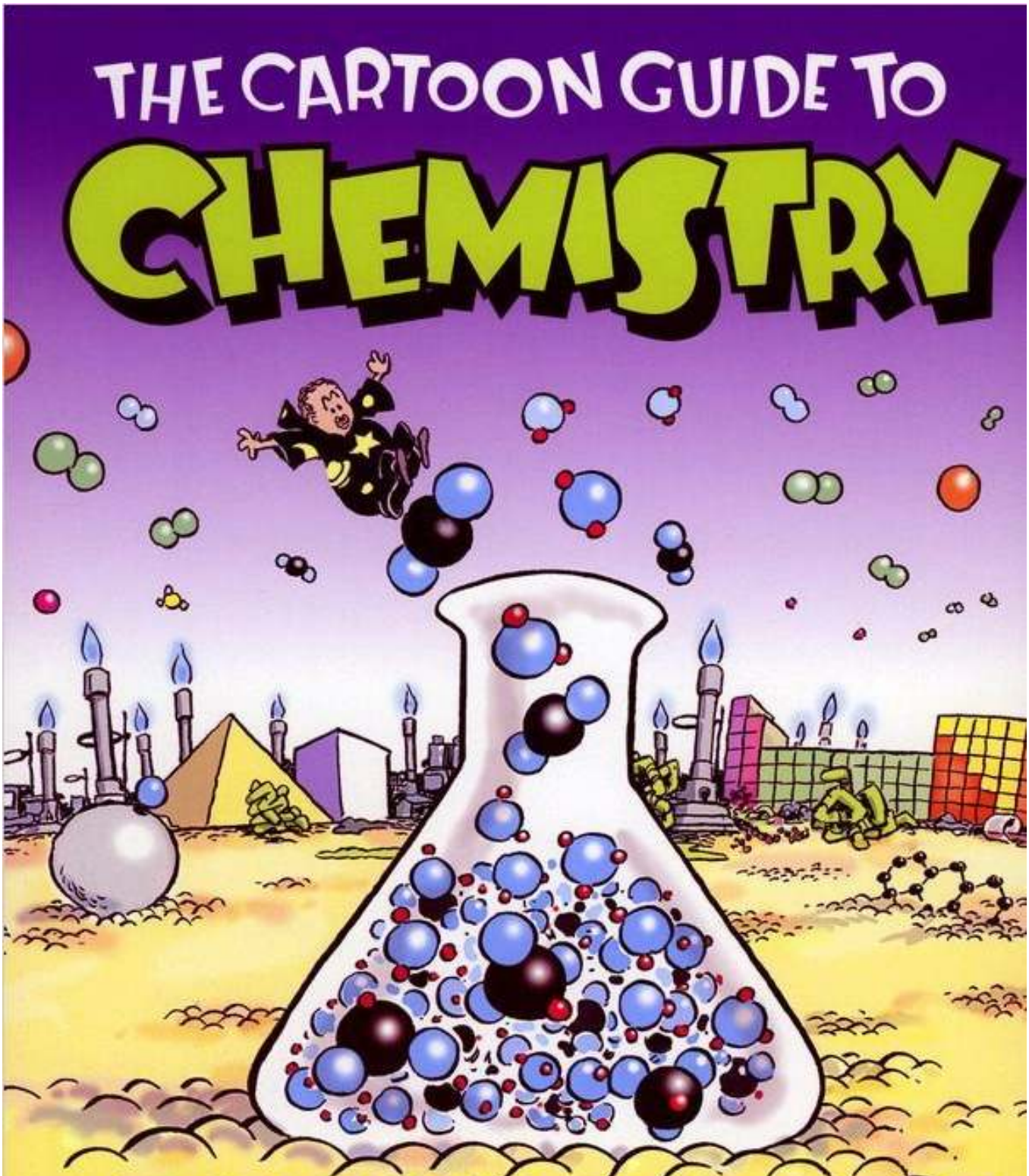
# THE CARTOON GUIDE TO CHEMISTRY




**LARRY GONICK & CRAIG CRIDDLE**

**Author of THE CARTOON HISTORY OF THE UNIVERSE**



HarperCollins*Publishers*

# THE CARTOON GUIDE TO CHEMISTRY

SÁCH NÀY CỦA: VÕ NGỌC BÌNH


D&3H - TẠP CHÍ DẠY VÀ HỌC HÓA HỌC

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# THE CARTOON GUIDE TO CHEMISTRY

LARRY GONICK
& CRAIG CRIDDLE

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TO

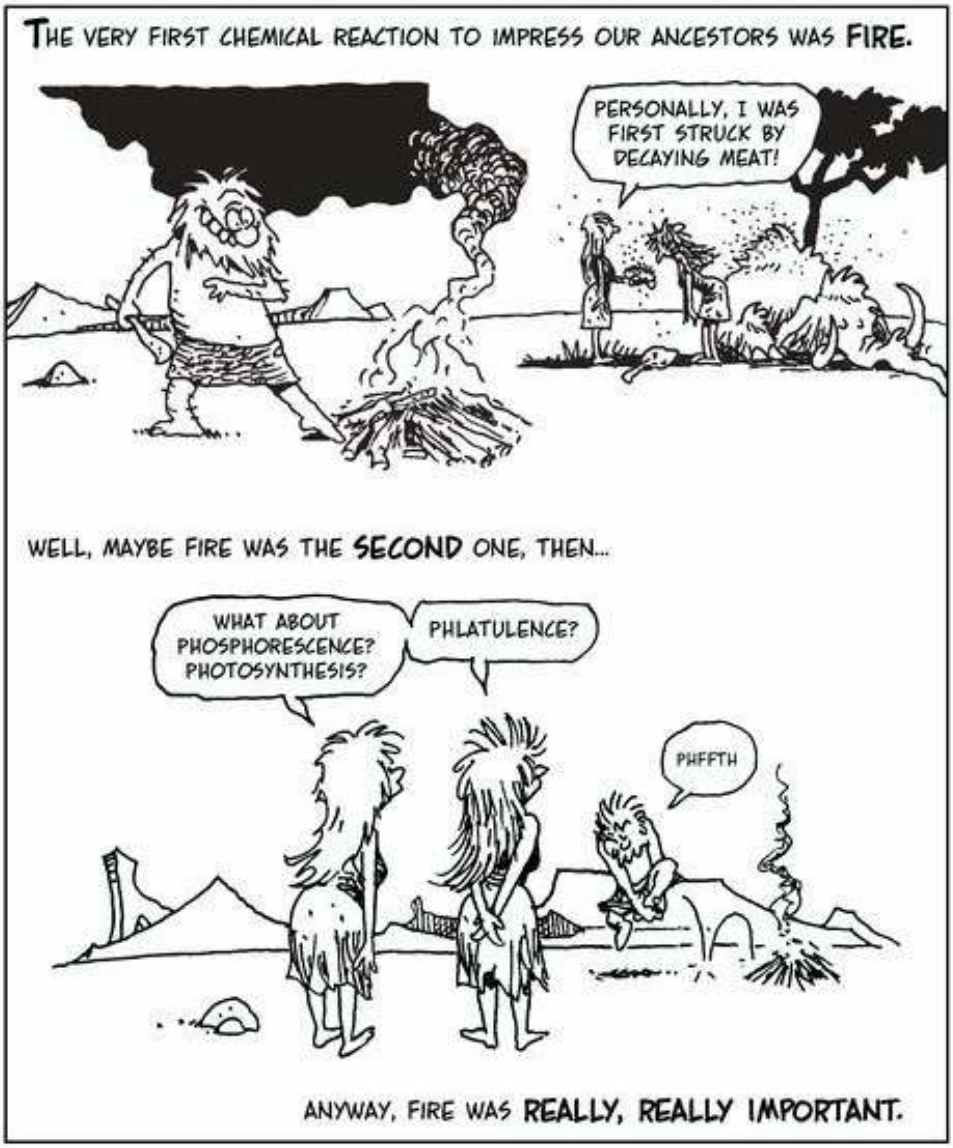
DEON CRIDDLE,
WHO ALWAYS HAD TIME TO HELP
HIS SON WITH SCIENCE FAIRS

AND

THE MEMORY OF EMANUEL GONICK AND
OTTO GOLDSCHMID, CHEMISTS BOTH

THE CARTOONIST WOULD LIKE TO THANK HIS ASSISTANT, HEMENG "MOMO" ZHOU, WITHOUT WHOSE COMPUTER SKILLS, ARTISTIC ABILITY, AND GOOD HUMOR THIS BOOK WOULD HAVE TAKEN FOREVER...

# Chapter 1
# Hidden Ingredients



FIRE—AND THOSE OTHER PROCESSES—REVEALED **HIDDEN FEATURES OF MATTER.** IF YOU HEAT A PIECE OF WOOD, ALL YOU GET IS A HOT PIECE OF WOOD, AT FIRST... BUT SUDDENLY, AT SOME POINT, THE WOOD BURSTS INTO FLAME. WHERE DID **THAT** COME FROM?


**CHEMISTRY** IS THE SCIENCE THAT ANSWERS THAT QUESTION, AND **CHEMICAL REACTIONS** ARE THE STRANGE TRANSFORMATIONS THAT REVEAL MATTER'S **HIDDEN PROPERTIES.**

CHEMISTRY IS A SCIENCE ABOUT THE OCCULT, THE HIDDEN, THE INVISIBLE. NO WONDER IT TOOK SO LONG FOR CHEMICAL SECRETS TO COME OUT... AND IT ALL STARTED WITH **FIRE.**

PROBABLY THE BEST THING ABOUT FIRE WAS THAT IT COULD BE USED TO CONTROL **OTHER** CHEMICAL REACTIONS: COOKING, FOR EXAMPLE!


YOU KNOW HOW SCIENTISTS ARE: IF THEY CAN COOK ONE THING, THEY'LL COOK ANOTHER. PRETTY SOON, THEY WERE COOKING ROCKS.


