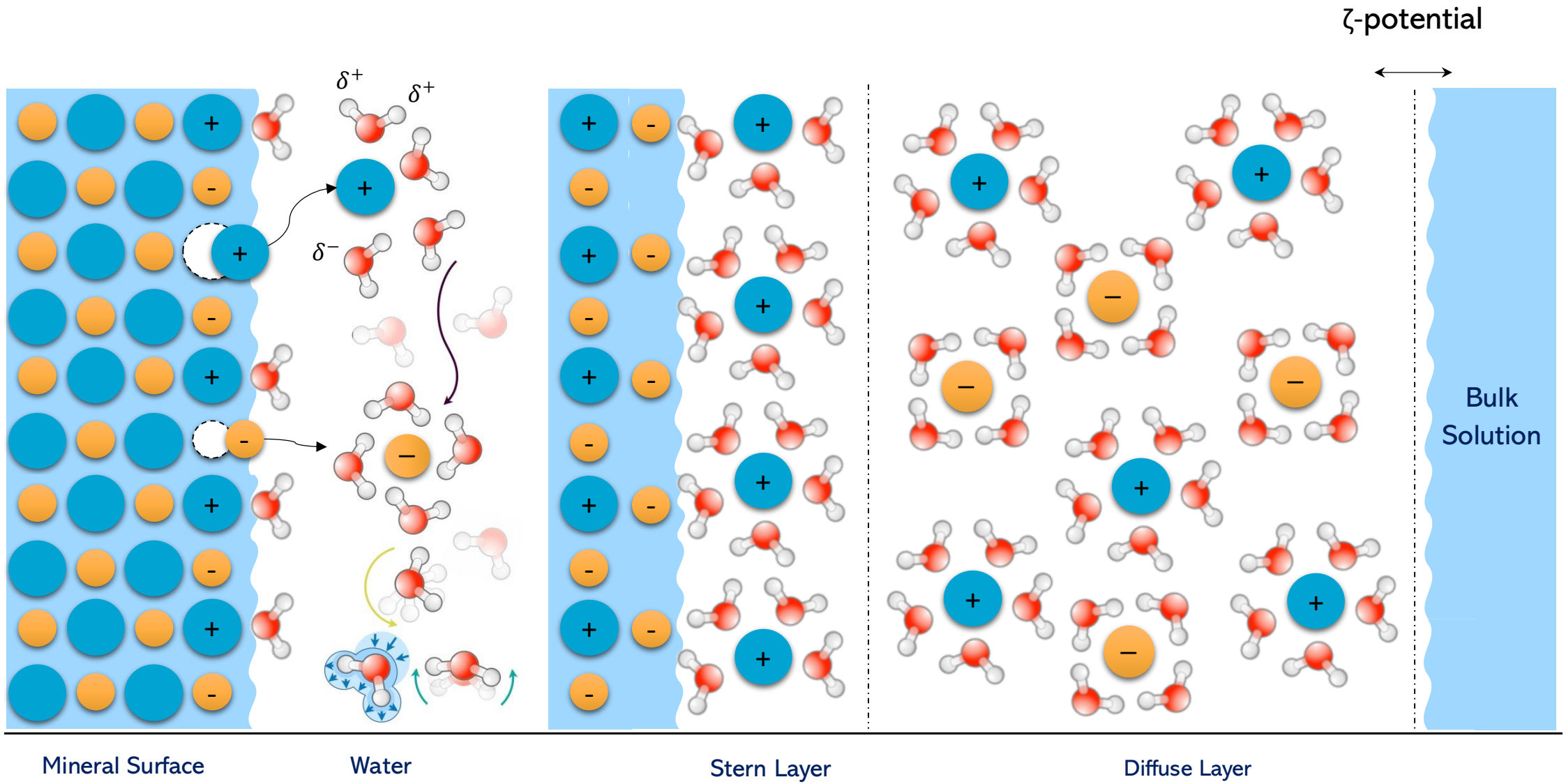


$pH = -\log[H^+]$



Quartz surface protonation as a function of solution pH.

Mineral–Water Interface



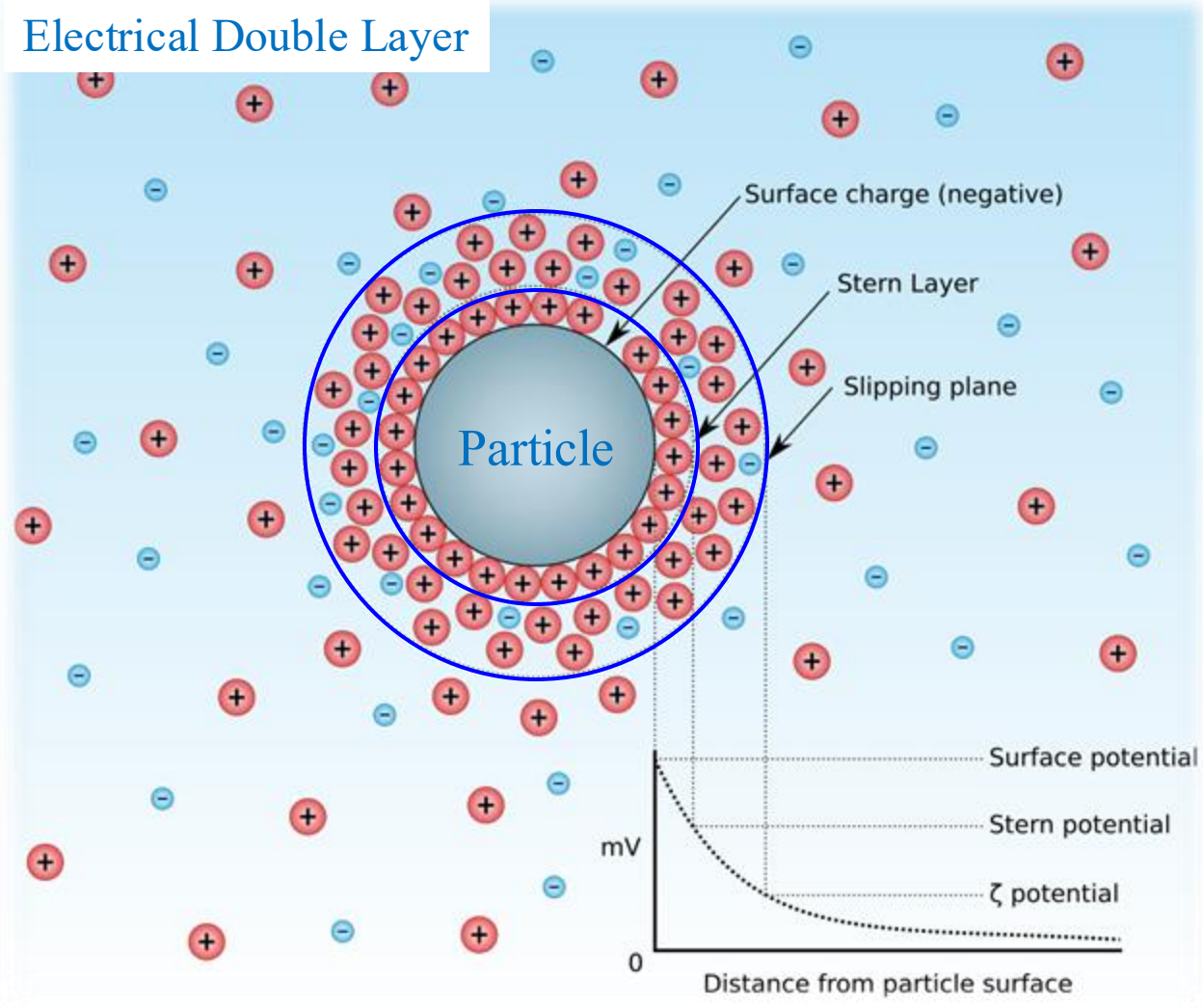
Effect of solution acidity (pH)

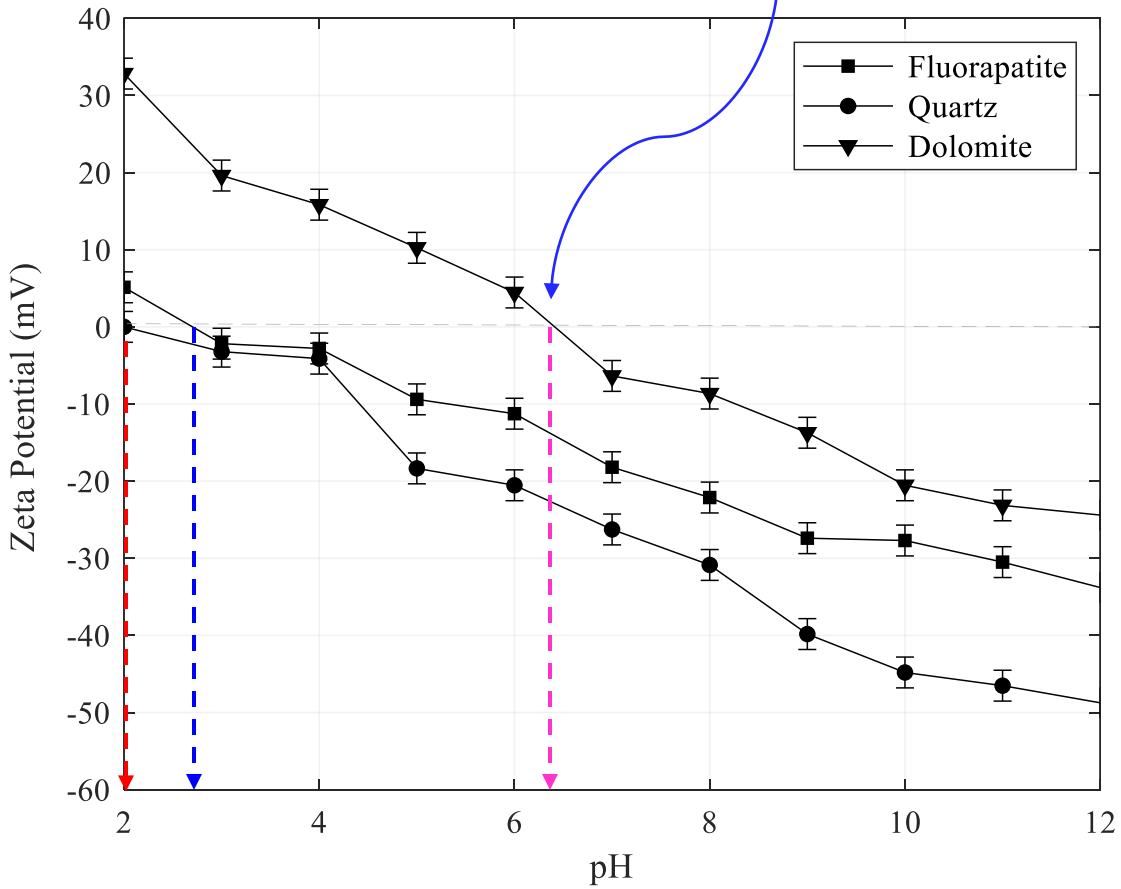
pH = -log[H+]

A pH in which mineral surface has equal number of positive and negative charges (cations and anions), which neutralize each other.