SOUNDS CRAZY, BUT ONE OF THOSE GREEN, CRUMBLY ROCKS MELTED, CHANGED, AND BECAME AN ORANGE LIQUID THAT COOLED INTO SHINY, METALLIC **COPPER.**


THIS ENCOURAGED THEM TO SMELT RED ROCKS INTO IRON... BAKE MUD INTO BRICKS... SAUTE FAT AND ASHES INTO SOAP... AND (WITHOUT FIRE) TO CURDLE MILK INTO YOGURT... FERMENT GRAIN INTO BEER... AND CABBAGE INTO KIMCHEE. THE NEXT THING YOU KNEW, CHEMISTRY HAD CAUSED **CIVILIZATION!**

# Chapter 2
# Matter Becomes Electric

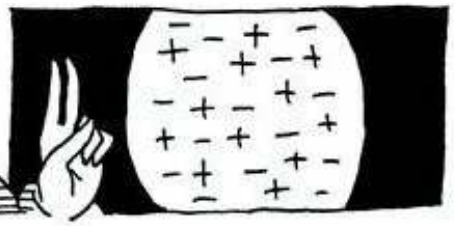
NATURE HAD ANOTHER SECRET BESIDES FIRE... AT LEAST, IT LOOKED LIKE ANOTHER SECRET AT FIRST...


THIS ONE INVOLVED **AMBER**... OR AS THE GREEKS CALLED IT, **ELEKTRA**.


THEN PEOPLE NOTICED THAT THERE WERE REALLY TWO KINDS OF "ELECTRIC" MATERIALS: ONE REPELLED WHAT THE OTHER ATTRACTED, AND VICE VERSA.

AROUND 1750, **BENJAMIN FRANKLIN** (1706–1790) FIRST CALLED THESE TWO KINDS OF ELECTRICITY **POSITIVE** AND **NEGATIVE.**

POSITIVE, SAID FRANKLIN, REPELS POSITIVE; NEGATIVE REPELS NEGATIVE; AND POSITIVE AND NEGATIVE ATTRACT EACH OTHER AND CANCEL EACH OTHER OUT. IN ORDINARY, **NEUTRAL** MATTER, OPPOSITE CHARGES ARE PRESENT IN EQUAL AMOUNT.

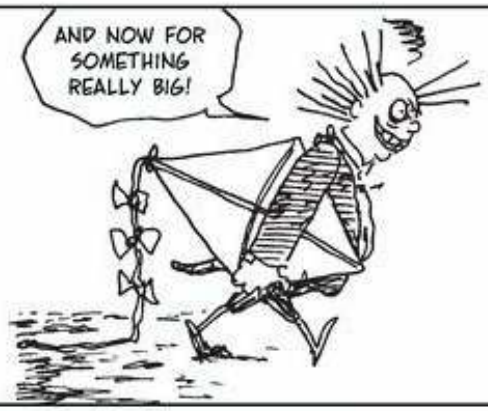


NEGATIVE CHARGES CAN SOMETIMES FLOW OUT OF A SUBSTANCE, CREATING A CHARGE **IMBALANCE**—AN EXCESS OF NEGATIVITY HERE AND POSITIVITY THERE...

BUT BECAUSE OF THE MUTUAL ATTRACTION, THE NEGATIVES MAY SUDDENLY FLOW BACK TO THE POSITIVE CHARGE WITH A SPARK.

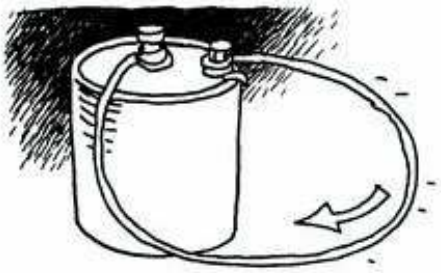
"TWO NIGHTS AGO, BEING ABOUT TO KILL A TURKEY BY THE SHOCK FROM TWO LARGE GLASS JARS,* CONTAINING AS MUCH ELECTRICAL FIRE AS FORTY COMMON PHIALS, I INADVERTENTLY TOOK THE WHOLE THROUGH MY OWN ARMS AND BODY, BY RECEIVING THE FIRE FROM THE UNITED TOP WIRES WITH ONE HAND WHILE THE OTHER HELD A CHAIN CONNECTED WITH THE OUTSIDE OF BOTH JARS."

—BENJAMIN FRANKLIN, 1750

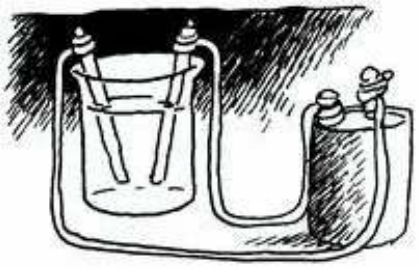



*JUST ONE OF THE WAYS THE FUN-LOVING FOUNDING FATHER LIKED TO AMUSE HIMSELF!

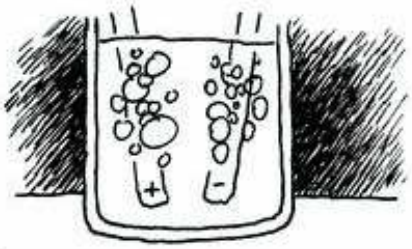
WITH THE INVENTION OF THE ELECTRIC BATTERY (BY VOLTA IN 1800), ONE COULD RUN A STEADY STREAM OF NEGATIVE CHARGE— A **CURRENT**—THROUGH A COPPER WIRE, AND MAYBE THROUGH OTHER MATERIALS AS WELL.



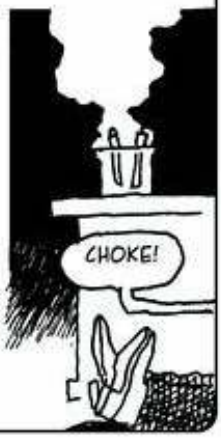
CHEMISTS TRIED RUNNING ELECTRICITY THROUGH ORDINARY WATER. TWO METAL STRIPS, OR ELECTRODES, WERE CONNECTED TO A BATTERY AND IMMERSED IN WATER.



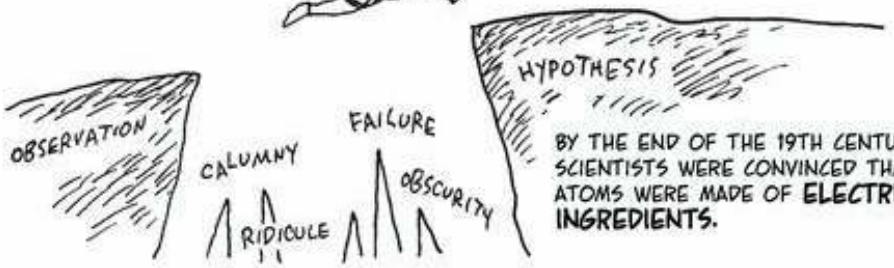
AS CHARGE BUILT UP ON THE ELECTRODES, BUBBLES OF **HYDROGEN GAS** APPEARED AT THE NEGATIVE STRIP, OR **CATHODE**. BUBBLES OF **OXYGEN** FORMED AT THE POSITIVE STRIP, OR ANODE.




ELECTRICITY SPLITS WATER! SCIENTISTS SOON TRIED THIS **ELECTROLYSIS** (ELECTRIC SPLITTING) ON OTHER SUBSTANCES. MELTED TABLE SALT, THEY FOUND, YIELDS METALLIC **SODIUM** AT THE CATHODE AND GREEN, TOXIC **CHLORINE GAS** AT THE ANODE.



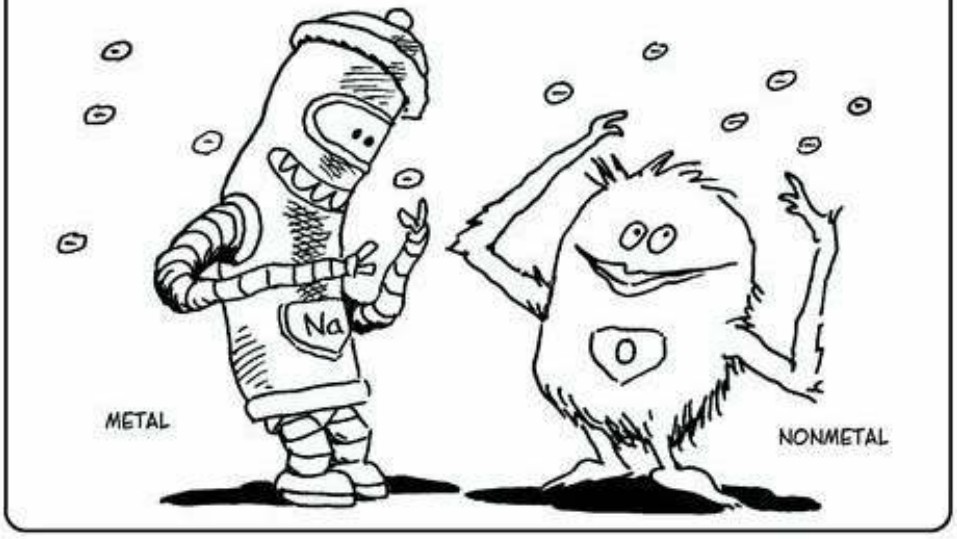

IT'S A BIG LEAP FROM FINDING ELECTRICITY IN A FEW PLACES TO SEEING IT EVERYWHERE, BUT THAT'S SCIENCE FOR YOU!


BY THE END OF THE 19TH CENTURY, SCIENTISTS WERE CONVINCED THAT ATOMS WERE MADE OF **ELECTRIC INGREDIENTS.**

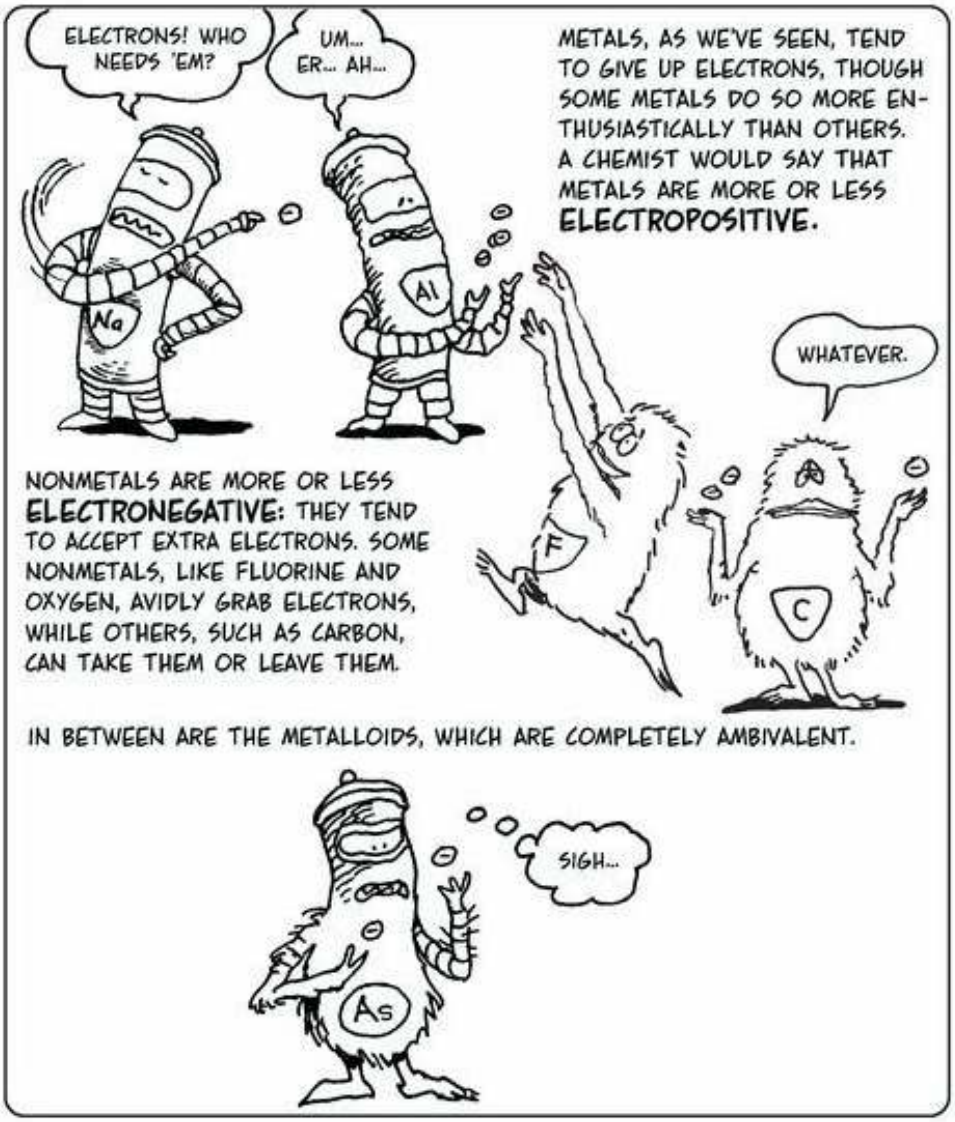
# Chapter 3
# Togetherness

BUT IN REALITY, CHEMISTRY IS A SORT OF FRENZY OF TOGETHERNESS. MOST ATOMS ARE GREGARIOUS LITTLE CRITTERS... AND THAT'S HOW WE'RE GOING TO DRAW THEM, SOMETIMES... AS LITTLE CRITTERS.




THE COMBINATIONS ARE ENDLESS. METALS BOND TO METALS, NONMETALS TO NONMETALS, METALS TO NONMETALS. SOMETIMES ATOMS CLUMP TOGETHER IN LITTLE CLUSTERS AND SOMETIMES IN IMMENSE CRYSTAL ARRAYS. NO WONDER THE SUBJECT IS SO... SEXY!

ATOMS COMBINE WITH EACH OTHER BY EXCHANGING OR SHARING ELECTRONS. THE DETAILS DEPEND ON THE PREFERENCES OF THE PARTICULAR ATOMS INVOLVED. DOES AN ATOM "WANT" TO SHED AN ELECTRON OR TO PICK ONE UP? AND HOW BADLY?



## Chapter 4

# Chemical Reactions

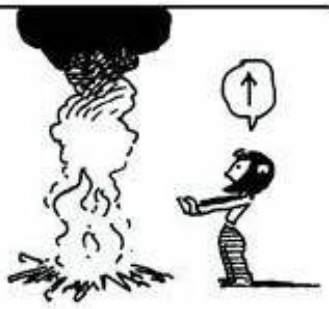
OOPS! SOMEHOW WE FIND OURSELVES MAROONED ON A DESERT ISLAND. HOW ARE WE GOING TO SURVIVE? MAYBE WE CAN MAKE SOMETHING USEFUL OUT OF THE MATERIALS AT HAND...

# Combustion, Combination, Decomposition


LET'S WRITE A **REACTION EQUATION** FOR FIRE. WOOD CONTAINS MANY DIFFERENT MATERIALS, BUT IT'S MAINLY MADE OF C, H, AND O IN THE RATIO 1:2:1. WE CAN WRITE THE EMPIRICAL FORMULA FOR WOOD AS $CH_2O$, AND THEN FIRE LOOKS LIKE THIS:*

$$CH_2O\,(s) + O_2\,(g) \rightarrow CO_2\,(g)\uparrow + H_2O\,(g)\uparrow$$

THE NOTATION EXPLAINED: THE SUBSTANCES ON THE LEFT OF THE HORIZONTAL ARROW → ARE CALLED **REACTANTS.** ON THE RIGHT ARE THE **REACTION PRODUCTS.** $\xrightarrow{\Delta}$ WILL MEAN THAT HEAT WAS ADDED. THE SMALL LETTERS IN PARENTHESES SHOW THE PHYSICAL STATE OF THE CHEMICALS: g = GAS; s = SOLID; l = LIQUID; aq = DISSOLVED IN WATER. ↑ MEANS AN ESCAPING GAS, AND ↓ WILL MEAN A SOLID SETTLING OUT OF SOLUTION, OR **PRECIPITATING.**



SO OUR EQUATION READS: SOLID WOOD PLUS GASEOUS OXYGEN AND HEAT MAKES GASEOUS CARBON DIOXIDE PLUS WATER VAPOR. THIS IS A TYPICAL **COMBUSTION REACTION.** (YOU CAN TEST FOR THE WATER BY HOLDING A COOL GLASS OVER THE FLAME; DROPLETS WILL CONDENSE ON IT.)

*WE'RE LEAVING OUT PARTIALLY OR WHOLLY NONCOMBUSTED PRODUCTS SUCH AS SOOT, SMOKE, CO, ETC.

NOW THAT WE HAVE FIRE, WE'LL MAKE A BETTER FUEL: **CHARCOAL.** WE PUT DRY WOOD AND COCONUT SHELLS IN A PIT (TO LIMIT AVAILABLE OXYGEN) AND FIRE IT UP. THE REACTION IS*

$$CH_2O \xrightarrow{\Delta} C(s) + H_2O(g)\uparrow$$

THIS IS A **DECOMPOSITION** REACTION (OF THE FORM AB → A + B). IT MAKES ELEMENTAL CARBON, OR CHARCOAL.

WE BUILD A STONE STOVE AND FUEL IT WITH CHARCOAL. CHARCOAL'S COMBUSTION IS A **COMBINATION** REACTION (A+B → AB):

$$C(s) + O_2(g) \rightarrow CO_2(g)\uparrow$$


IN THIS OVEN WE CAN MAKE **POTTERY.** WE SCOOP A FINE-GRAINED MINERAL, KAOLINITE, FROM THE LAKE BOTTOM AND GRIND IT WITH A LITTLE WATER TO MAKE A SMOOTH KAOLIN CLAY, $Al_2Si_2O_5(OH)_4$. WE SHAPE THIS INTO VESSELS AND FIRE THEM IN A HOT OVEN:

$$3Al_2Si_2O_5(OH)_4\,(s) \xrightarrow{\Delta} Al_6Si_2O_{13}(s) + 4SiO_2\,(s) + 6H_2O\,(g)\uparrow$$

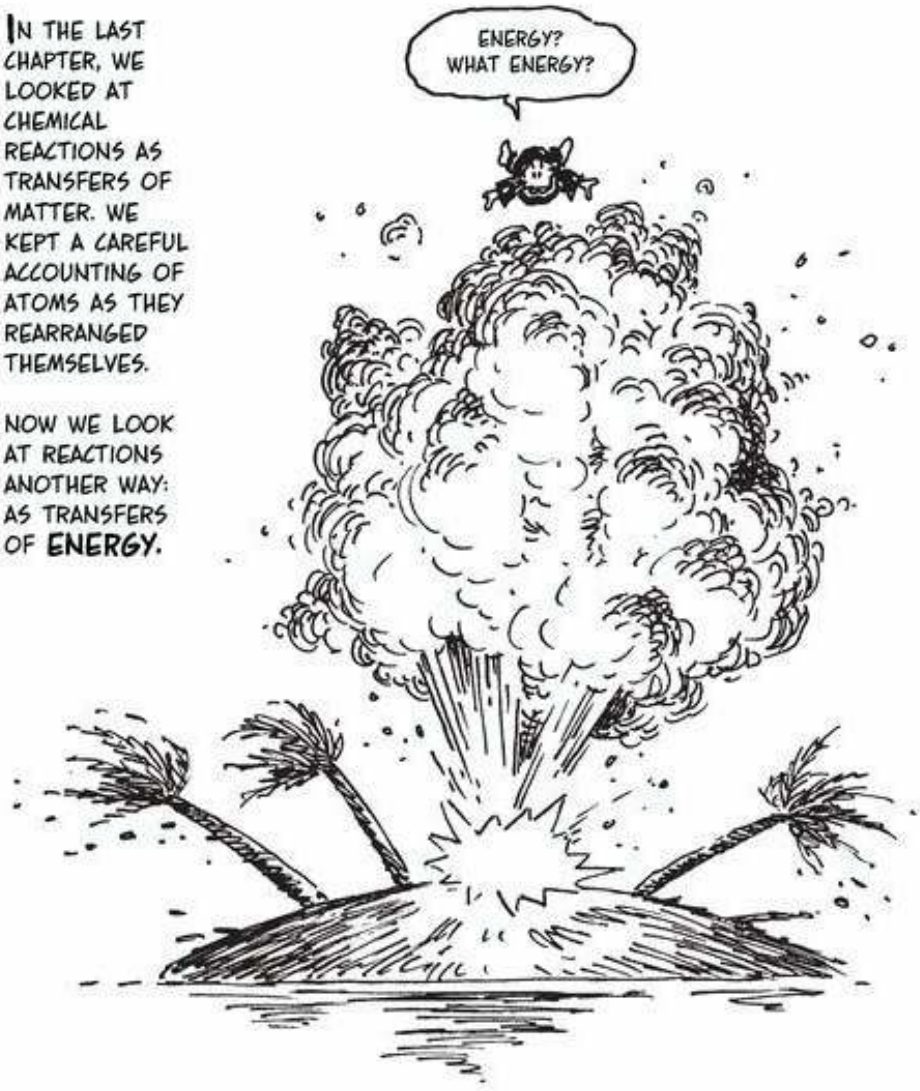
THE FIRST PRODUCT IS CALLED **MULLITE.** THE SECOND, $SiO_2$, IS **SILICA,** OR SAND—AND MELTED, IT'S **GLASS.** WHEN THE CLAY IS FIRED, MULLITE FUSES WITH THE GLASSY SILICA TO FORM A VERY HARD, WATERPROOF POT.