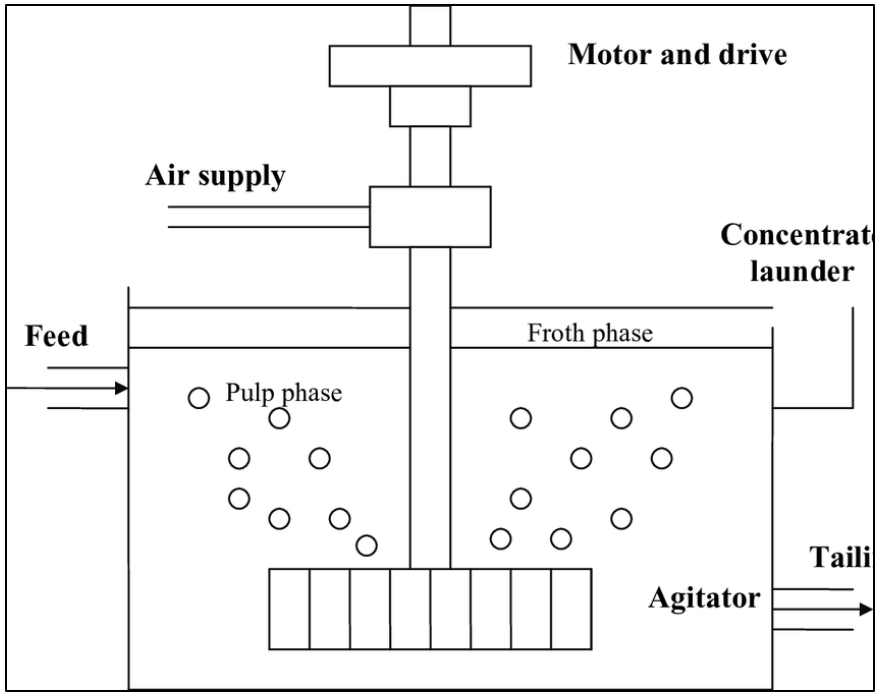
IEP = Isoelectric Point

Electrical Double Layer

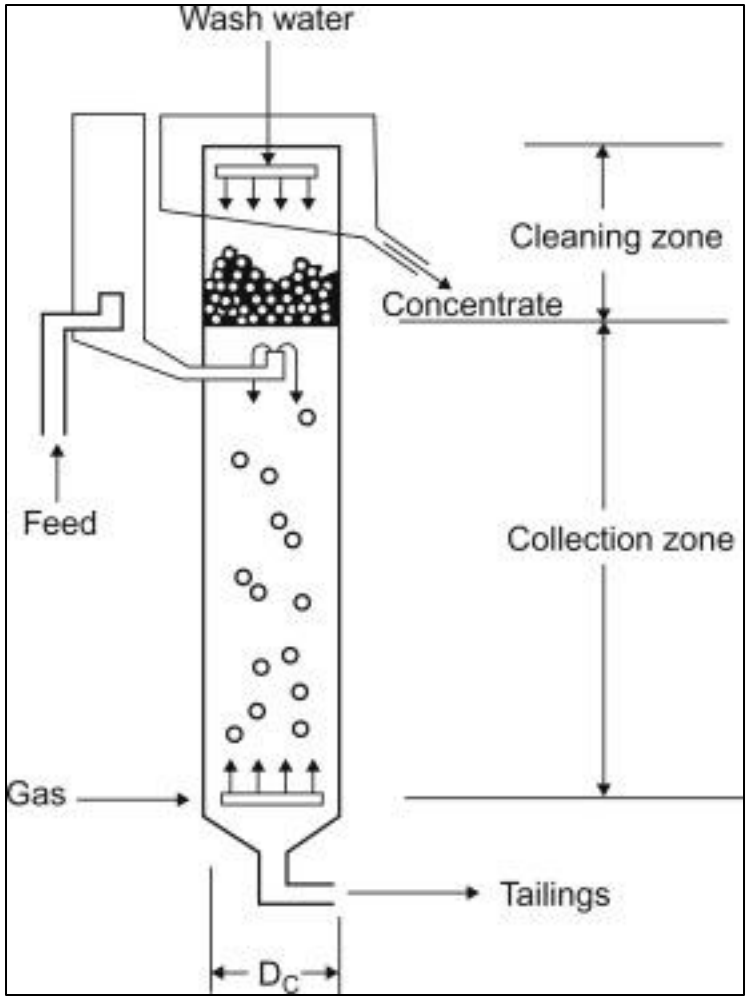




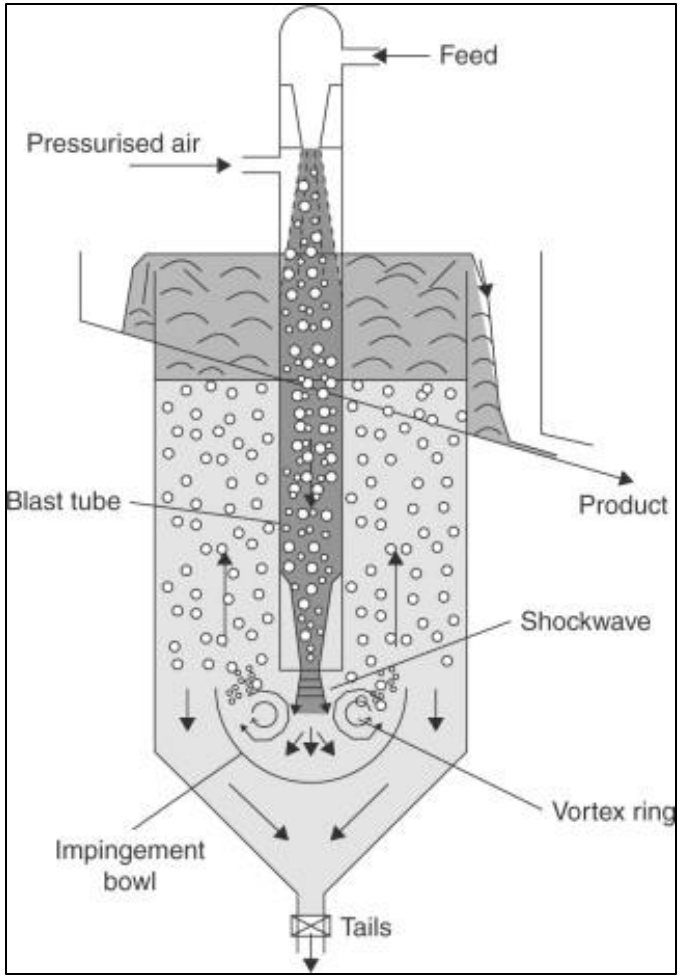
Flotation Machines



Mechanical Cell



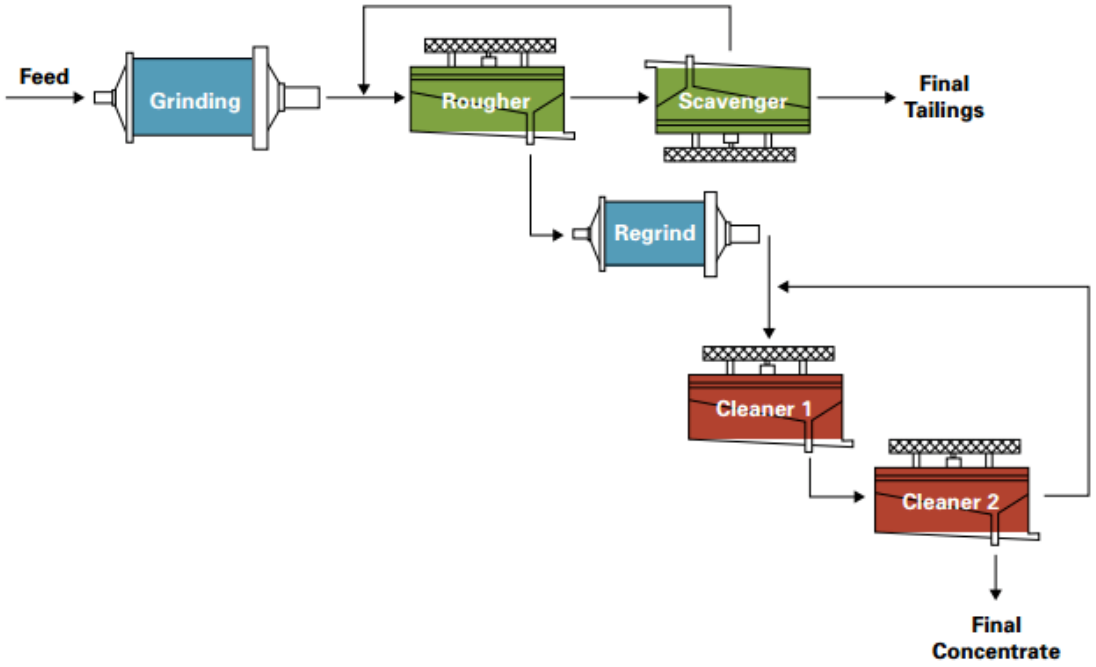
Column Cell



Jameson Cell

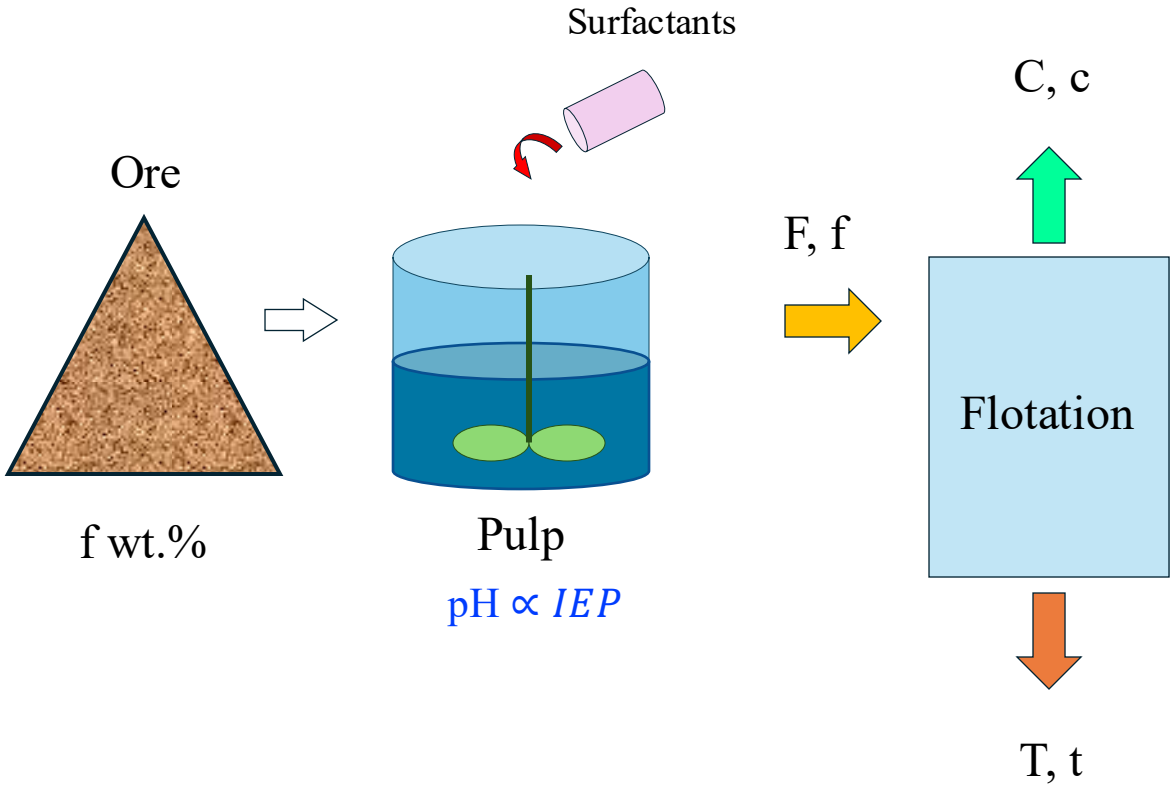
In industrial setting





https://www.911metallurgist.com/

Flotation Metallurgical Performance

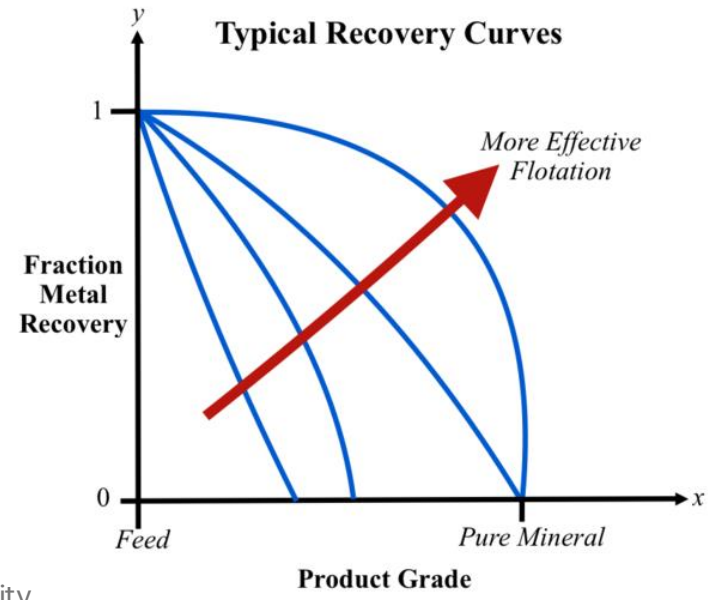


$$F = C + T$$

$$F.f = C.c + T.t \rightarrow \frac{C}{F} = \frac{f-t}{c-t}$$

$$Metal\ Recovery = \frac{C.c}{F.f} = \frac{c(f-t)}{f(c-t)}$$

f = metal grade in ore
c = metal grade in flotation product
t = metal grade in flotation tailing



$$F = C + T \quad \rightarrow F - C$$

$$F \cdot f = C \cdot c + T \cdot t \quad \rightarrow 1 - n$$

$$\rightarrow n$$

$$\times \frac{1}{F} \rightarrow f = \frac{C}{F} \cdot c + \left(1 - \frac{C}{F}\right) \cdot t$$

$$\Rightarrow \frac{C}{F} = \frac{f - t}{c - t} \qquad \Rightarrow R(\%) = \frac{C \cdot c}{F \cdot f} = \frac{c(f-t)}{f(c-t)}$$



Example Problem:

A copper ore contains 0.6% Cu (f).
After flotation, the concentrate grade is 25% Cu (c), and the tailing grade is 0.1% Cu (t).
If 1000 tons of ore (F) are processed, calculate:

1. The mass of concentrate (C) and tailings (T).
2. The copper recovery (%) to the flotation concentrate.

Step 1. Mass balance

$$F = C + T$$

$$1000 = C + T$$

$$F \cdot f = C \cdot c + T \cdot t$$

$$1000 \times 0.006 = C \times 0.25 + T \times 0.001$$

$$6 = 0.25C + 0.001T$$

Step 2. Substitute T = 1000−C

$$6 = 0.25C + 0.001(1000 - C)$$

$$6 = 0.25C + 1 - 0.001C$$

$$5 = 0.249C$$

$$C \approx 20.1 \,\text{tons}$$

$$T = 1000 - 20.1 \approx 979.9 \,\text{tons}$$

Step 3. Copper recovery

$$\text{Recovery} = \frac{C \cdot c}{F \cdot f} \times 100$$

$$= \frac{20.1 \times 0.25}{1000 \times 0.006} \times 100$$

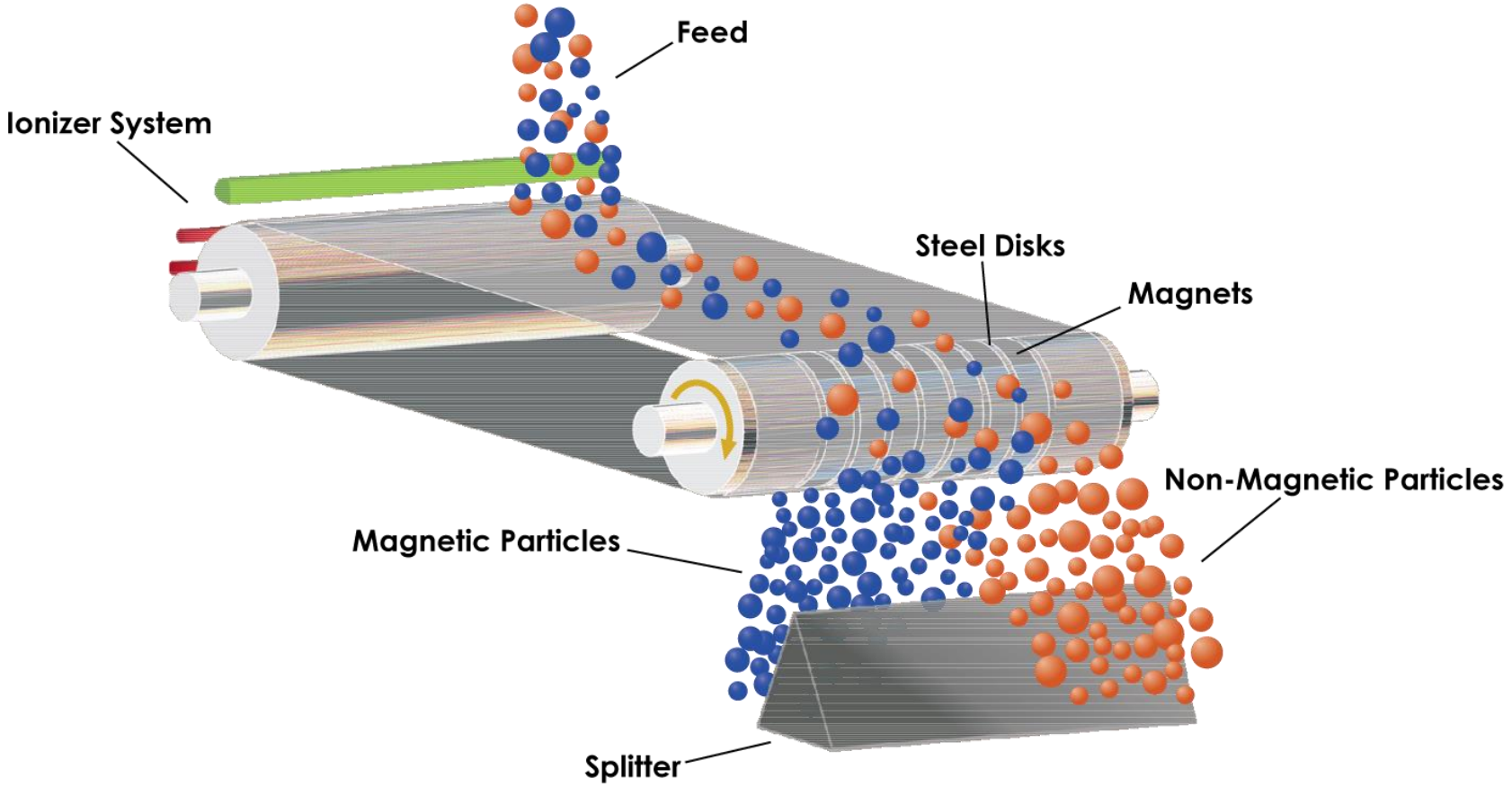
$$= \frac{5.03}{6} \times 100 \approx 83.9\%$$

Magnetic Concentration

... separating minerals using the difference in their magnetic susceptibility.

Magnetic Concentration

… is a process that separates minerals based on their different magnetic properties, such as ferromagnetic, paramagnetic, and diamagnetic.

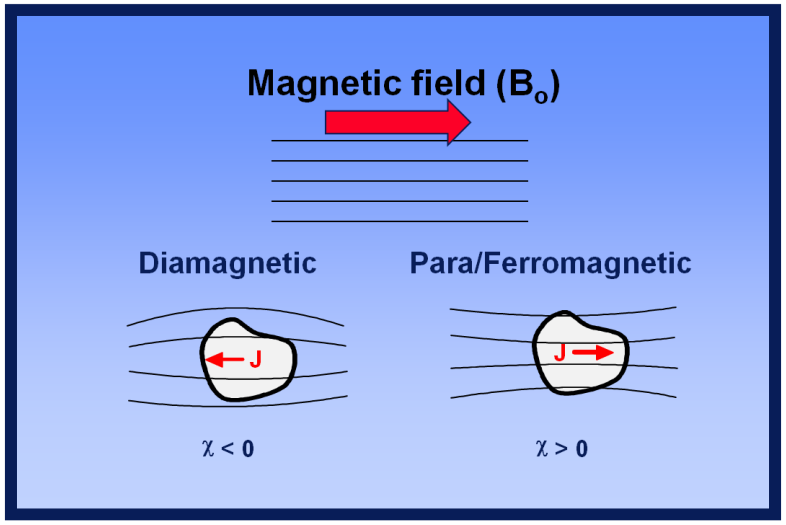


https://www.imsc-group.com/

Magnetic Susceptibility

A measure of how much a material will become magnetized in an applied magnetic field.

In response to an applied magnetic field: an alignment with the magnetic field, $\chi > 0$, called paramagnetism, or an alignment against the field, $\chi < 0$, called diamagnetism.



polarization (J)

Mineral		Density[1]	Susceptibility[2]
Barite	$BaSO_4$	4.5	-
Chalcopyrite	$CuFeS_2$	4.2	0.4
Pyrite	FeS_2	5.02	5
Pyrrhotite	Fe(1-x)S (x=0-0.17)	4.62	3,200
Sphalerite	(Zn,Fe)S	4	0.8
Galena	PbS	7.5	-0.03
Magnetite	Fe_3O_4	5.18	5,700
Hematite	Fe_2O_3	5.26	40

[1]Densities from Klein and Hurlbut (1985).

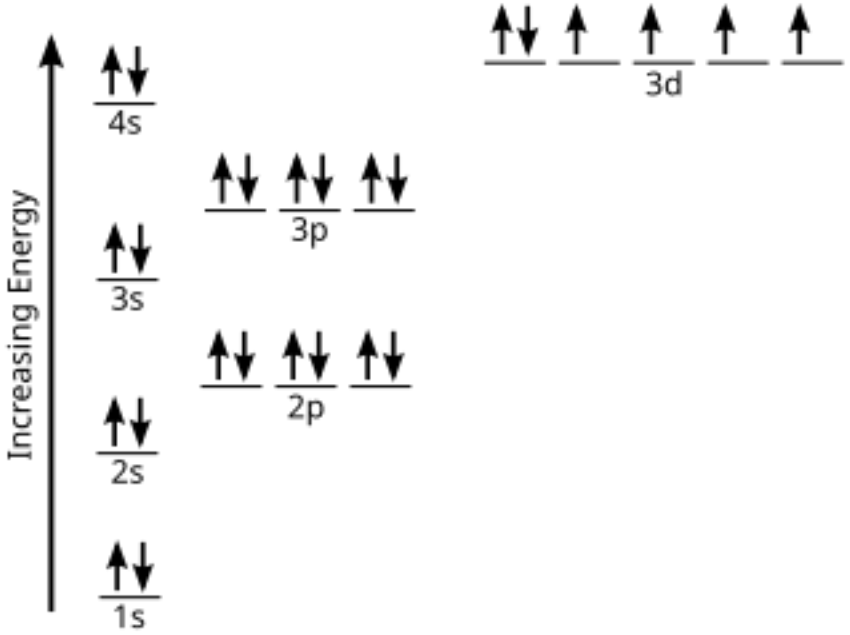
[2]Susceptibilities from Hunt and others (1995).