*MORE OR LESS. AGAIN WE IGNORE TRACE REACTANTS AND PRODUCTS.

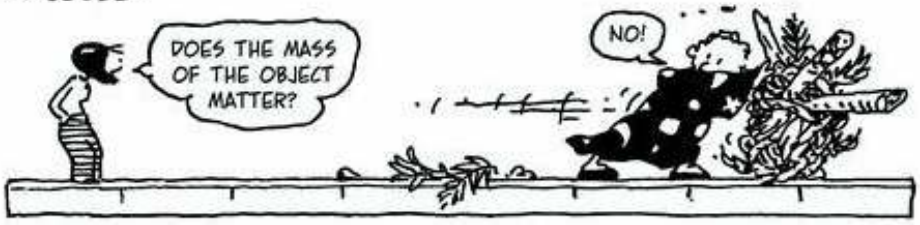
# Chapter 5
# Heat of Reaction

IN THE LAST CHAPTER, WE LOOKED AT CHEMICAL REACTIONS AS TRANSFERS OF MATTER. WE KEPT A CAREFUL ACCOUNTING OF ATOMS AS THEY REARRANGED THEMSELVES.

NOW WE LOOK AT REACTIONS ANOTHER WAY: AS TRANSFERS OF **ENERGY.**

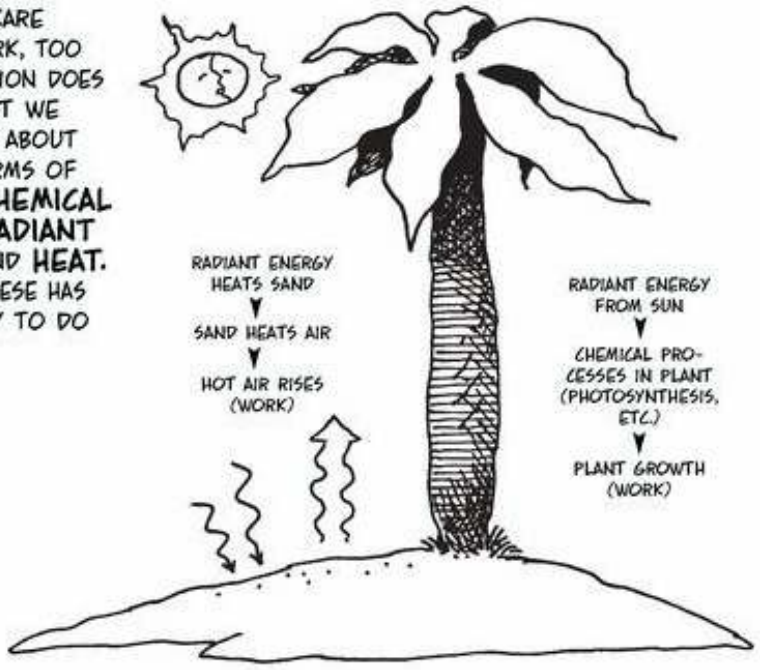


PHYSICISTS DEFINE ENERGY MECHANICALLY, AS THE ABILITY TO DO **WORK.*** WORK IS WHAT HAPPENS WHEN A FORCE OPERATES ON AN OBJECT OVER A DISTANCE: WORK = FORCE X DISTANCE. THE METRIC UNIT OF ENERGY IS THE NEWTON-METER, OR **JOULE.**




1 JOULE = WORK DONE BY A FORCE OF ONE NEWTON OPERATING OVER A DISTANCE OF ONE METER.

CHEMISTS CARE ABOUT WORK, TOO (AN EXPLOSION DOES WORK), BUT WE ALSO CARE ABOUT OTHER FORMS OF ENERGY: **CHEMICAL** ENERGY, **RADIANT** ENERGY, AND **HEAT.** EACH OF THESE HAS THE ABILITY TO DO WORK.



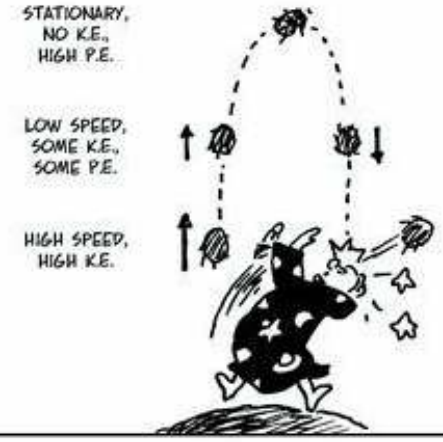

ONE KIND OF ENERGY CAN BE CONVERTED INTO ANOTHER KIND, BUT ENERGY IS NEVER CREATED OR DESTROYED. THAT'S A LAW—THE LAW OF **CONSERVATION OF ENERGY.**

*NOT TO BE CONFUSED WITH USEFUL WORK.

LET'S EXAMINE MECHANICAL ENERGY MORE CLOSELY. IF I PUSH THIS COCONUT, IT MOVES... AND THE LONGER AND/OR HARDER I PUSH, THE FASTER IT GOES. (THIS IS CLEARER IN OUTER SPACE, AWAY FROM FRICTION AND GRAVITY.) BY DOING WORK ON THE COCONUT, I ADD ENERGY TO IT: **KINETIC ENERGY (K.E.)**, THE ENERGY OF MOTION.

$$K.E. = \frac{1}{2}mv^2$$

BACK ON EARTH, I PUSH THE COCONUT AGAIN, BUT IN AN UPWARD DIRECTION. THE COCONUT FLIES UP, BUT IT SLOWS UNDER THE PULL OF GRAVITY. EVENTUALLY IT STOPS AND BEGINS TO FALL. WHAT BECAME OF THE ENERGY I ADDED??




AS THE COCONUT SLOWS AND LOSES K.E., IT GAINS **POTENTIAL ENERGY (P.E.)**. THIS IS ENERGY THAT DEPENDS ON THE BODY'S POSITION IN THE EARTH'S GRAVITATIONAL FIELD. K.E. + P.E. IS CONSTANT.

IT TURNS OUT THAT **ALL** FORMS OF ENERGY CAN BE UNDERSTOOD IN TERMS OF KINETIC AND POTENTIAL ENERGY. RADIANT ENERGY, FOR INSTANCE, IS THE K.E. OF MOVING PHOTONS, OR LIGHT PARTICLES.* THERE IS POTENTIAL ENERGY STORED IN CHEMICAL BONDS. AND HEAT IS... HEAT IS... WHAT **IS** HEAT, ANYWAY?


*THE "LIGHT" NEED NOT BE VISIBLE. MOVING PHOTONS CONVEY THE ENERGY OF ALL ELECTROMAGNETIC RADIATION, FROM X-RAYS TO RADIO WAVES.

# Chapter 6
# Matter in a State

UNDER ORDINARY CONDITIONS—OUTSIDE OF STARS, SAY—MATTER COMES IN THREE STATES: SOLID, LIQUID, AND GAS.

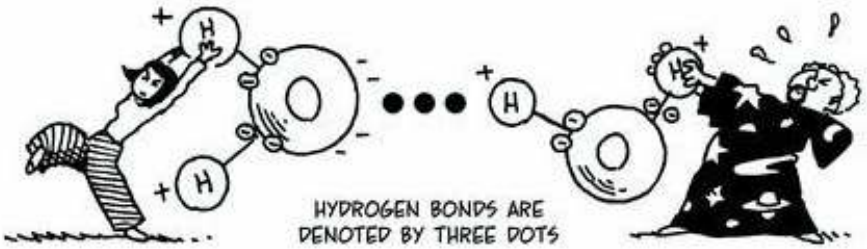
IN SOLIDS, PARTICLES ARE LOCKED TOGETHER IN A RIGID STRUCTURE. A SOLID HAS BOTH A DEFINITE SHAPE AND VOLUME.

IN LIQUIDS, PARTICLES CLING TOGETHER, BUT OVERALL STRUCTURE IS LACKING. A LIQUID HAS A DEFINITE VOLUME, BUT ITS SHAPE CONFORMS TO ITS CONTAINER.

IN GASES, STRUCTURE IS ABSENT. PARTICLES FLY AROUND ALMOST TOTALLY INDEPENDENTLY. A GAS HAS NEITHER A FIXED SHAPE NOR VOLUME, BUT WILL EXPAND TO FILL ANY CONTAINER.

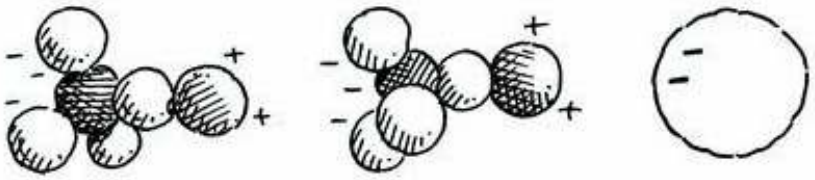

WHAT HOLDS SOLIDS AND LIQUIDS TOGETHER? THE ANSWER LIES WITH **INTERMOLECULAR FORCES** (IMFs) WITHIN THE SUBSTANCE. THESE ARE ATTRACTIONS BETWEEN MOLECULES (AS OPPOSED TO THE BONDS WITHIN A MOLECULE).