Geophysical characteristics of volcanogenic massive sulfide deposits, LA Morgan, USGS, 2012

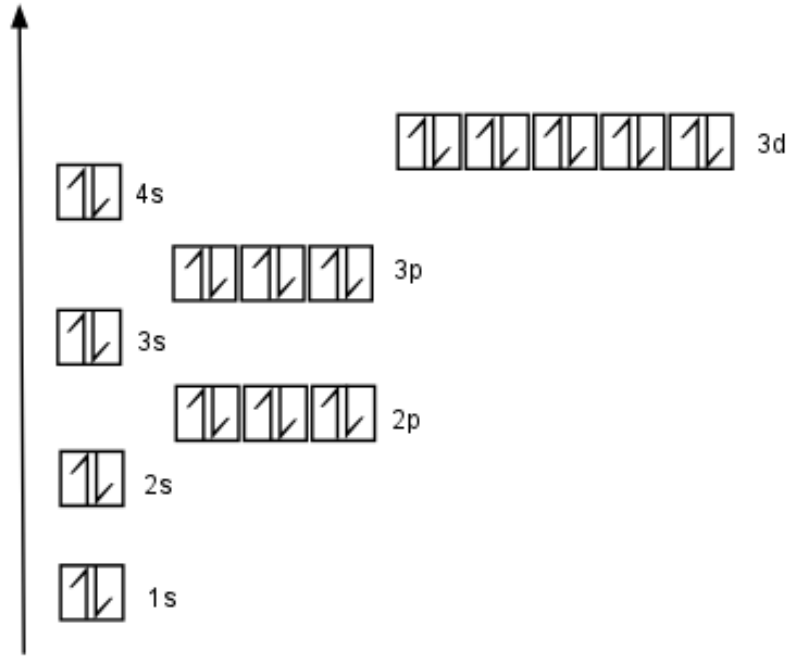
https://mriquestions.com/what-is-susceptibility-chi.html

Magnetism and Electron Configuration

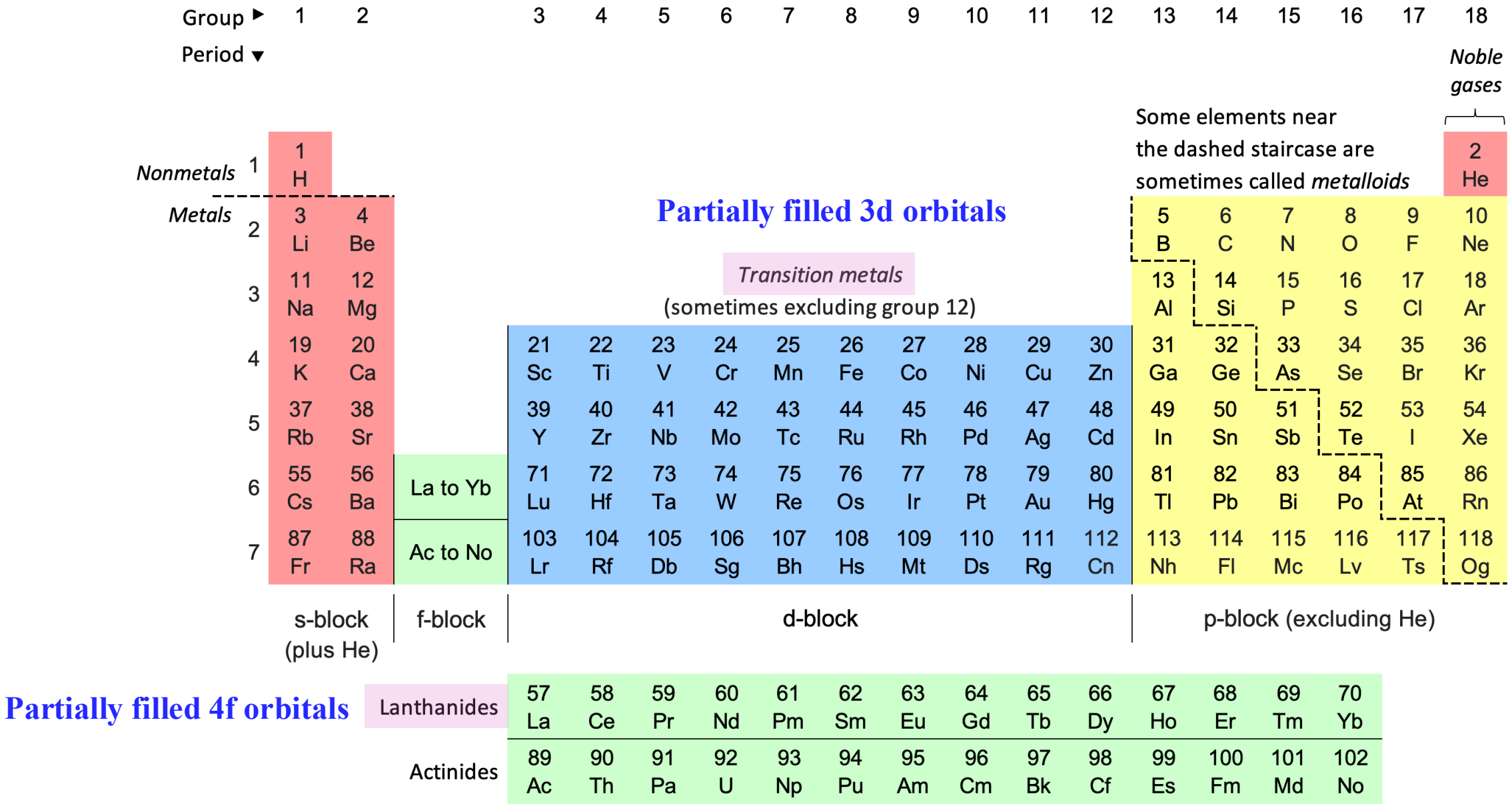
Iron



Zinc



1. Find the electron configuration
2. Draw the valence orbitals
3. Look for unpaired electrons
4. Paramagnetic (one or more electrons unpaired) or diamagnetic (all electrons paired)


Group ▶ 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Period ▼
Noble gases
Some elements near the dashed staircase are sometimes called metalloids
Nonmetals
Metals
Partially filled 3d orbitals
Transition metals
(sometimes excluding group 12)
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
La to Yb
71 Lu
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
Ac to No
103 Lr
104 Rf
105 Db
106 Sg
107 Bh
108 Hs
109 Mt
110 Ds
111 Rg
112 Cn
113 Nh
114 Fl
115 Mc
116 Lv
117 Ts
118 Og
s-block (plus He)
f-block
d-block
p-block (excluding He)
Partially filled 4f orbitals
Lanthanides
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
Actinides
89 Ac
90 Th
91 Pa
92 U
93 Np
94 Pu
95 Am
96 Cm
97 Bk
98 Cf
99 Es
100 Fm
101 Md
102 No

Pyrite *vs.* Pyrrhotite, why?

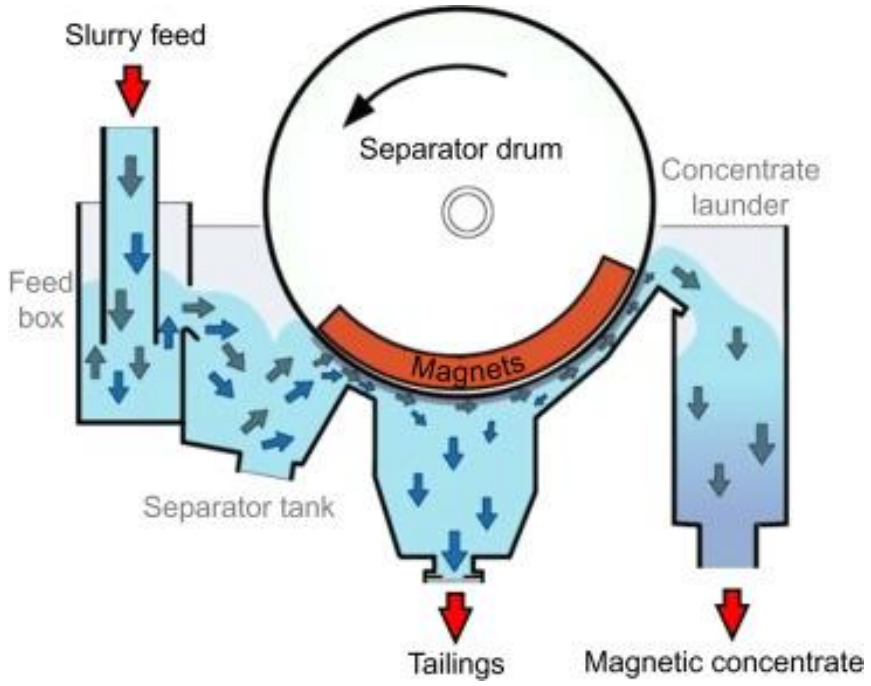


FeS_2

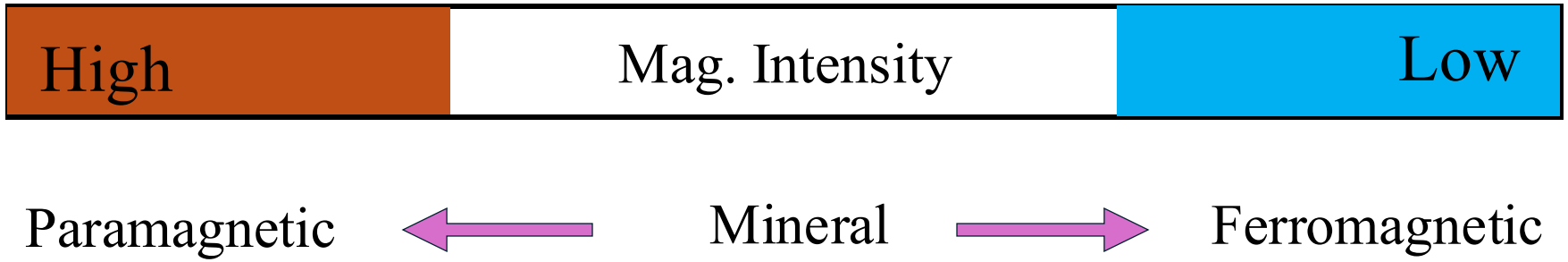


$Fe_{(1-x)}S$

Magnetic Separators



- Low-intensity separators (LIMS)
- High-intensity separators (HIMS)
- Each can be designed for either wet or dry operation.
- Each can be drum, belt, or disk.
- In LIMS, the applied magnetic field strength is less than 0.2 T, while in HIMS the field strength exceeds 2 T.
- LIMS are typically employed to concentrate strongly magnetic minerals, such as magnetite and pyrrhotite.

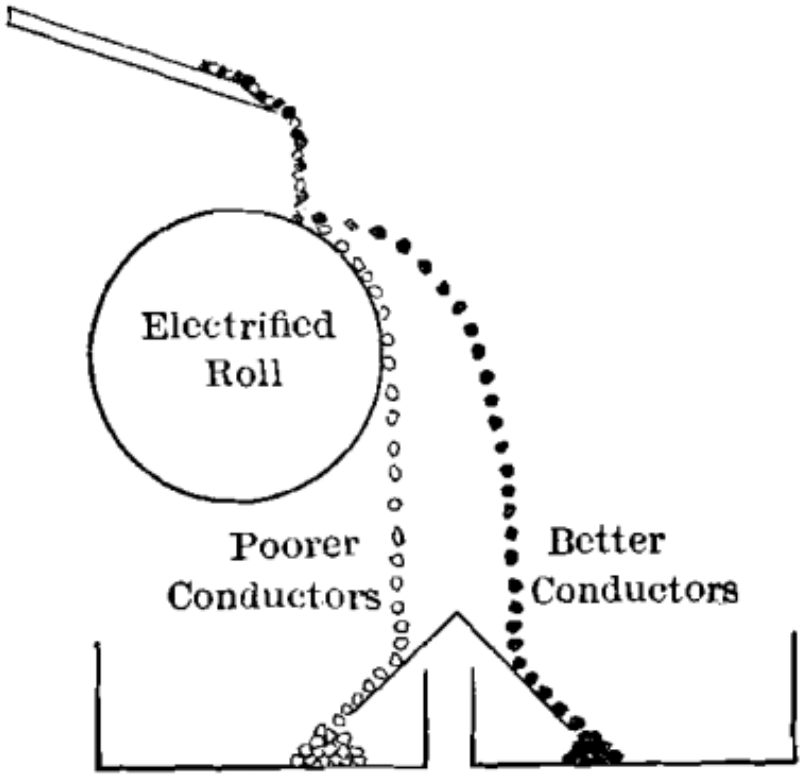


Electrostatic Concentration

... separating minerals using the difference in their electrical conductivity.

How it works?

Electrostatic separation can be used to separate conducting minerals from nonconducting minerals.

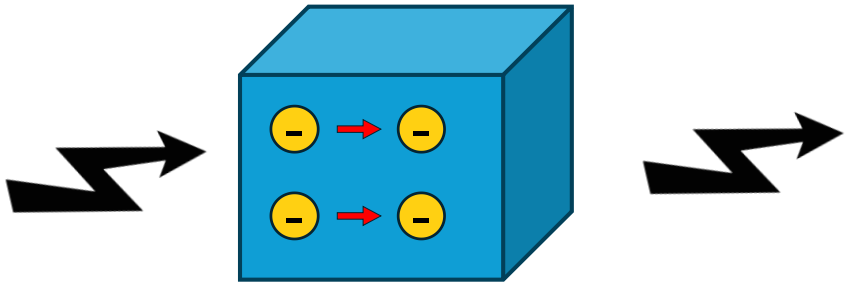


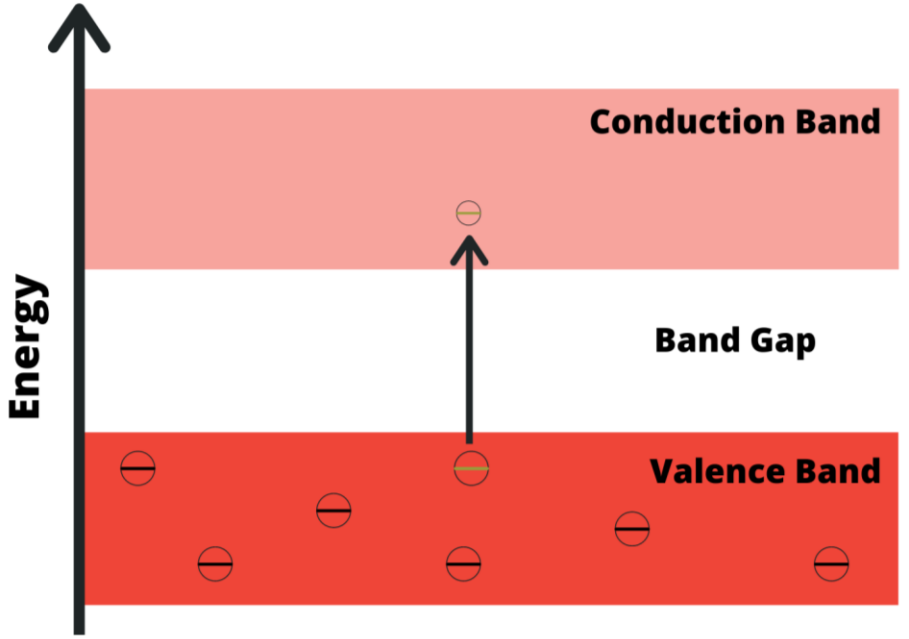
https://www.911metallurgist.com/

- Electrical separation relies on differences in electrical conductivity between minerals.
- Although most minerals differ in conductivity, practical use is limited.
- Requires perfectly dry feed, which restricts application.
- Mainly used to separate heavy minerals from beach or placer deposits.
- Works for particles of 60–500 μm.

Electrical Conductivity

Electrical conductivity is a material's ability to conduct an electric current, which is essentially the flow of electrons through the material.

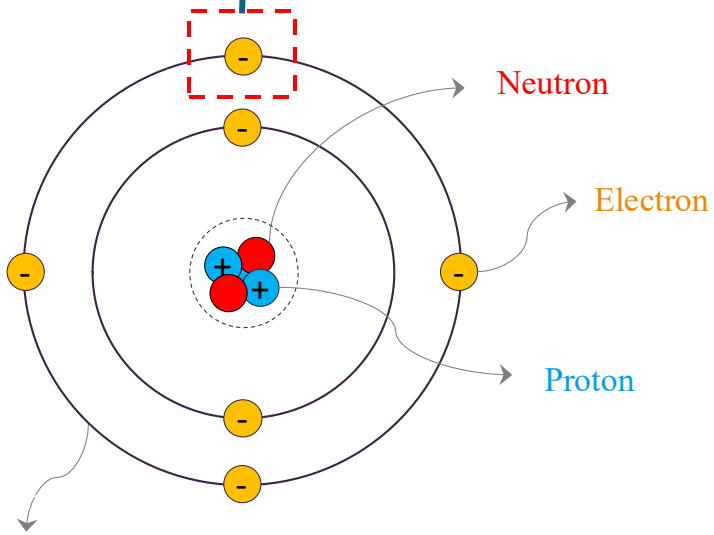




Material = Atoms + Atoms

Atom = Nuclei + Electrons

\+ −



Some Minerals in Electrostatic Separation

Minerals that stick to the electrode	Minerals that are repelled from the electrode
Apatite	Cassiterite
Barite	Chromite
Quartz	Galena
Zircon	Rutile
Monazite	Ilmenite

This method is commonly used to separate **rutile and ilmenite** from **monazite and zircon**.

Gravity Concentration

... separating minerals using the difference in their densities.

How it works?

Gravity concentration is the separation of minerals based upon the difference in density (their relative movement in response to gravity and fluid resistance).

For effective separation, a marked density difference should exist between the mineral and the gangue.



Gold panning

Concentration criterion:

$$\Delta\rho = \frac{\rho_h - \rho_f}{\rho_l - \rho_f}$$

$$|\Delta\rho| > 2.5$$

ρ_h is the density of the heavy mineral
ρ_l is the density of the light mineral
ρ_f is the density of the fluid medium

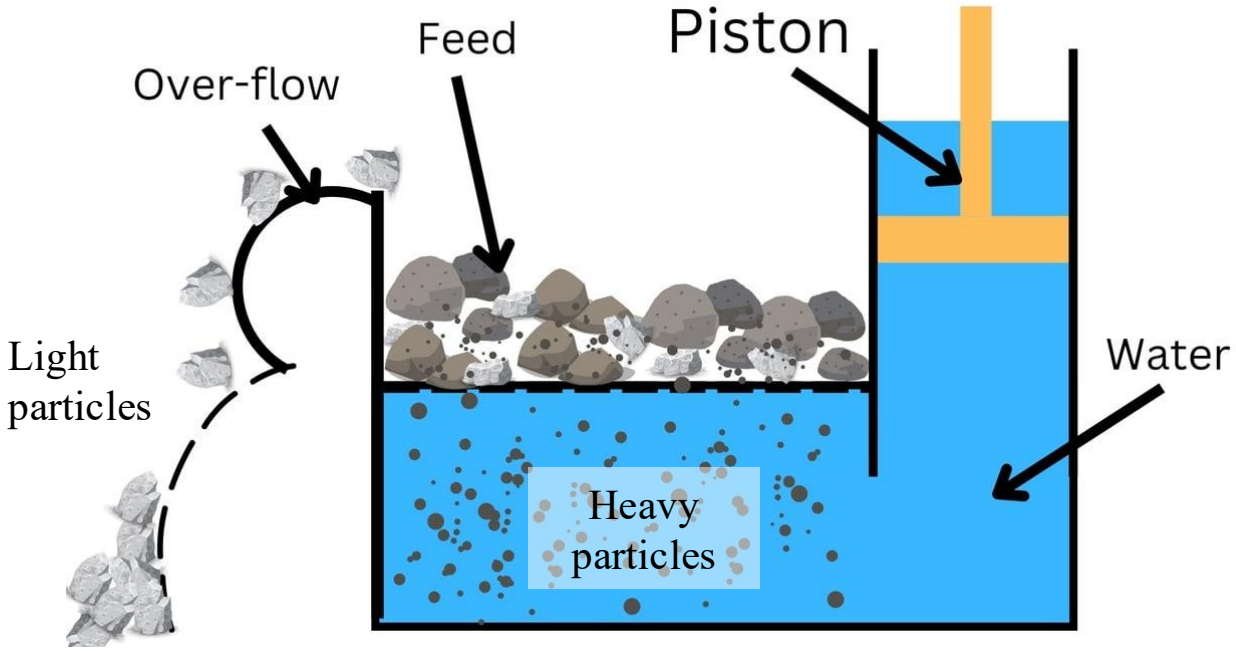
Principles of gravity separation

- Gravity separation uses differences in specific gravity (density) to separate minerals.
- Denser particles settle faster than lighter ones in a fluid medium (water).
- Centrifugal force can enhance the settling process in some methods.
- Effective for coarse particles and large density differences.
- Efficiency decreases for fine particles or when minerals have similar densities.



Gravity keeps us grounded on earth, gives us our weight, holds the universe together and keeps planets in orbit …!

Jig concentrator



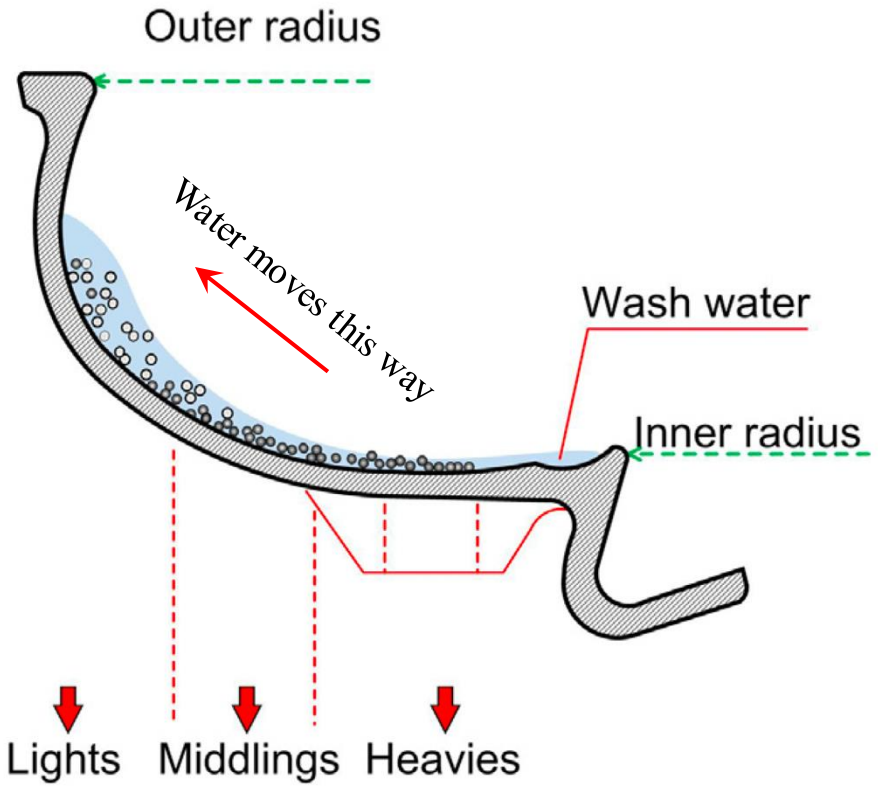


Jigging

Spiral concentrator



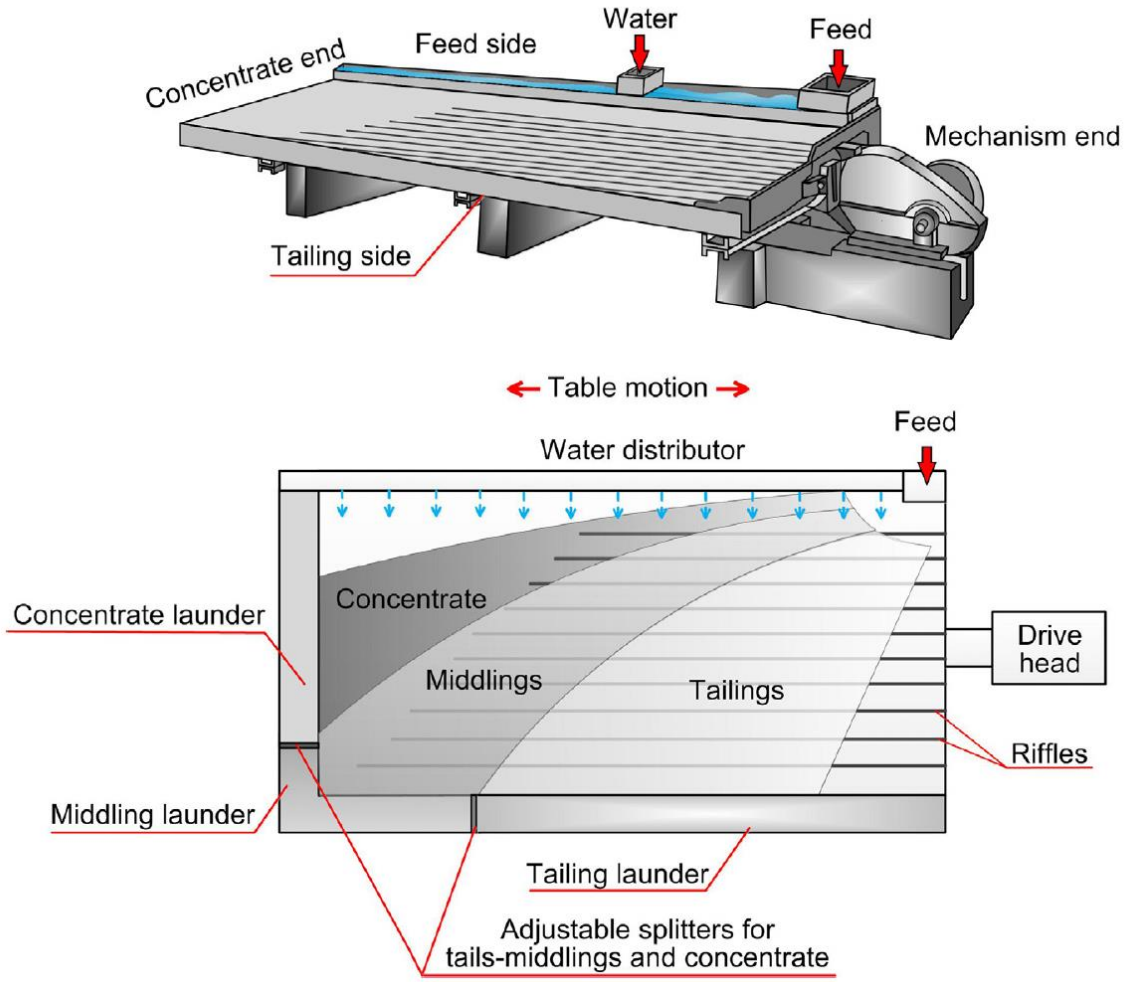
Spiral cross section

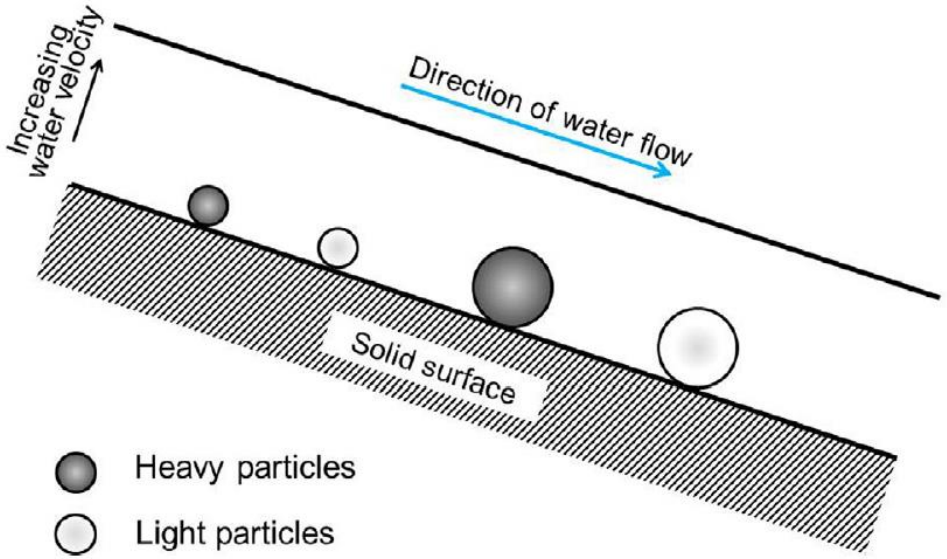




Wills' Mineral Processing Technology, B. Wills, J. Finch, 2016

Shaking table





Motion of particle on flowing film

Dewatering

... to recover and recycle water back to the processing plant.

Water in mineral processing



Copper ore processing plant - source: www.at-minerals.com

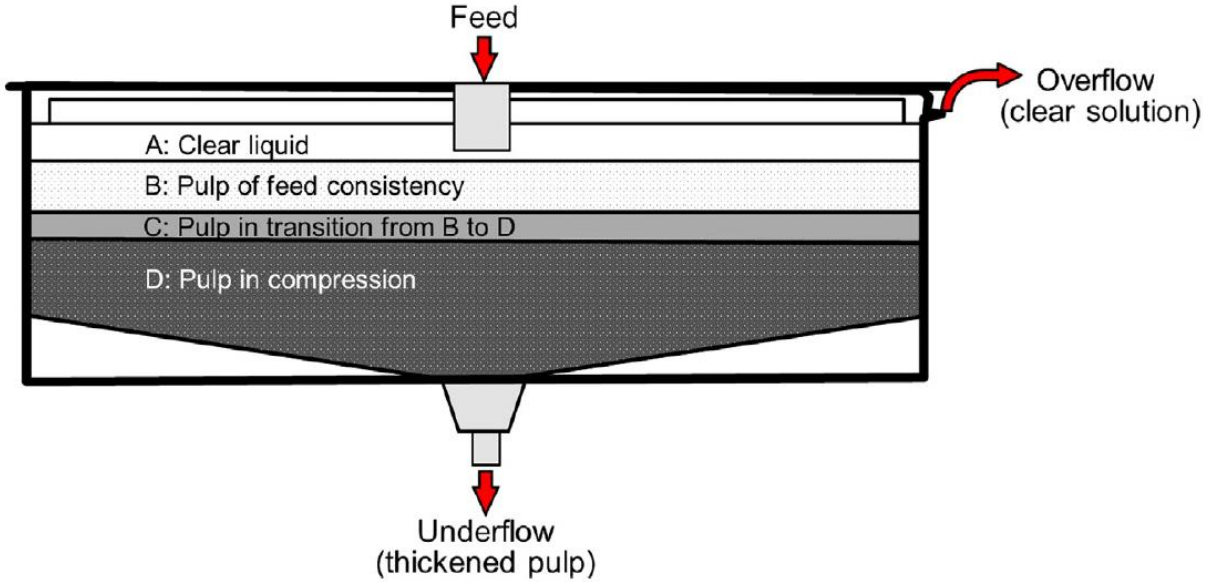
"In the southwestern United States, approximately 2.5 to 3 metric ton of water are required to process 1 ton of copper porphyry ore that contains roughly 0.5 percent copper."

USGS report by Donald I. Bleiwas - 2012

Dewatering by Thickeners



https://www.metso.com/



Principles of Thickeners

- For a large difference between the solid and liquid densities, **sedimentation** is the most effective method.
- When particles are **very fine (micron-sized)**, their **settling velocity is very low**.
- To overcome this, we use centrifugal settling or **flocculation (aggregation of fine particles)**.
- For a given feed rate, the separation capacity is determined by the **thickener diameter**.
- The surface area must be large enough so that the overflow velocity of water is always less than the settling velocity of the slowest-settling particles.

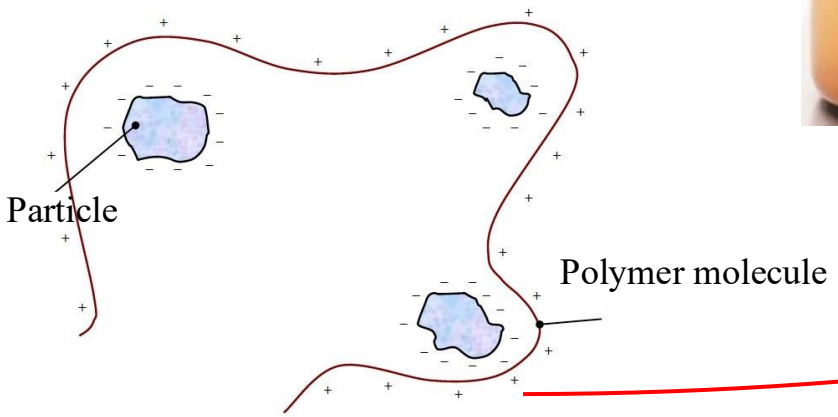
Coagulation & flocculation

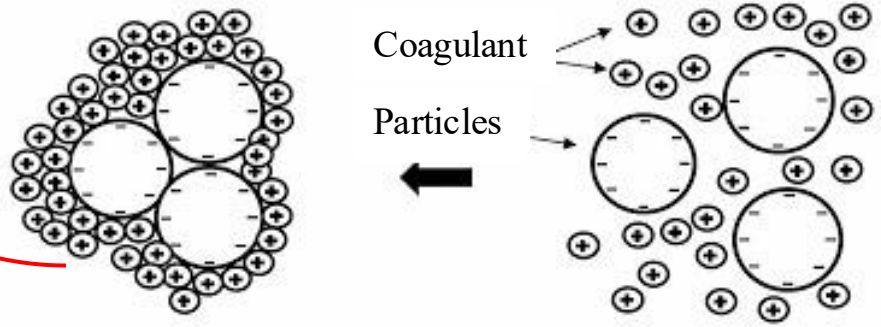
- Particles exert **attractive van der Waals forces** on each other, which act only at very short distances.
- Particles have an electrical double layer, a **repulsive force** between particles keeps them dispersed.
- These repulsive forces slow down their settling.