ONE IMF WE HAVE ALREADY ENCOUNTERED IS THE **HYDROGEN BOND.** IN WATER MOLECULES, ELECTRONS STAY CLOSER TO THE OXYGEN ATOM, SO THE HYDROGEN ATOMS EFFECTIVELY CARRY A POSITIVE CHARGE. THIS ATTRACTS THEM TO THE NEGATIVE POLE OF ANOTHER WATER MOLECULE.




HYDROGEN BONDS ARE DENOTED BY THREE DOTS

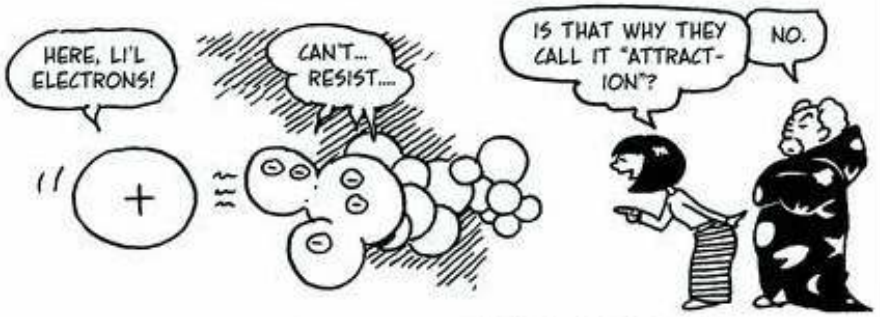
BECAUSE OF ITS TWO ELECTRIC POLES, A WATER MOLECULE IS CALLED A **DIPOLE.** MANY OTHER MOLECULES ARE DIPOLES, TOO, AND THEY ATTRACT EACH OTHER END TO CHARGED END. DIPOLES MAY ALSO ATTRACT IONS.



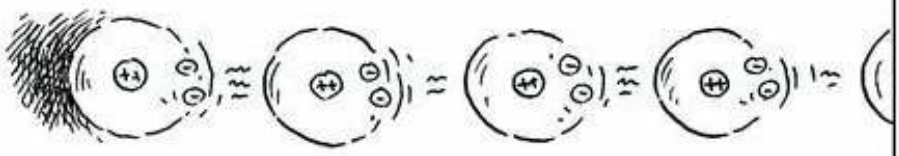
DIPOLE-DIPOLE ATTRACTION

ION-DIPOLE ATTRACTION

NONPOLAR MOLECULES CAN BECOME DIPOLES. FOR EXAMPLE, WHEN AN ION NEARS A MOLECULE, THE ION'S CHARGE CAN PUSH OR PULL THE MOLECULE'S ELECTRONS TOWARD ONE END. THE MOLECULE BECOMES AN **INDUCED DIPOLE,** AND ONE END IS ATTRACTED TO THE ION. A DIPOLE CAN INDUCE ANOTHER DIPOLE, TOO.



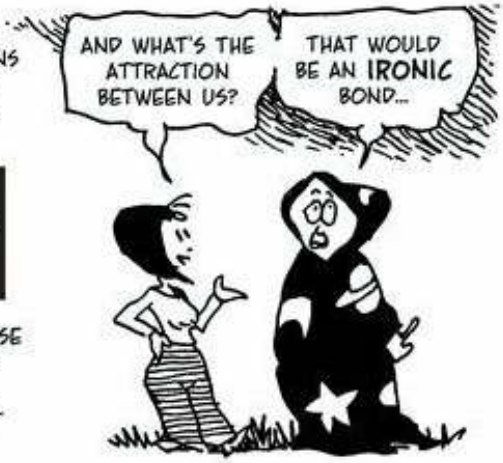

EVEN THE GHOSTLY FLIGHT OF ELECTRONS **WITHIN AN ATOM** OR MOLECULE CAN MAKE IT AN "INSTANTANEOUS" DIPOLE—WHICH CAN THEN INDUCE A NEARBY ATOM OR MOLECULE TO BECOME A DIPOLE, ETC. THE RESULTING RIPPLING ATTRACTION IS CALLED THE **LONDON DISPERSION FORCE.**



A TEMPORARY CHARGE IMBALANCE SETS OFF A RIPPLE OF DIPOLE-DIPOLE ATTRACTIONS.

ALTHOUGH THEY ARE CALLED INTER-**MOLECULAR** FORCES, THESE ATTRACTIONS DO NOT OPERATE ON MOLECULES ONLY. NOBLE GAS ATOMS, FOR INSTANCE, FEEL THE LONDON DISPERSION FORCE.

FROM NOW ON, WE'LL BE A LITTLE LOOSE WITH LANGUAGE AND SOMETIMES REFER TO IMFS AS BONDS. BONDS OR IMFS: THEY'RE ALL ELECTRIC ATTRACTIONS BE-TWEEN PARTICLES!



# Chapter 7
# Solutions

WE'VE JUST LOOKED AT STATES OF MATTER ONE AT A TIME... NOW LET'S COMBINE TWO OF THEM— OR RATHER, LET'S COMBINE SOMETHING, ANYTHING, WITH A LIQUID. FOR INSTANCE: ADD A PINCH OF TABLE SALT TO A FLASK OF WATER.

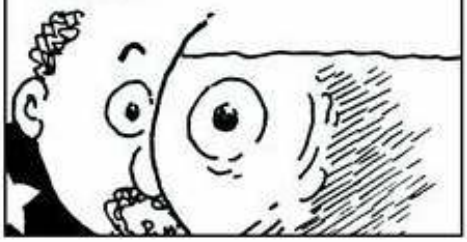

THE SALT, OF COURSE, COMPLETELY VANISHES.


THE SALT, AS WE SAY, **DISSOLVES** IN THE WATER.

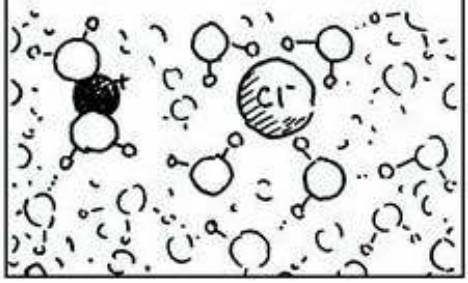

WHEN A SUBSTANCE DISSOLVES IN A LIQUID, THE COMBINATION IS CALLED A **SOLUTION.** THE LIQUID IS THE **SOLVENT,** AND THE DISSOLVED MATERIAL IS THE **SOLUTE.***

**Solute + Solvent ⟶ Solution**

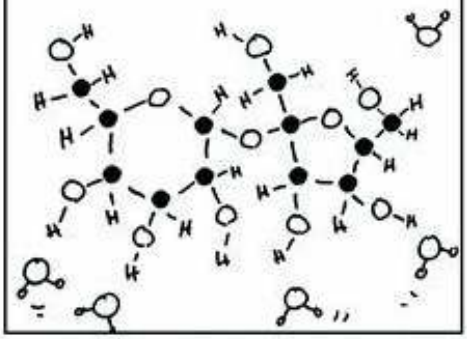
A DISSOLVED SOLID FALLS APART INTO ITS INDIVIDUAL CONSTITUENT PARTICLES, EITHER IONS OR MOLECULES. GASES ALSO DISSOLVE MOLECULE BY MOLECULE. THIS EXPLAINS WHY SOLUTIONS ARE USUALLY TRANSPARENT.



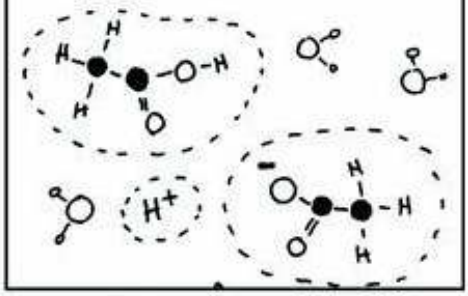
FOR EXAMPLE, SODIUM CHLORIDE, NaCl, DISSOCIATES IN WATER INTO SINGLE $Na^+$ AND $Cl^-$ IONS, WHICH BIND WITH THE WATER MOLECULES.




SUGAR—SUCROSE, $C_{12}H_{22}O_{11}$—BREAKS INTO WHOLE MOLECULES. (WATER MOLECULES LIKE ITS OH GROUPS.)

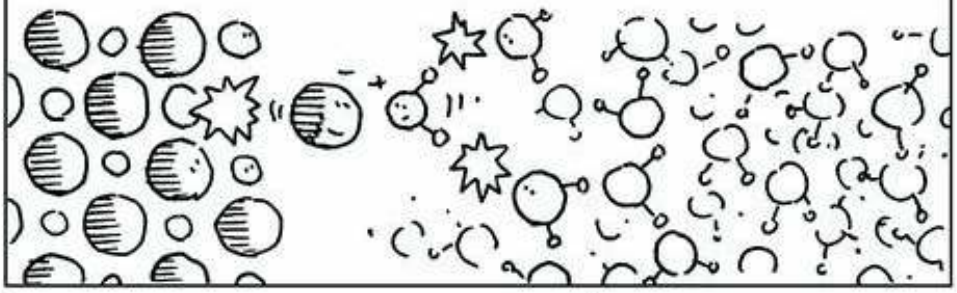


VINEGAR, A SOLUTION OF **ACETIC ACID,** $CH_3CO_2H$, CONTAINS HYDROGEN IONS, $H^+$, ACETATE IONS, $CH_3CO_2^-$, AND MUCH $CH_3CO_2H$ STILL IN COMBINATION.

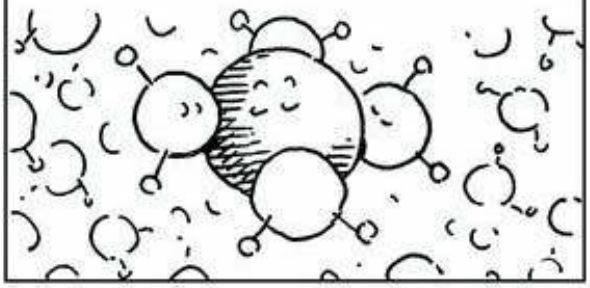



*ACTUALLY, A SOLUTION CAN BE SOLID OR GASEOUS TOO. ANY HOMOGENEOUS MIXTURE OF TWO OR MORE SUBSTANCES IS CONSIDERED A SOLUTION, WHATEVER ITS PHASE.