Flocculants bind tiny, suspended particles in water into larger, heavier clumps called "flocs," which then settle to the bottom of the container.



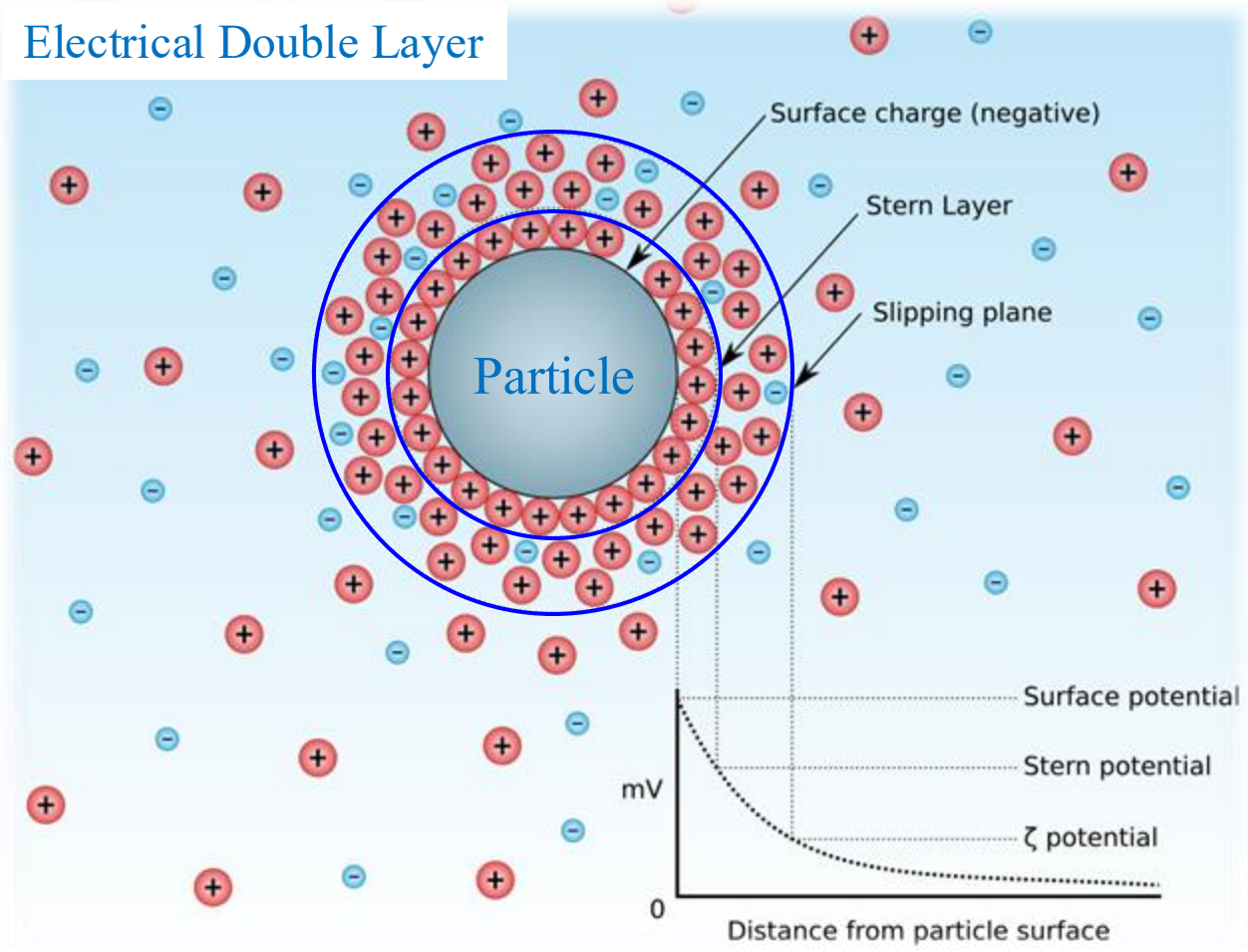
Coagulants (Al^{3+}, Fe^{3+}, Ca^{2+} salts) neutralize the particles' electrical charges, causing them to destabilize and aggregate.

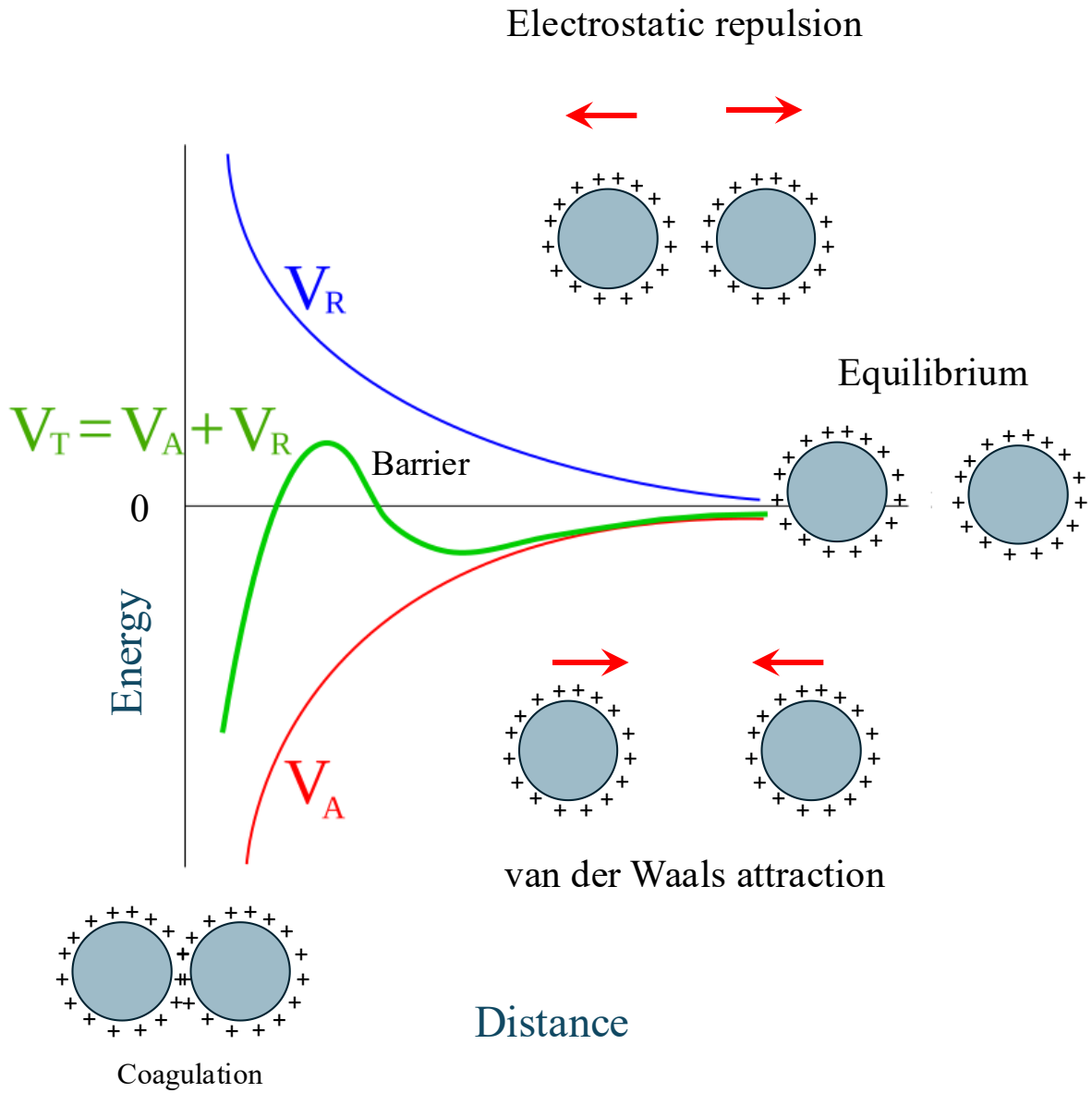




DLVO theory

… explains the stability of colloidal dispersions by describing the net interaction between two particles.





Dewatering by Filtration

When the densities of the solid and the slurry (pulp) are close, **filtration** is used.



Filter Press

https://www.cem-int.com.au/



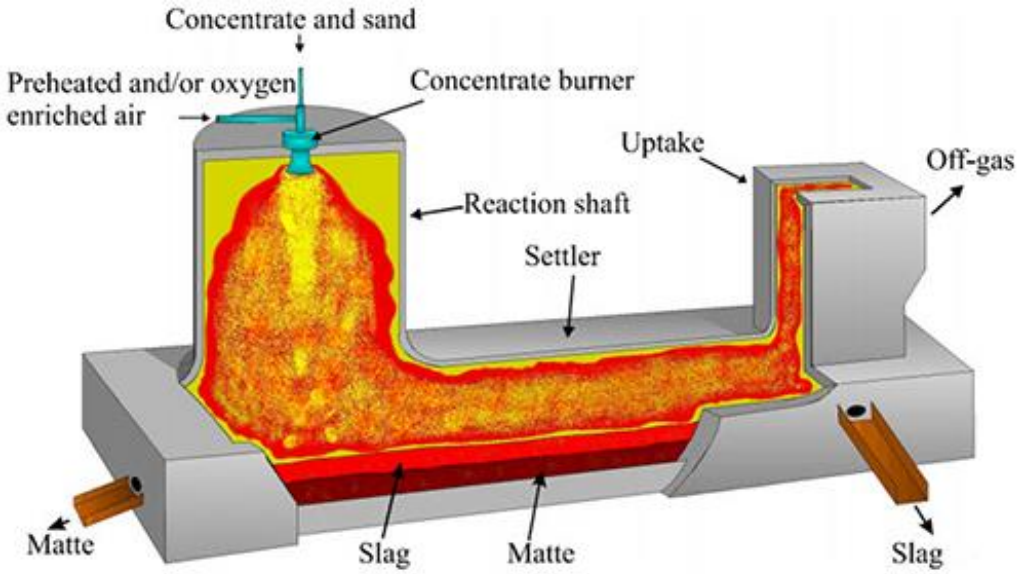
Disk Filter

Extractive Metallurgy

... extracting and refining metals from their mineral ores.

Smelting

- Processing **concentrate** (25 ~ 30% Cu) is heated in a smelting furnace (~2,300 °F) to get molten liquid.
- The molten liquid is poured into a slag-settling furnace, forming:
    - **Matte**: mixture of copper, sulfur, and iron (~58–60% Cu)
    - Slag: dense, glassy waste with silica and impurities
- Molten matte copper is sent to the converter furnace to burned off impurities to get **blister copper** (98% Cu).
- Blister copper is sent to the anode smelter, where oxygen is burned off to produce **anode copper** (99 % Cu).



Flash furnace: https://www.totalmateria.com/



Anode copper



Electrolysis … an electro-chemical reaction where a substance (its chemical bonds) is broken down by water.

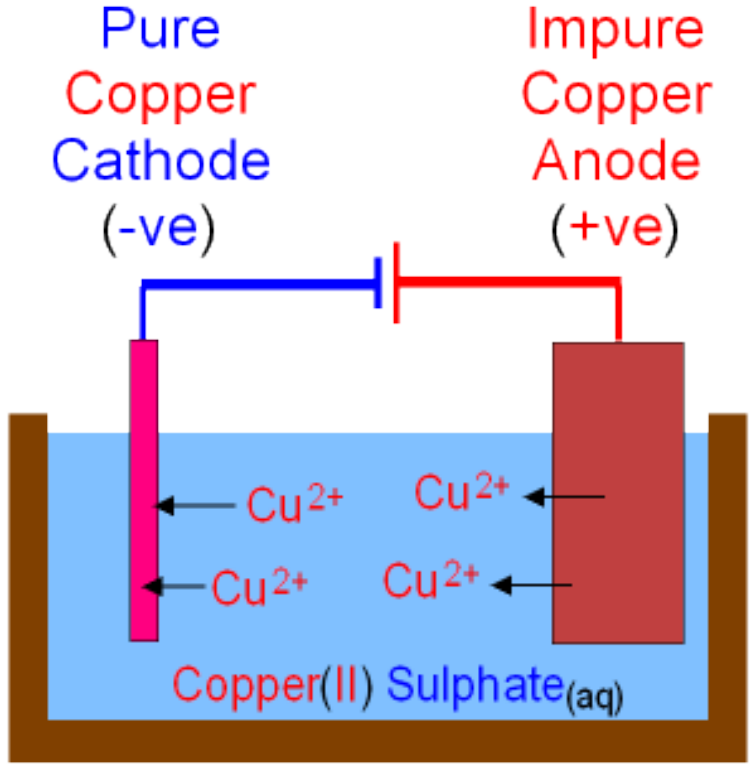
- The anode is a block of impure copper (99% Cu) obtained from smelting.
- The cathode is a thin piece of pure copper.
- The electrolyte is copper sulfate.
- When electricity is passed through the cell, copper is dissolved at the anode by oxidation and Cu^{2+} ions go into solution.

$$Cu_{(s)} - 2e^- \rightarrow Cu^{2+}_{(aq)}$$

- At the cathode, copper is deposited by reduction.

$$Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$$ **99.99% pure copper**

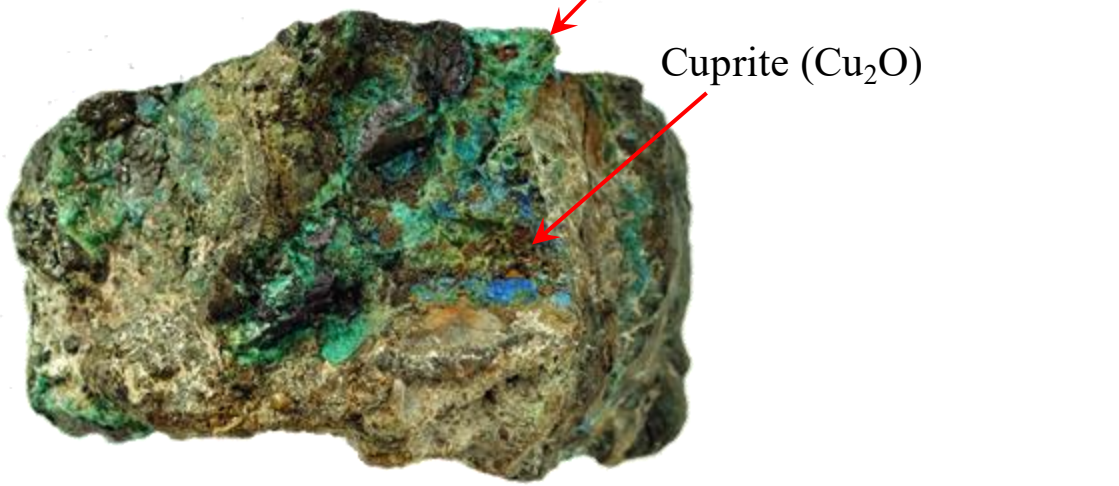
- As copper ions move from the anode to the cathode the anode gets smaller as the cathode gets bigger. This is a **redox** reaction.



14 days of electrolysis

Oxide ores

- Oxide ores are usually low-grade (less metal content)
- They are more abundant near the surface
- Difficult to separate by froth flotation or other physical concentration methods
- They are generally processed using **<u>hydrometallurgy</u>**



https://www.ftmmachinery.com/



Hydro + metallurgy

… is the process of extracting and purifying metals using aqueous (water-based) solutions from oxide ores, usually in three steps:

- Leaching
- Solvent extraction
- Electrowinning



Leaching

… is a process in which a solvent dissolves valuable metals from an ore.

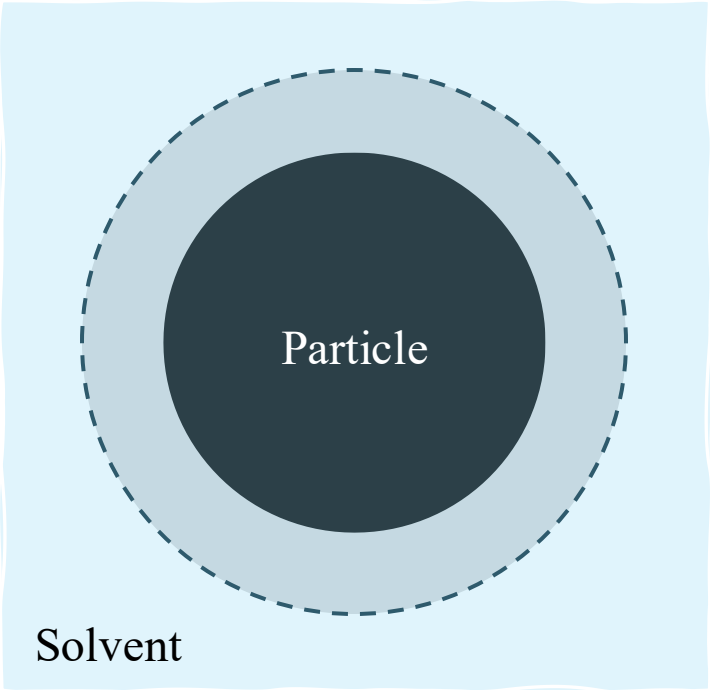
When malachite reacts with sulfuric acid, copper dissolves into solution as Cu^{2+}, forming copper sulfate, and releasing carbon dioxide and water.

$$Cu_2CO_3(OH)_2 + 2H_2SO_4 \rightarrow 2CuSO_4 + 3H_2O + CO_2 \uparrow$$

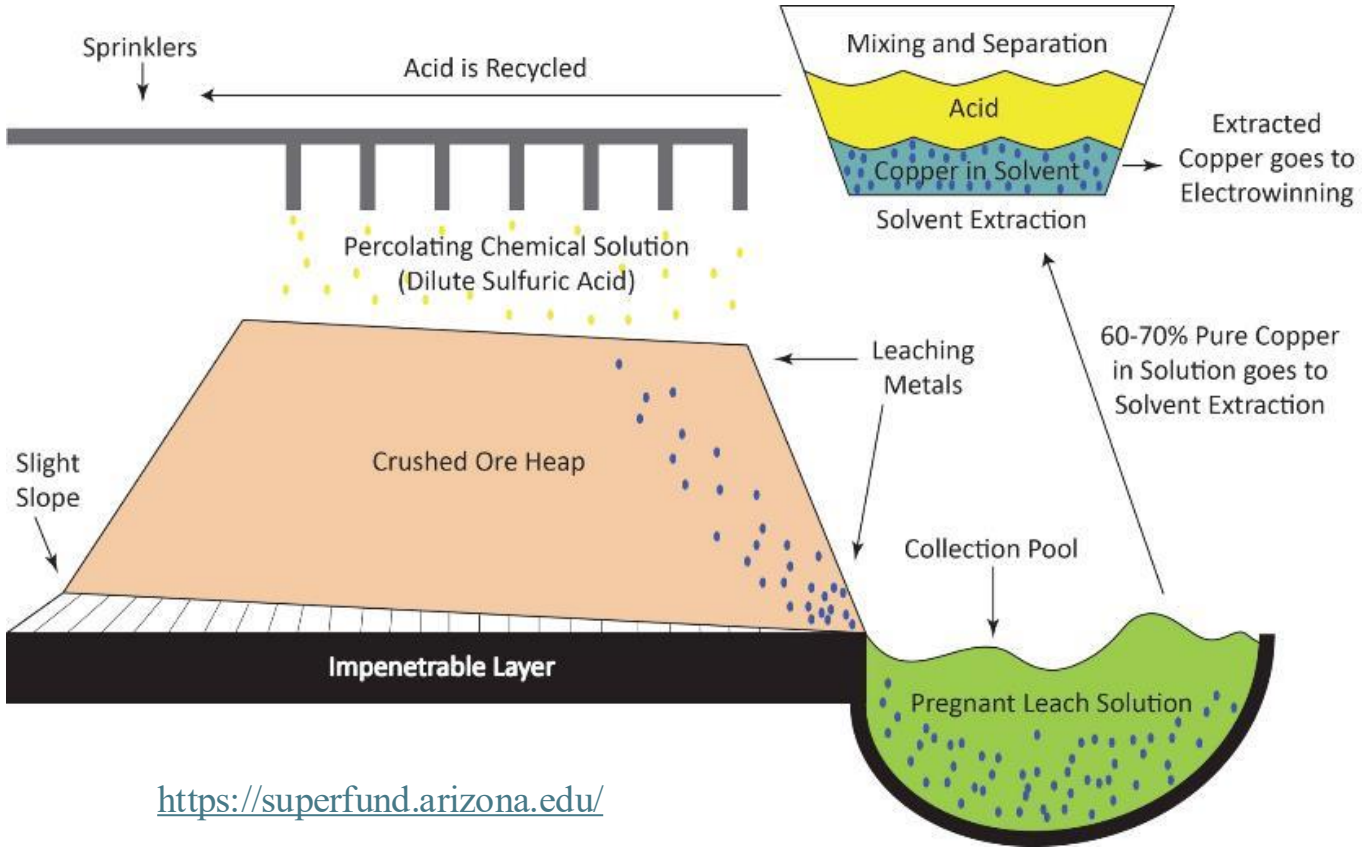
Malachite Acid

Leaching is often represented by the **shrinking core model**:

- The unreacted core of the particle shrinks over time.
- A porous product layer forms around it.
- The rate may be controlled by **diffusion** or **chemical reaction**, depending on conditions (e.g., Temp, Agitation).



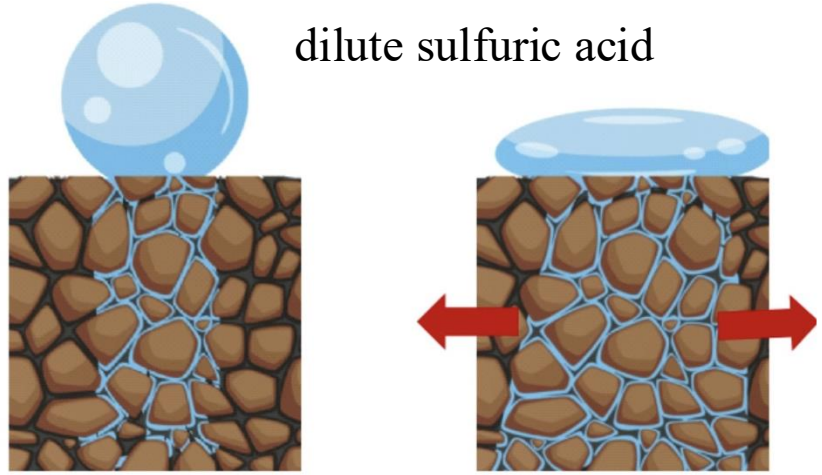
Heap leaching



https://superfund.arizona.edu/



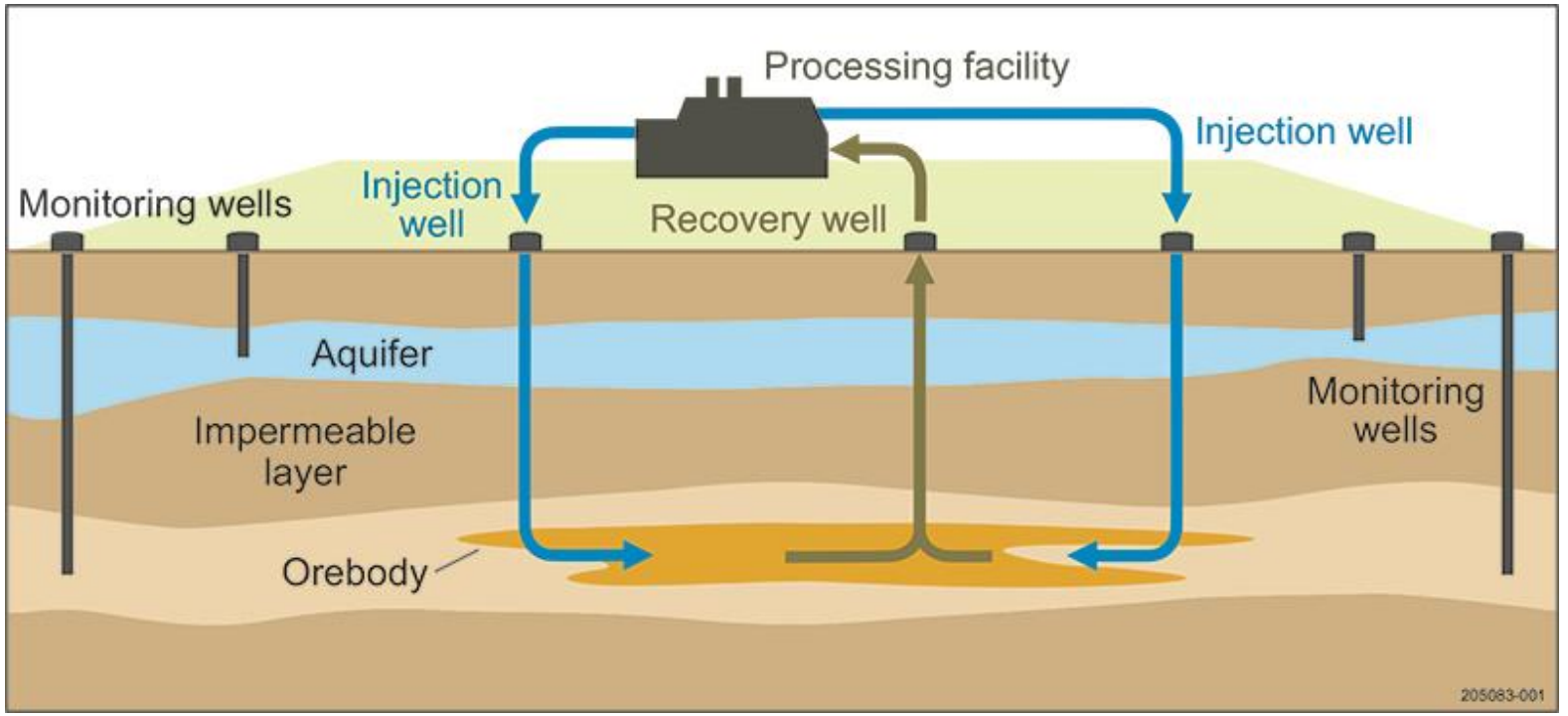
dilute sulfuric acid



https://energy-resources.basf.com/

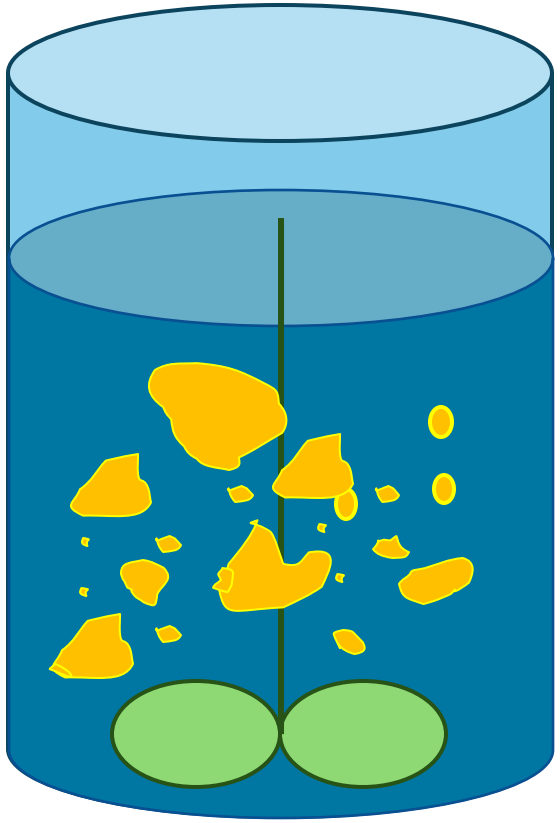
In-situ leaching

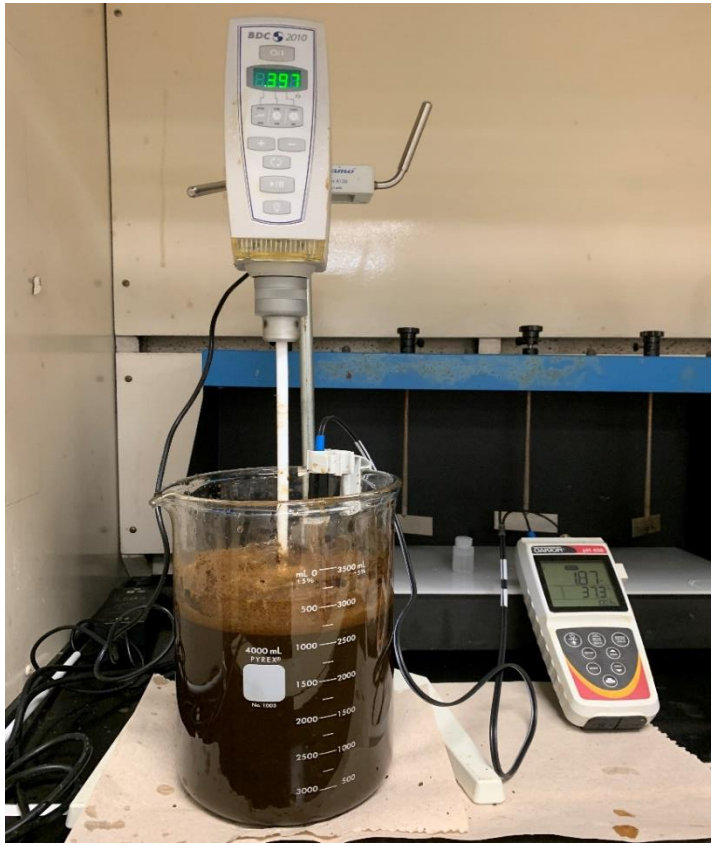
- Extracting minerals **without excavation**, using fluids injected into the ground.
- A **lixiviant** (water + chemicals) is pumped underground to dissolve minerals, then back to the surface.
- The **remaining solution is treated and recirculated** to continue extracting minerals.



https://www.energymining.sa.gov.au/

Tank leaching





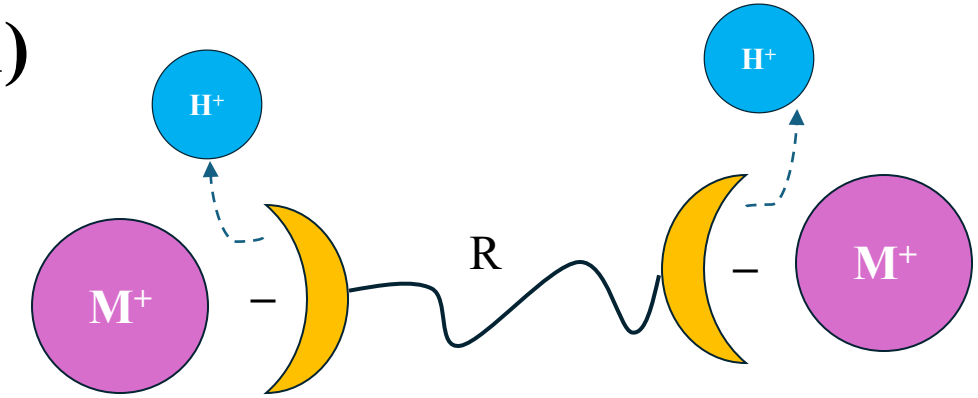


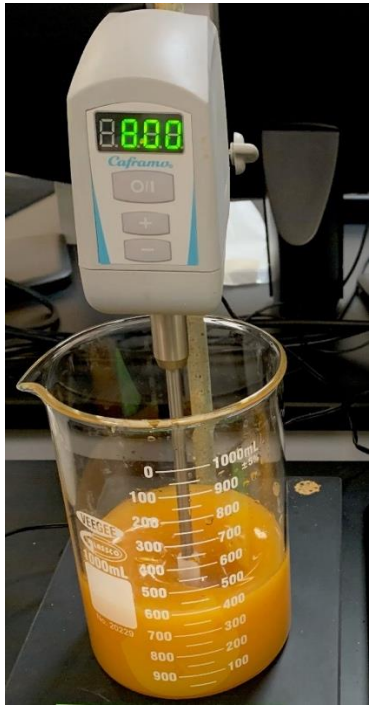
https://www.911metallurgist.com/

Solvent extraction (liquid-liquid extraction)

Aqueous phase: Pregnant Leach Solution (PLS)