LET'S LOOK MORE CLOSELY AT THE DISSOLVING PROCESS. IMAGINE A CHUNK OF MATERIAL IMMERSED IN LIQUID. IN ORDER TO DISSOLVE, SOME OF ITS PARTICLES MUST BREAK THE BONDS THAT HOLD THEM TOGETHER AND FORM NEW BONDS WITH MOLECULES OF LIQUID. SIMILARLY, IMFs WITHIN THE LIQUID MUST ALSO BE OVERCOME.



EACH FREE SOLUTE PARTICLE ATTRACTS ONE OR MORE MOLECULES OF SOLVENT, WHICH CLUSTER AROUND IT IN A SOLVENT "CAGE." THIS PROCESS OF BREAKING AND FORMING BONDS IS CALLED **SOLVATION.**



ALL THIS BOND REARRANGING MEANS THAT **DISSOLVING IS A CHEMICAL REACTION.** AMONG OTHER THINGS, THEN, IT HAS AN ASSOCIATED ENTHALPY CHANGE, WHICH MAY BE POSITIVE OR NEGATIVE.


FOR EXAMPLE, WHEN MAGNESIUM CHLORIDE, $MgCl_2$, DISSOLVES IN WATER, IT HAS AN ENTHALPY OF SOLVATION

$\Delta H$ = 119 kJ/mol

HIGHLY ENDOTHERMIC! A MERE 4 g OF $MgCl_2$ (= .042 mol) IN 50 mL (= 50 g) OF WATER DROPS THE WATER'S TEMPERATURE BY 23.9°C (BY THE BASIC CALORIMETRY EQUATION).

CHEMICAL COLD PACKS ARE IN FACT MADE FROM $MgCl_2$ AND OTHER SALTS THAT ABSORB HEAT WHEN DISSOLVED IN WATER.

# Chapter 8
# Reaction Rate and Equilibrium

IN CHEMISTRY, WE CARE ABOUT NOT ONLY **WHAT** REACTS, BUT ALSO **HOW FAST.** BLACK POWDER EXPLODES IN A FLASH, WHILE THE SUGAR IN YOUR COFFEE NEVER SEEMS TO DISSOLVE FAST ENOUGH. WE TRY TO SPEED UP ENVIRONMENTAL CLEANUP AND RETARD RUST AND AGING. IN OTHER WORDS, **RATES MATTER!**


"AT FIRST SIGHT, NOTHING SEEMS MORE OBVIOUS THAN THAT EVERYTHING HAS A BEGINNING AND AN END."

—SVANTE ARRHENIUS, 1903 NOBEL PRIZE WINNER IN CHEMISTRY

WHAT'S THE RATE OF A CHEMICAL REACTION? WE BEGIN WITH THE ULTRA-SIMPLE CASE OF ONLY ONE REACTANT:

$A \longrightarrow$ PRODUCTS

HERE THE **REACTION RATE** $r_A$ IS THE RATE AT WHICH REACTANT **A** IS USED UP OVER TIME. IT MAY BE EXPRESSED IN MOLES PER SECOND.

IF **A** IS IN SOLUTION, $r_A$ USUALLY REFERS TO THE RATE AT WHICH CONCENTRATION [A] CHANGES, IN MOLES PER LITER PER SECOND, AND IF **A** IS A GAS, $r_A$ MAY REFER EITHER TO CONCENTRATION OR PARTIAL PRESSURE $P_A$, WHICH AMOUNT TO THE SAME THING.


FOR EXAMPLE, IN THE LOWER ATMOSPHERE, SUNLIGHT FALLING ON NITROGEN DIOXIDE, $NO_2$, CAUSES IT TO BREAK INTO NITRIC OXIDE, NO, AND A LOOSE OXYGEN ATOM (CALLED A FREE RADICAL):

$$NO_2 \xrightarrow{\text{LIGHT}} NO + O$$

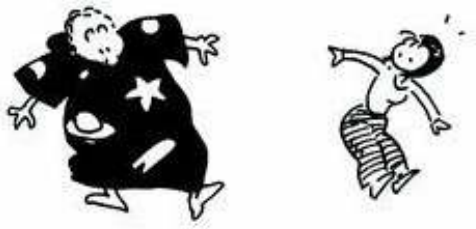
(THE FREE OXYGEN GOES ON TO BIND WITH $O_2$ TO FORM OZONE, $O_3$. OZONE AND THE NITROGEN OXIDES ARE AMONG OUR NASTIER AIR POLLUTANTS.)

AT MIDDAY, $NO_2$ MAKES UP ABOUT 20 PARTS PER BILLION OF THE AIR—20 MOL OF $NO_2$ PER BILLION MOL OF AIR—OR 20 MOL OF $NO_2$ IN $24.4 \times 10^9$ L OF AIR (AT 25°C). SO MOLAR CONCENTRATION IS $[NO_2] = 20/(24.4 \times 10^9) = 8.2 \times 10^{-10}$ MOL/L. LET'S TAKE AN AIR SAMPLE, AND MEASURE $[NO_2]$ EVERY 40 SECONDS AS IT DECOMPOSES. WE WRITE $[A]_t$ FOR THE CONCENTRATION OF $NO_2$ AT TIME t.


| t (SEC.) | $[A]_t$ ($\times 10^{-10}$ MOL/L) | |
|---|---|---|
| 0 | 8.20 | $[A]_0$ |
| 40 | 5.80 | |
| 80 | 4.10 | $([A]_0)/2$ |
| 120 | 2.90 | |
| 160 | 2.05 | $([A]_0)/4$ |
| 200 | 1.45 | |
| 240 | 1.02 | $([A]_0)/8$ |
| 280 | .72 | |
| 320 | .51 | $([A]_0)/16$ |
| 360 | .36 | |

THE REACTION CERTAINLY SLOWS OVER TIME. IN $10^{10}$ LITERS OF AIR, **2.4** MOL ($[A]_0 - [A]_{40}$) WERE USED UP IN THE FIRST 40 SEC., BUT ONLY **0.21** MOL IN THE 40 SECONDS BETWEEN $t = 280$ AND $t = 320$ ($[A]_{280} - [A]_{320}$).

THE DECLINE HAS A PATTERN: **HALF THE REMAINING REACTANT IS CONSUMED EVERY 80 SECONDS.** AT $t = 80$ SEC., HALF THE $NO_2$ IS LEFT... AT 160 SEC., A FOURTH REMAINS... AT 240, AN EIGHTH, ETC. WE SAY THE REACTION HAS A **HALF-LIFE,** h, OF 80 SECONDS. DURING **ANY** INTERVAL OF LENGTH h, HALF THE REACTANT IS CONSUMED. IN n HALF LIVES, THEN:



$$[A]_{nh} = (1/2)^n [A]_0$$

n HALF LIVES

# Chapter 9
# Acid Basics

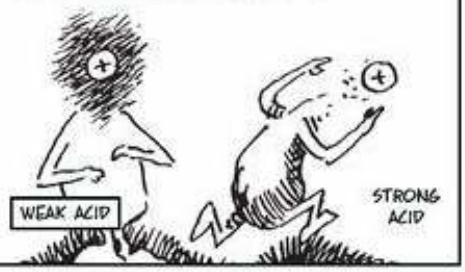
ACIDS, SOUR AND AGGRESSIVE, ARE EVERYWHERE: IN SALAD DRESSING, RAINWATER, CAR BATTERIES, SOFT DRINKS, AND YOUR STOMACH. THEY CAN BURN, CORRODE, DIGEST, OR ADD A PLEASANT TANG TO FOOD AND DRINK...

BASES, BITTER AND SLIPPERY, MAY BE LESS FAMILIAR, BUT ARE EXACTLY AS COMMON AS ACIDS. YOU'LL FIND THEM IN BEER, BUFFERIN, SOAP, BAKING SODA, AND DRAIN CLEANERS...

ACIDS AND BASES ARE SOMETIMES USEFUL, OFTEN HARMFUL, AND ALWAYS A GREAT OPPORTUNITY TO PLAY WITH EQUILIBRIUM CONSTANTS!

ACIDS AND BASES ARE INTIMATELY CONNECTED VIA PROTONS, I.E., HYDROGEN IONS, $H^+$.

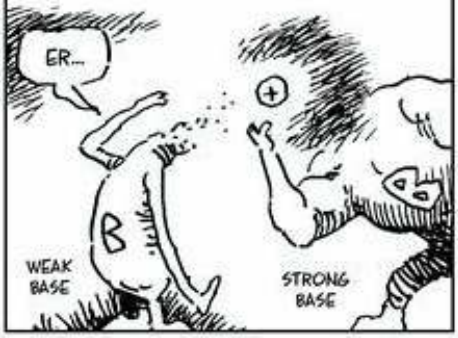
AN **ACID** IS ANY SUBSTANCE THAT THROWS OFF PROTONS. THE STRONGER THE ACID, THE MORE EASILY IT SHEDS $H^+$.



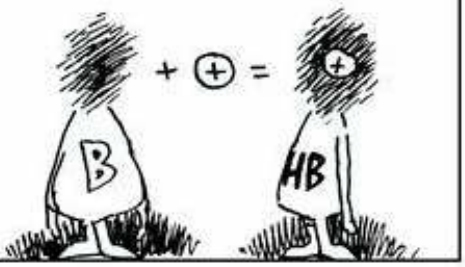

SINCE NAKED PROTONS ARE WILD, AGGRESSIVE CREATURES, STRONG ACIDS ARE VERY REACTIVE.


A **BASE** IS ANY SUBSTANCE THAT TAKES UP PROTONS. BASES GENERALLY HAVE AN EXPOSED ELECTRON PAIR WHERE A PROTON CAN NESTLE.


THE STRONGER THE BASE, THE MORE STRONGLY IT WANTS TO BOND TO A PROTON.




AS YOU CAN SEE, AN ACID IS JUST A PROTON ATTACHED TO A BASE! AN ACID AND BASE PAIRED IN THIS WAY ARE CALLED **CONJUGATE** TO EACH OTHER.




BY DEFINITION, THE STRONGER AN ACID, THE WEAKER ITS CONJUGATE BASE, AND VICE VERSA.