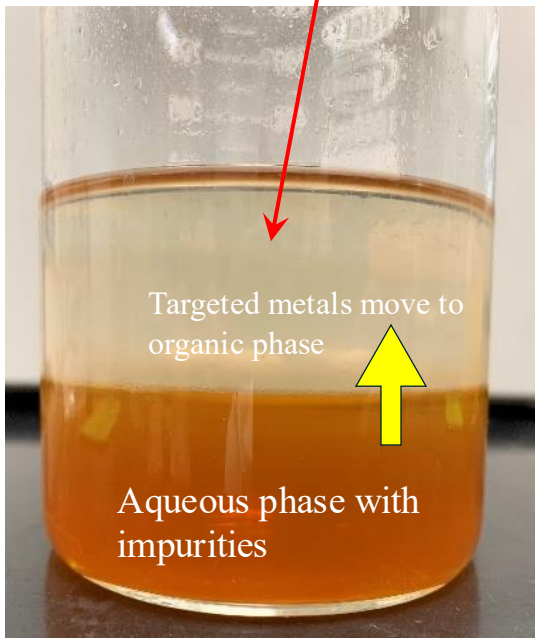
Organic phase: 0.5 M/L DEHPA + Kerosene



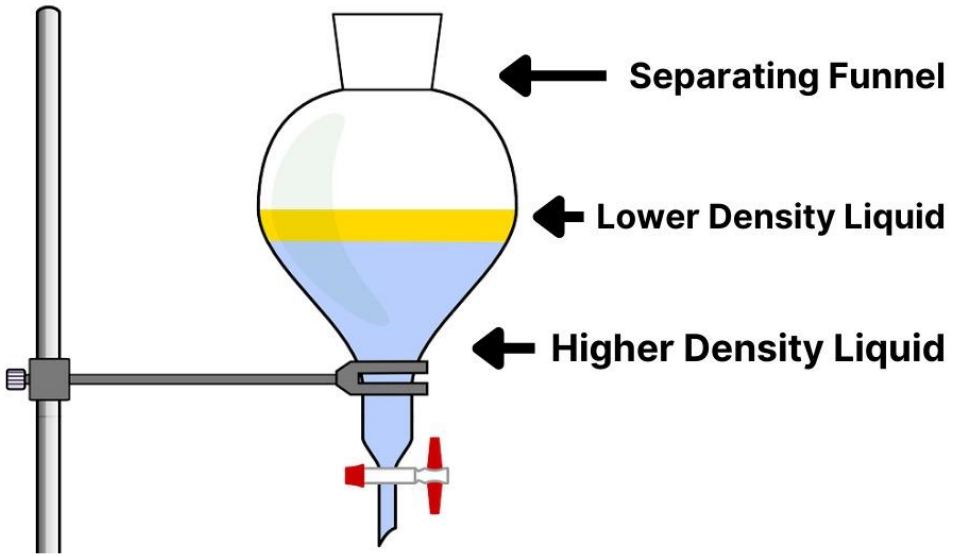


Mixing organic and aqueous phases

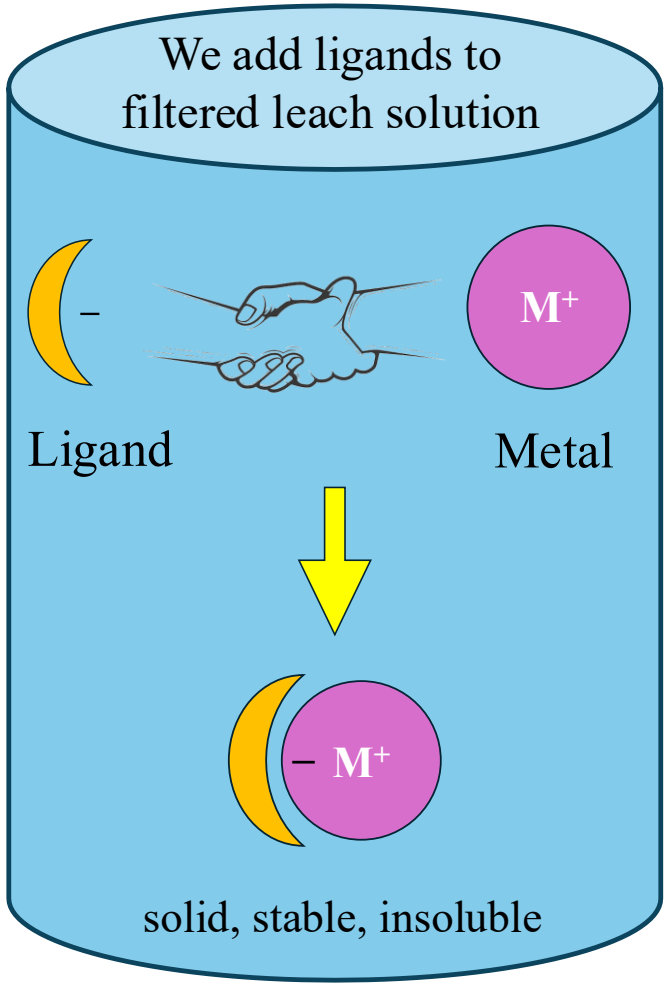
Metal-loaded organic phase



Extraction of metallic ions



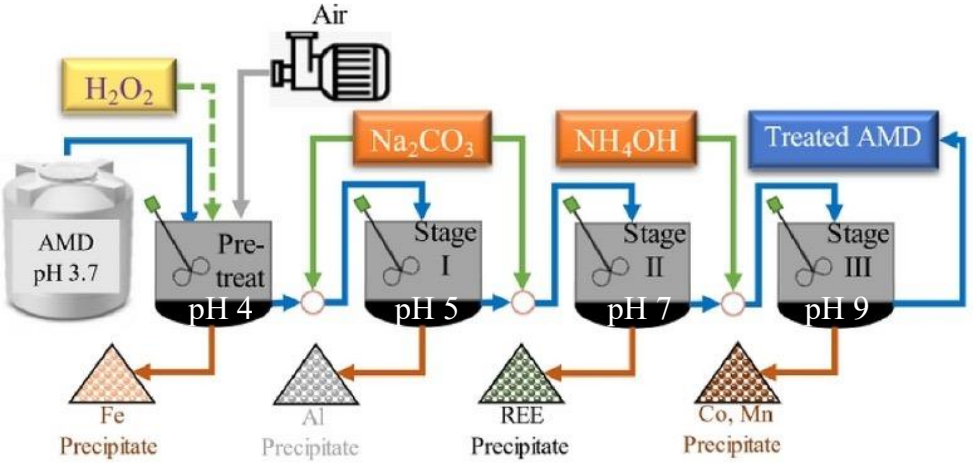
Precipitation

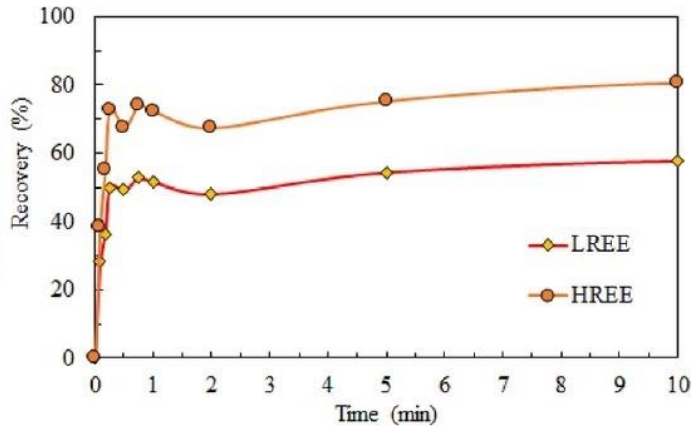


… occurs when a metal ion and a ligand react to form an insoluble solid. This often happens when an acid-base reaction between an aqueous metal ion and a base ligand (like hydroxide) causes the metal complex to become neutral and unreactive, precipitating out of solution.

Ligands are ions or molecules with a lone pair of electrons that can form a coordinate covalent bond with a central metal ion to form a complex.

pH Matters!





Vaziri, B. et al., 2023 - Resources, Conservation and Recycling

Electronegativity

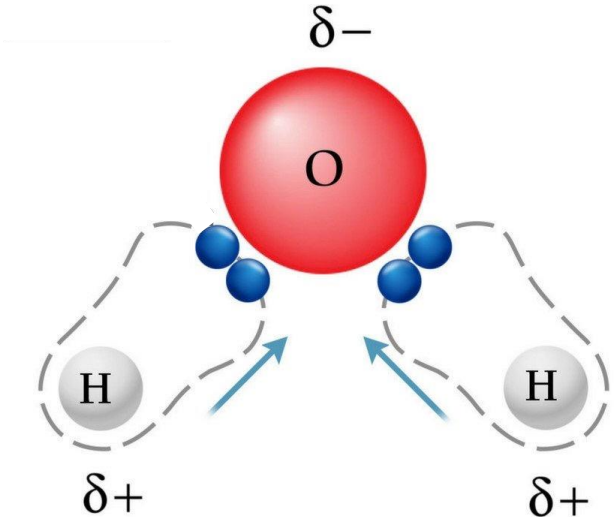
… is the tendency of an atom to attract shared electrons in a chemical bond.

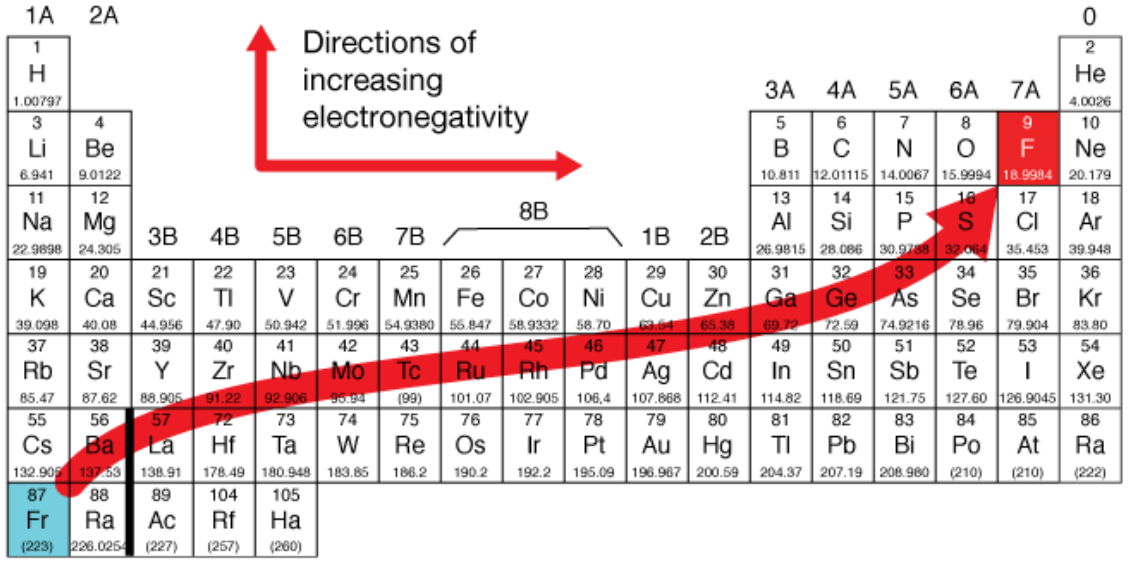
The difference in electronegativity between two atoms determines the nature of the bond:

Nonpolar covalent bond: very little or no difference in electronegativity.

Polar covalent bond: a significant difference, electrons are pulled closer to the electronegative atom, giving it a partial negative charge and the other a partial positive charge.

Ionic bond: very large, causing one atom to essentially take the electron(s) from the other.





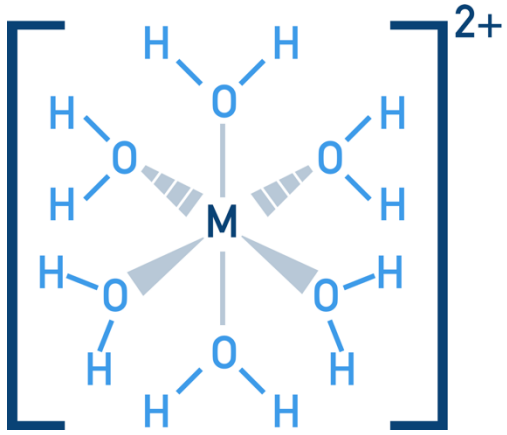
https://chemistrytalk.org/

Coordination

In water, metal ions are not free but are surrounded by water molecules (hydration), forming aqua complexes.

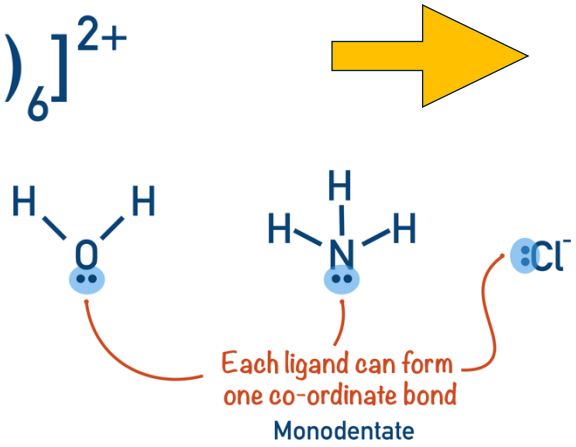
The ions of metals in the +2 and +3 oxidation states have a coordination number of 6.

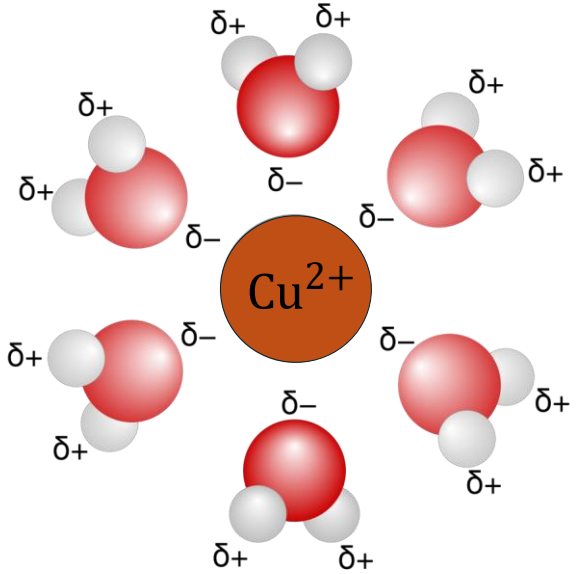
$$[Cu(H_2O)_6]^{2+}$$



=

$[M(H_2O)_6]^{2+}$





Solubility and Solubility Product

Solubility Product Constant (K_{sp}):
The equilibrium constant that represents the dissolution of a sparingly soluble salt. It indicates how much of the compound can dissolve in water.

$$K_{sp} = [A^+]^a[B^-]^b$$

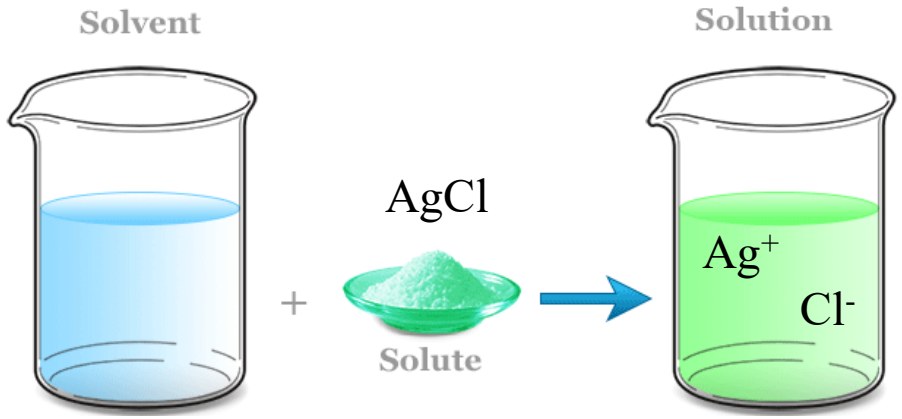
Ion Product (Q):
The ion product is calculated the same way as K_{sp} but using the current (not equilibrium) ion concentrations.

Comparing **Q** with **K_{sp}** shows whether a solution is unsaturated, saturated, or supersaturated, and whether precipitation will occur:

- If **Q > K_{sp}**, precipitation occurs (supersaturated).
- If **Q < K_{sp}**, no precipitation occurs (unsaturated).
- If **Q = K_{sp}**, the solution is at equilibrium (saturated).

For **silver chloride (AgCl)**:

$$\mathrm{AgCl\,(s)} \rightleftharpoons \mathrm{Ag^+}(aq) + \mathrm{Cl^-}(aq)$$



$$K_{sp} = [\mathrm{Ag^+}][\mathrm{Cl^-}]$$

At 25 °C:

$$K_{sp}(\mathrm{AgCl}) = 1.8 \times 10^{-10}$$

If a solution has:

$$[\mathrm{Ag^+}] = 2.0 \times 10^{-5}\ \mathrm{M}, \quad [\mathrm{Cl^-}] = 2.0 \times 10^{-5}\ \mathrm{M}$$

$$Q = (2.0 \times 10^{-5})(2.0 \times 10^{-5}) = 4.0 \times 10^{-10}$$

Q > K_{sp}, AgCl will precipitate.

Ionic Strength (IS)

… is a measure of the total concentration and charge of all ions in a solution.

$$\mu = \frac{1}{2}\sum_{i=1}^{n} c_i z_i^2$$

c_i: the concentration of ion i (mol/L, M)
z_i: the charge of that ion

Calculate the IS of a solution of 0.10 M NaCl. Repeat the calculation for a solution of 0.10 M Na_2SO_4.

For 0.10 M NaCl:

$$\mu = \tfrac{1}{2}\{[Na^+] \times (+1)^2 + [Cl^-] \times (-1)^2\}$$
$$\mu = \tfrac{1}{2}\{(0.10) \times (+1)^2 + (0.10) \times (-1)^2\} = 0.10\ M$$

For 0.10 M Na_2SO_4:

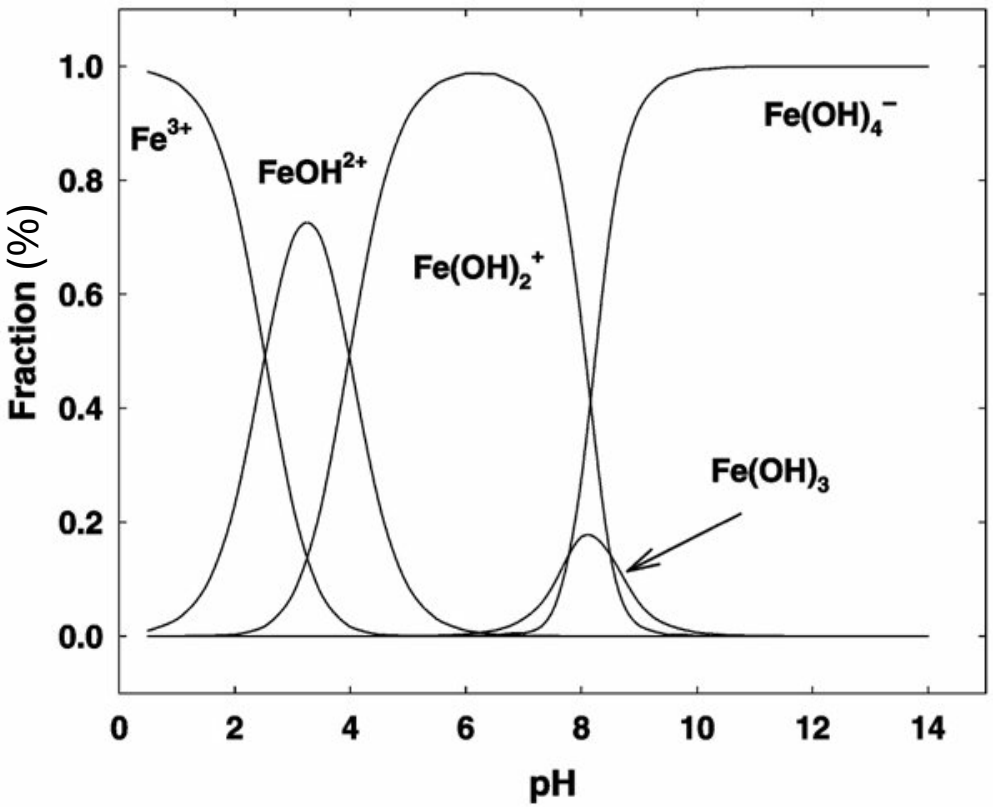
$$\mu = \tfrac{1}{2}\{[Na^+] \times (+1)^2 + [SO_4^{2-}] \times (-2)^2\}$$
$$\mu = \tfrac{1}{2}\{(0.20) \times (+1)^2 + (0.10) \times (-2)^2\} = 0.30\ M$$

We ignore H_3O^+ (hydronium), OH^- and HSO_4^- as their concentrations are are negligible.

- Ionic strength controls the activity (effective concentration, $a = \gamma \cdot C$) and solubility of metal ions in a solution.
- IS increases, there are **more ions** in solution. They shield each other and become **less** thermodynamically active.
- We can adjust IS by adding an inert electrolyte (e.g., $NaNO_3$). Increased IS, ions stay dissolved (nearing Q = K_{sp}).

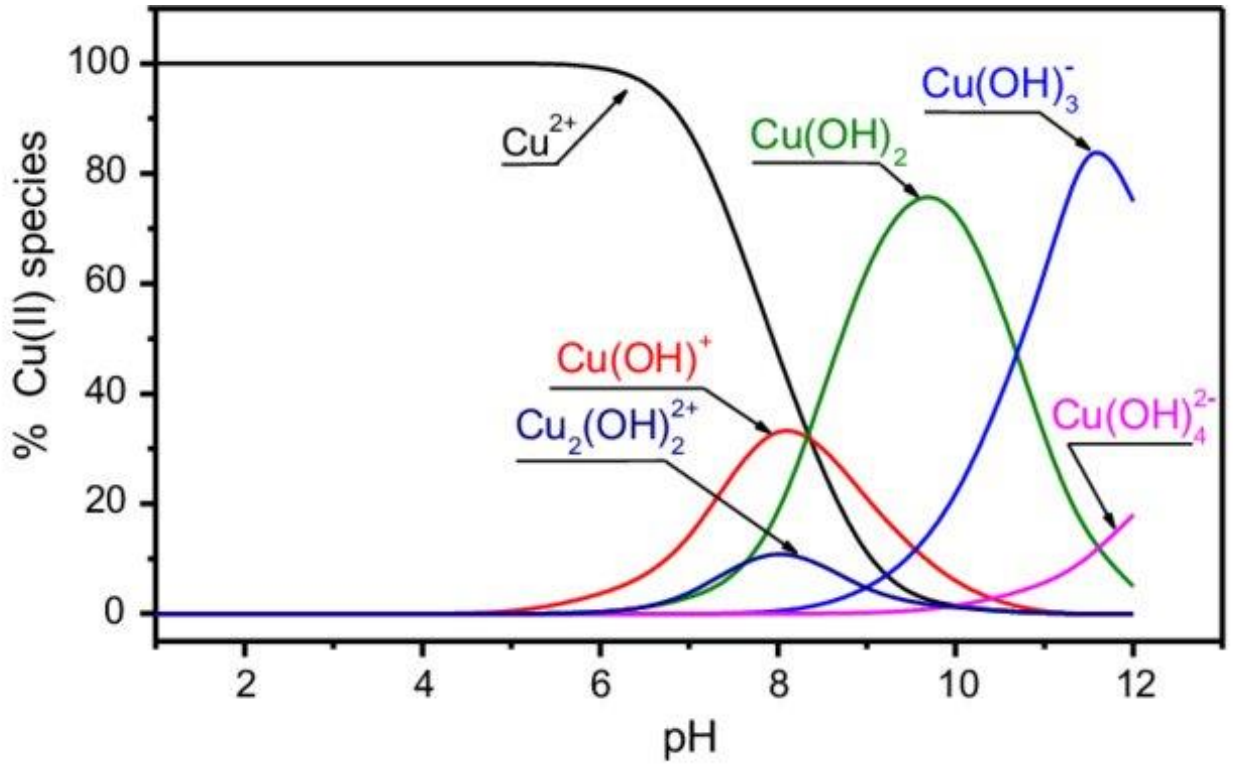
Speciation diagrams

Metals occur in different physical and chemical forms in the solution.



Speciation diagram of Fe(III) in 0.7 m NaCl at 25 °C

Frank Millero, 2001, Geochemical Transactions

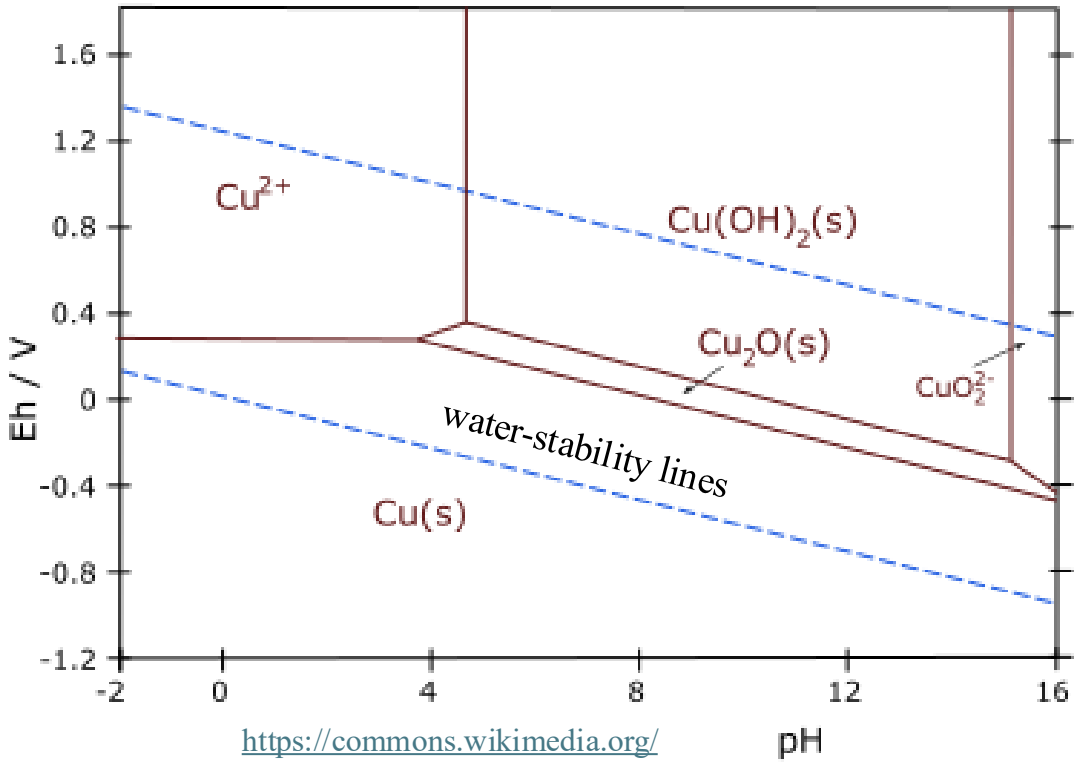


Speciation diagram of Cu at 25 °C.

Reda R. Sheha, 2012, Chemical Engineering Journal

Eh - pH (Pourbaix) diagrams

… summarize the thermodynamic stability of different metal species (solid, aqueous) as a function of both pH and redox potential (E_h).



https://commons.wikimedia.org/

Example Calculation: $[Cu^{2+}] = 0.056$ M

Boundary: $Cu^{2+} \rightleftharpoons Cu(s)$

Reaction (reduction direction):

$$Cu^{2+} + 2e^- \rightarrow Cu(s)$$

Standard potential at 25 °C:

$$E^\circ = +0.337 \text{ V}$$

Nernst equation (298 K):

$$E_h = E^\circ - \frac{0.05916}{n} \log Q = E^\circ + \frac{0.05916}{2} \log[Cu^{2+}]$$

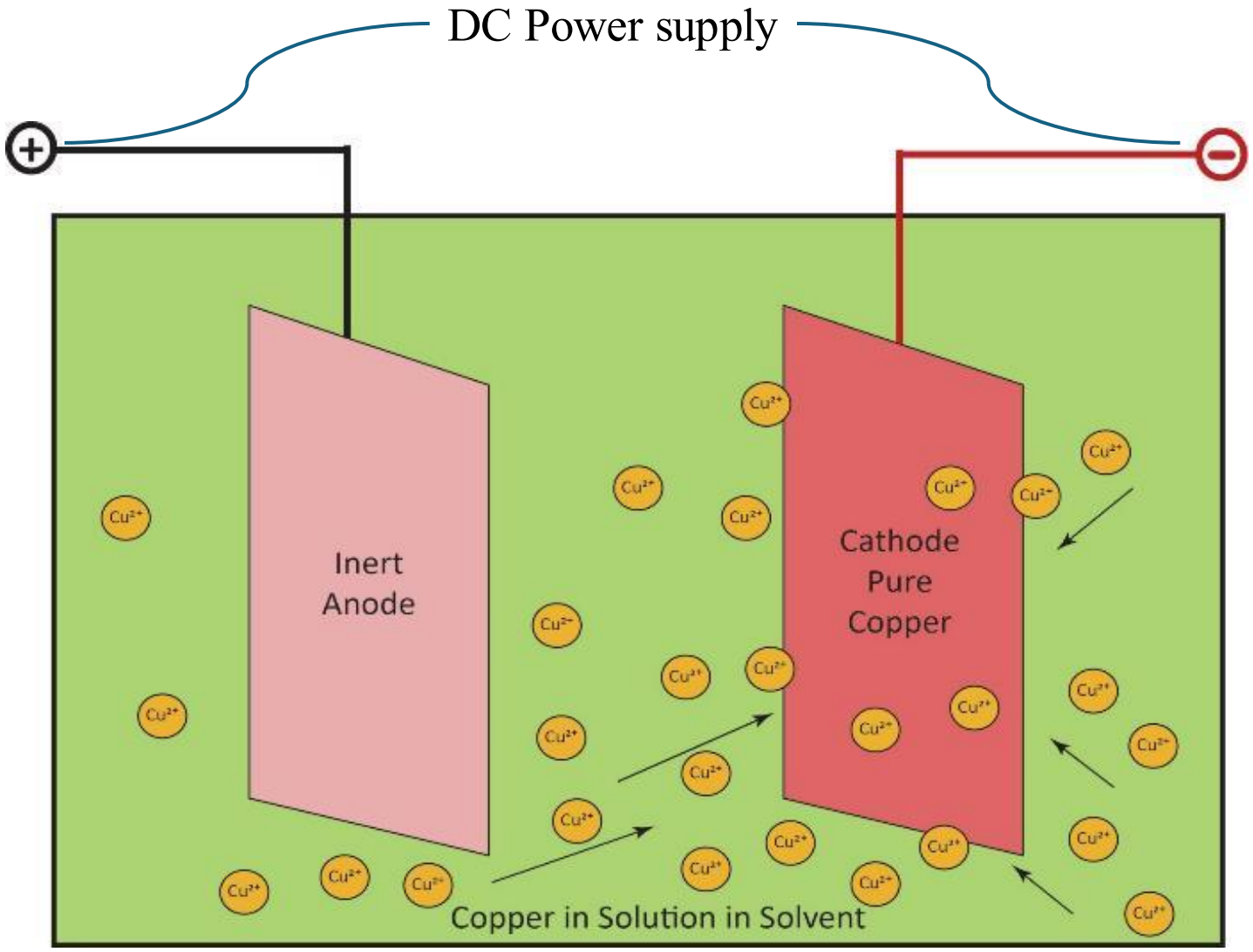
$$E_h = 0.337 + \frac{0.05916}{2} \log(0.056) = 0.337 - 0.037 = \boxed{0.300 \text{ V}}$$

A positive value of Eh indicates a tendency for a reaction to proceed in the direction of reduction.

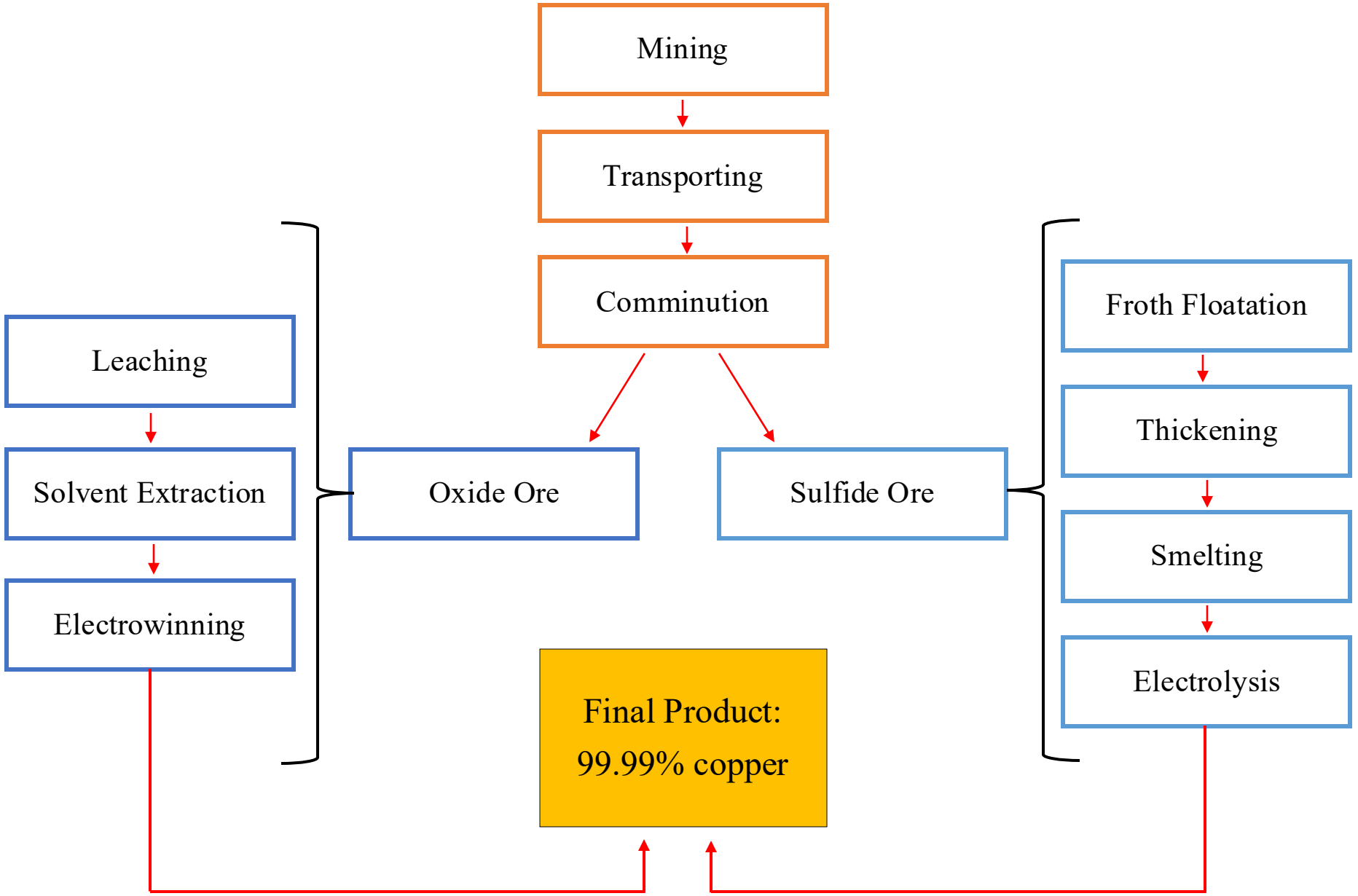
Electrowinning

- Electrical current passes through an inert anode (positive electrode) and through the copper solution from the previous step, which acts as an electrolyte.
- Positively-charged copper ions (cations) come out of solution and are plated onto a cathode (negative electrode) as **~99.99% pure copper**

$$Cu^{2+} + 2e^{-} \rightarrow Cu\ (s)$$



Electrowinning, Inspiration Consolidated Copper Co., Globe AZ. By Keyes, Cornelius M. 1972. U.S. National Archives and Records Administration. Public domain via Wikimedia Commons.


Mining
Transporting
Comminution
Leaching
Solvent Extraction
Electrowinning
Oxide Ore
Sulfide Ore
Froth Floatation
Thickening
Smelting
Electrolysis
Final Product:
99.99% copper

Thank You!

Amir Eskanlou

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