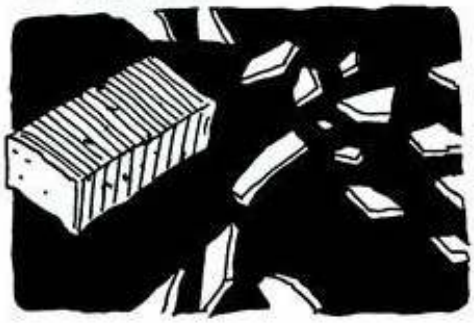

STRONG ACID, WEAK CONJUGATE BASE, LOOSE PROTON

WEAK ACID, STRONG CONJUGATE BASE, TIGHTLY BOUND PROTON

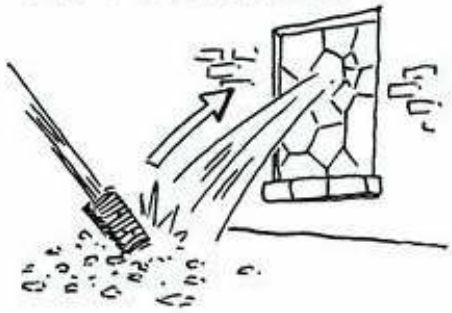
# Chapter 10
# Chemical Thermodynamics


THE REASSURING THEME OF THIS CHAPTER IS: THE UNIVERSE GETS **LESS IMPROBABLE** ALL THE TIME.

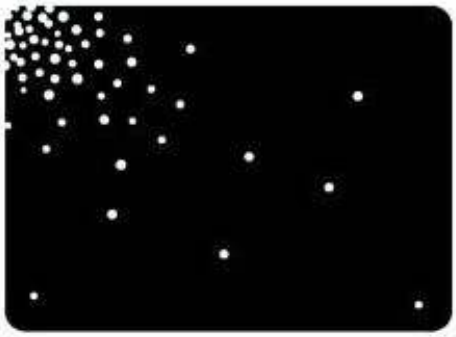
FOR EXAMPLE, A BRICK FLIES THROUGH A WINDOW, AND THE GLASS SHATTERS AND GOES FLYING.



YOU NEVER SEE A BRICK HIT A PUDDLE OF GLASS FRAGMENTS AND CAUSE THEM TO FLY UP TO MAKE A WINDOW!



OR: SOME AIR IS LET INTO A VACUUM CHAMBER AND QUICKLY FILLS UP THE SPACE.



YOU NEVER SEE ALL THE AIR IN A ROOM FLY INTO THE CORNER. (OR IF YOU DO, YOU DON'T LIVE TO TELL THE TALE.)


THE REASON IS THE SAME IN BOTH CASES: THERE ARE MANY, MANY, **MANY** MORE WAYS FOR THINGS TO **FLY APART** OR **SPREAD OUT** THAN THERE ARE FOR THEM TO FLY TOGETHER AND GET CONCENTRATED. SPREADING OUT IS VASTLY MORE PROBABLE. IT'S A GENERAL PRINCIPLE OF THE UNIVERSE:

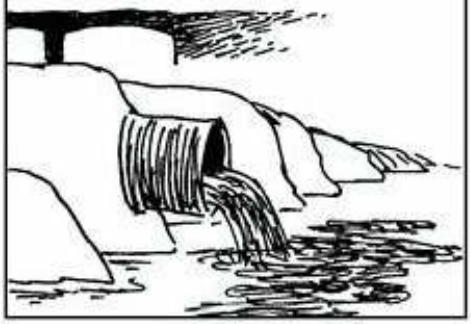
**Spontaneous processes tend to spread things out.**

YOU MAY OBJECT:

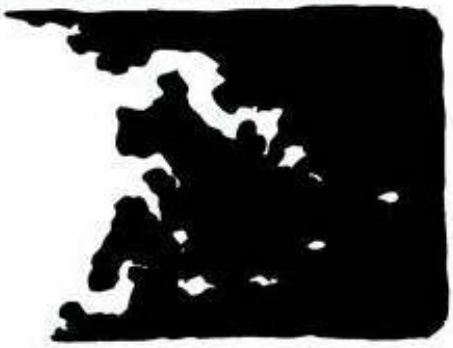
YOU MAY OBJECT THAT PICKING UP A BROOM AND SWEEPING THE GLASS SPLINTERS TOGETHER IS A CONCENTRATING PROCESS. AND YOU'D BE RIGHT.

BUT I REPLY THAT IN ORDER TO SWEEP, I HAVE TO MOVE MY BODY. MOVING INVOLVES CHEMICAL REACTIONS THAT SPREAD HEAT INTO THE ENVIRONMENT.

IN FACT, I COULDN'T HAVE MOVED IN THE FIRST PLACE WITHOUT EATING, AND EATING GENERATES WASTE THAT GETS SPREAD AROUND TOO.



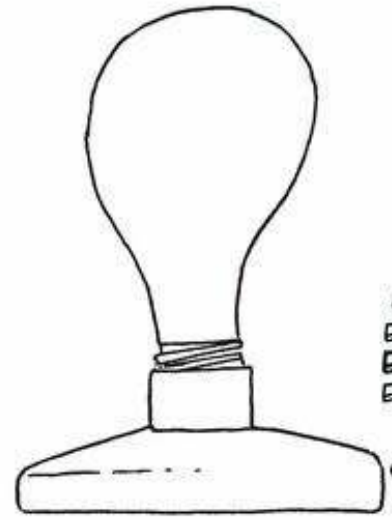
THE FOOD I EAT ULTIMATELY DEPENDS ON SOLAR ENERGY, WHICH SPREADS A TERRIFIC AMOUNT OF MATTER AND ENERGY INTO THE UNIVERSE.



YOU HAVE TO LOOK AT THE BIG PICTURE! ANY PROCESS THAT CONCENTRATES MATTER AND/OR ENERGY IN A SYSTEM IS **MORE THAN OFFSET** BY A GREATER AMOUNT OF SPREADING-OUT ELSEWHERE IN THE UNIVERSE. **THE OVERALL EFFECT IN THE UNIVERSE AS A WHOLE IS TO SPREAD THINGS OUT.**

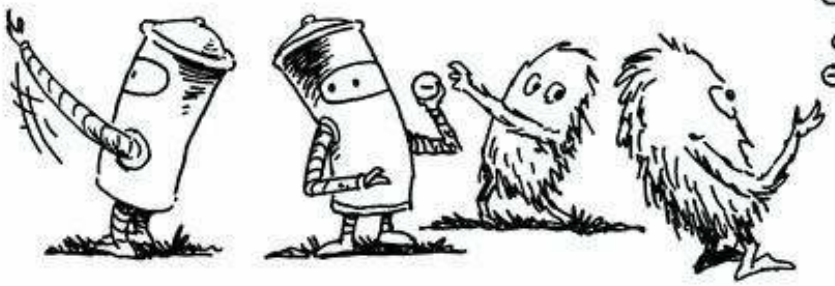
# Chapter 11
# Electrochemistry

IN WHICH LIGHTS BLAZE AND BELLS RING, UNTIL THE BATTERY RUNS DOWN...



IN THE LAST CHAPTER, WHEN WE SAID ENERGY COULD BE EXTRACTED FROM CHEMICAL REACTIONS, WE SECRETLY HAD A CERTAIN KIND OF ENERGY IN MIND: **ELECTRICAL** ENERGY.

REACTIONS THAT MOVE ELECTRONS AROUND, YOU MAY RECALL FROM CHAPTER 4, ARE CALLED **REDOX REACTIONS.** REDOX REACTIONS TRANSFER ELECTRONS FROM ONE ATOM TO ANOTHER, AND WE WOULD LIKE TO MAKE THAT TRANSFER HAPPEN BY A ROUNDABOUT PATH, PASSING THROUGH A LIGHT BULB, FOR INSTANCE!



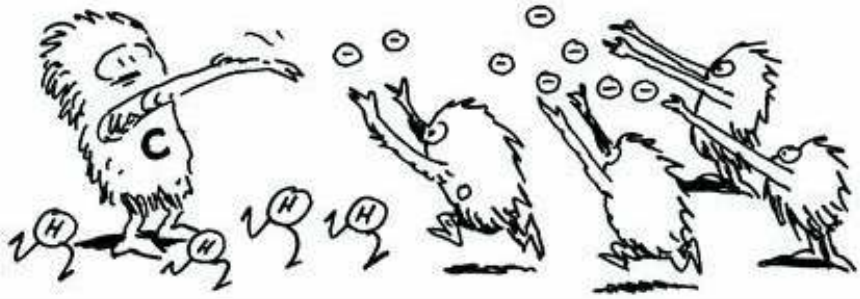
# Redox Redux

REDOX IS SHORT FOR **REDUCTION-OXIDATION.** IN A REDOX REACTION, THE ATOM DONATING THE ELECTRONS IS OXIDIZED, AND THE ONE ACCEPTING THEM IS REDUCED.


AN ATOM'S **OXIDATION NUMBER** IS THE NUMBER OF EXCESS CHARGES DUE TO THE LOSS OR GAIN OF ELECTRONS. FOR INSTANCE:

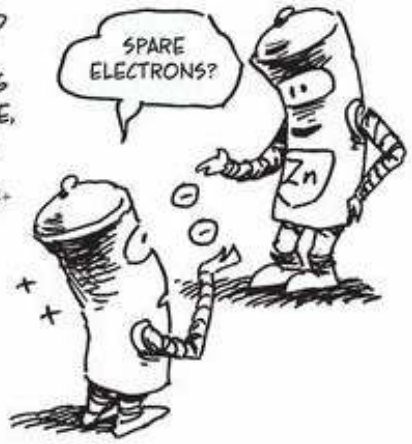
$$\underset{-4\ \ +1}{CH_4} + \underset{0}{2O_2} \longrightarrow \underset{+4\ \ -2}{CO_2} + \underset{+1\ \ -2}{2H_2O}$$


ON THE LEFT SIDE OF THE EQUATION, OXYGEN'S NUMBER IS ZERO. EACH OXYGEN ATOM TAKES ON TWO ELECTRONS AND SO IS REDUCED TO -2. THESE EIGHT ELECTRONS (2 X 4) COME FROM CARBON AND OXIDIZE IT FROM -4 TO +4. HYDROGEN IS NEITHER OXIDIZED NOR REDUCED.

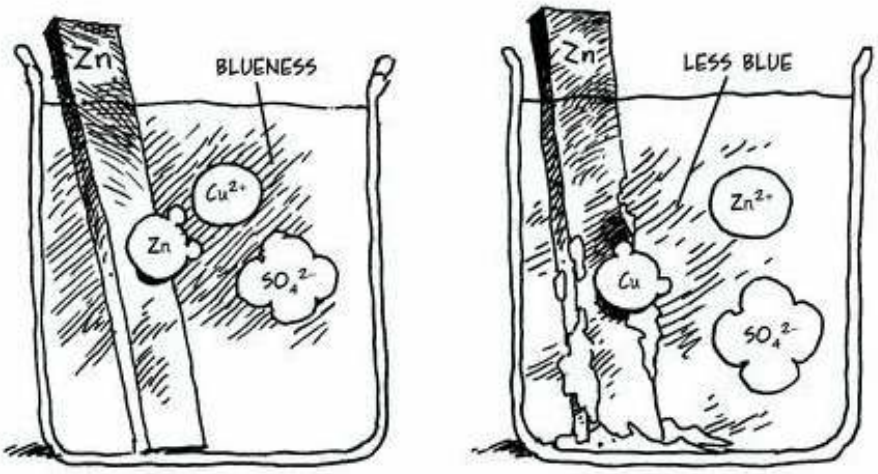


IN CHAPTER 4, WE SAW OXIDATIONS PERFORMED MOSTLY BY NON-METALS LIKE OXYGEN, BUT REDOX REACTIONS ARE ALSO COMMON AMONG **METALS AND THEIR IONS.** FOR EXAMPLE, ZINC SHEDS ELECTRONS MORE READILY THAN COPPER. WHEN Zn MEETS A $Cu^{2+}$ ION, TWO ELECTRONS JUMP FROM ZINC TO COPPER. $Cu^{2+}$ **OXIDIZES** Zn, AND Zn **REDUCES** $Cu^{2+}$.

$$Zn + Cu^{2+} \longrightarrow Zn^{2+} + Cu$$




IF A ZINC BAR IS IMMERSED IN A SOLUTION OF COPPER (II) SULFATE,* $CuSO_4$, THE ZINC METAL SLOWLY OXIDIZES AND DISSOLVES, WHILE COPPER IONS PICK UP ELECTRONS AND FALL OUT OF SOLUTION AS PURE METALLIC COPPER.




IN THIS REACTION, ELECTRONS MOVE STRAIGHT FROM ONE ATOM OR ION TO ANOTHER. BUT NOW WE DO SOMETHING CLEVER: **SEPARATE** THE OXIDATION FROM THE REDUCTION, BUT CONNECT THE REACTION SITES BY A CONDUCTING WIRE.

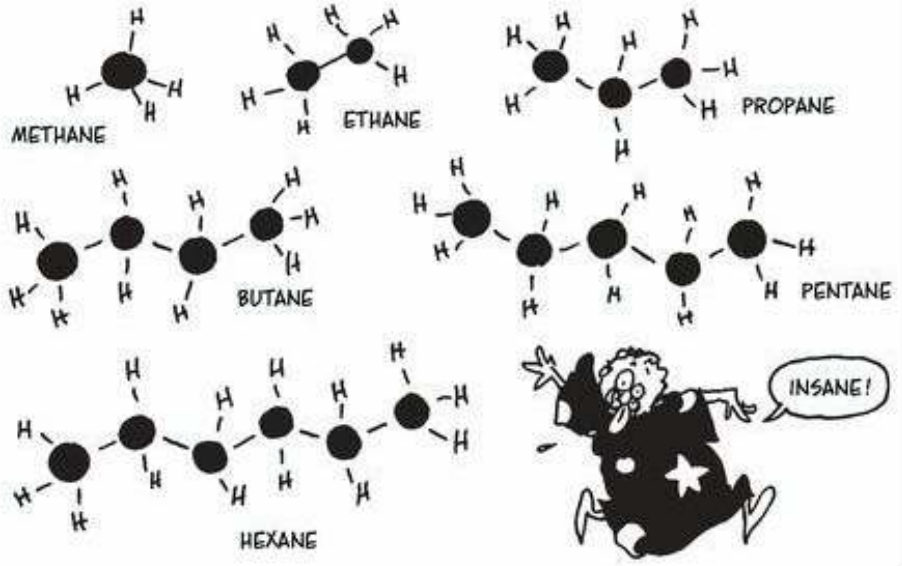
*IT'S BLUE, BY THE WAY!

# Chapter 12
# Organic Chemistry

IT'S ALIVE... OR IS IT?

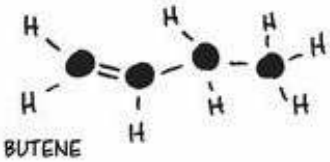
OF THE NINETY-TWO NATURALLY OCCURRING ELEMENTS, SOME HAVE COMMANDED MORE OF OUR ATTENTION THAN OTHERS: HYDROGEN, FOR ITS ROLE IN ACIDS; OXYGEN, FOR ITS REACTIVITY AND LOVE OF HYDROGEN; BUT ONLY ONE ELEMENT DESERVES ITS VERY OWN BRANCH OF CHEMISTRY: **CARBON.**

THANKS TO ITS FOUR OUTER ELECTRONS, CARBON ATOMS CAN BOND WITH EACH OTHER TO FORM LONG CHAINS, WITH OTHER ATOMS ATTACHED TO THE LEFTOVER ELECTRONS. THE SIMPLEST OF THESE CHAINS ARE THE **HYDROCARBONS,** WHICH CONTAIN NOTHING BUT CARBON AND HYDROGEN.

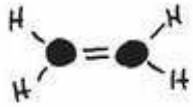



**CRUDE OIL** IS MADE MAINLY OF HYDROCARBONS. SINCE LONG CHAINS HAVE HIGHER BOILING POINTS THAN SHORT ONES, OIL REFINERIES CAN SEPARATE ("FRACTIONATE") THEM BY LENGTH AND THEN CHEMICALLY "CRACK" THE LONG CHAINS INTO SHORTER ONES. GASOLINE IS A MIXTURE OF CHAINS WITH 5 - 10 CARBONS (OCTANE HAS 8).

HYDROCARBONS LIKE THOSE ON THE PREVIOUS PAGE, WITH SINGLE BONDS ONLY, ARE CALLED **ALKANES***. A DOUBLE BOND TURNS AN ALKANE INTO AN ALK**ENE**, AND A TRIPLE BOND MAKES IT AN ALK**YNE**. INDIVIDUAL MOLECULES ARE NAMED ACCORDINGLY.



BUTENE



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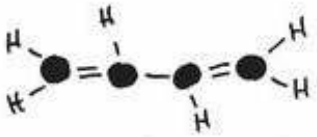
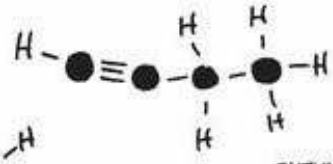


BUTADIENE (TWO DOUBLE BONDS)



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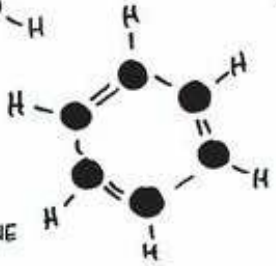
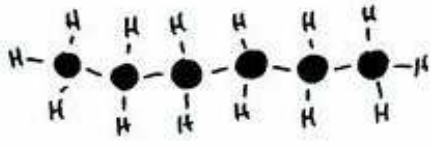
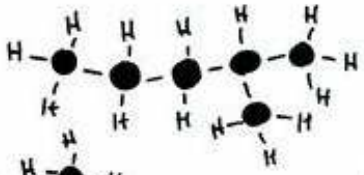


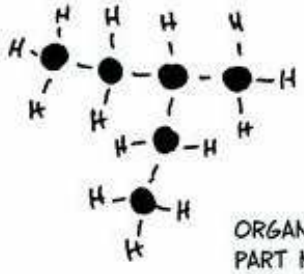
BENZENE

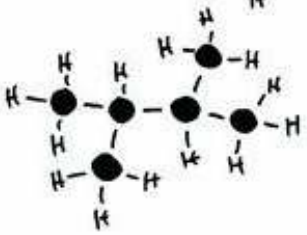
RING-SHAPED STRUCTURES HAPPEN TOO!

TO COMPLICATE MATTERS FURTHER, TWO COMPOUNDS WITH THE SAME CHEMICAL FORMULA CAN HAVE DIFFERENT STRUCTURES. VARIANTS OF THE "SAME" MOLECULE ARE CALLED **ISOMERS**.









ORGANIC CHEMISTRY IS PART CHEMISTRY, PART NAME GAME, AND PART GEOMETRY!

*THEY ARE ALSO CALLED SATURATED HYDROCARBONS, SINCE THEY HAVE THE MAXIMUM POSSIBLE NUMBER OF HYDROGENS. ANYTHING WITH A DOUBLE OR TRIPLE BOND IS CALLED UNSATURATED.

# Index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**Larry Gonick** has been creating comics that explain history, science, and other big subjects for over thirty years—he wrote his first guide in 1971: *Blood from a Stone: A Cartoon Guide to Tax Reform.* He has been a Knight Science Journalism Fellow at MIT and is currently staff cartoonist for *Muse* magazine.
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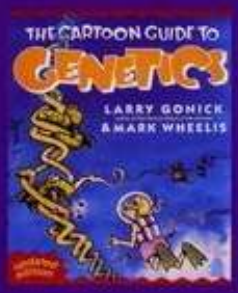


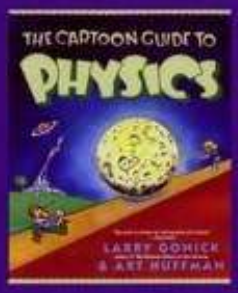


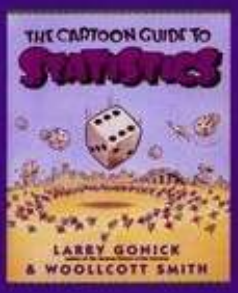


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