Mathematics and Science in Schools in Sub-Saharan Africa
Material Science

POLYMERS
Examples
Lab: Which Polymer is Which?
Lab: Which Polymer is Which?

*Data Chart*

<table>
<thead>
<tr>
<th>Polymer (Before)</th>
<th>Polymer (After)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Poly & Mer
# Elements Found in Polymers

<table>
<thead>
<tr>
<th>H</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>Be</td>
</tr>
<tr>
<td>Na</td>
<td>Mg</td>
</tr>
<tr>
<td>K</td>
<td>Ca</td>
</tr>
<tr>
<td>Sc</td>
<td>Ti</td>
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<tr>
<td>V</td>
<td>Cr</td>
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<tr>
<td>Mn</td>
<td>Fe</td>
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<tr>
<td>Co</td>
<td>Ni</td>
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<tr>
<td>Cu</td>
<td>Zn</td>
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<tr>
<td>Ga</td>
<td>Ge</td>
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<tr>
<td>As</td>
<td>Se</td>
</tr>
<tr>
<td>Br</td>
<td>Kr</td>
</tr>
<tr>
<td>Rb</td>
<td>Sr</td>
</tr>
<tr>
<td>Y</td>
<td>Zr</td>
</tr>
<tr>
<td>Nb</td>
<td>Mo</td>
</tr>
<tr>
<td>Tc</td>
<td>Ru</td>
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<tr>
<td>Rh</td>
<td>Pd</td>
</tr>
<tr>
<td>Ag</td>
<td>Cd</td>
</tr>
<tr>
<td>In</td>
<td>Sn</td>
</tr>
<tr>
<td>Sb</td>
<td>Te</td>
</tr>
<tr>
<td>I</td>
<td>Xe</td>
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<tr>
<td>Cs</td>
<td>Ba</td>
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<tr>
<td>La</td>
<td>Ce</td>
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<td>Pr</td>
<td>Nd</td>
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<td>Pm</td>
<td>Sm</td>
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<td>Eu</td>
<td>Gd</td>
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<td>Tb</td>
<td>Dy</td>
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<tr>
<td>Ho</td>
<td>Er</td>
</tr>
<tr>
<td>Tm</td>
<td>Yb</td>
</tr>
<tr>
<td>Lu</td>
<td>Ac</td>
</tr>
<tr>
<td>Th</td>
<td>Pa</td>
</tr>
<tr>
<td>U</td>
<td>Np</td>
</tr>
<tr>
<td>Pu</td>
<td>Am</td>
</tr>
<tr>
<td>Cm</td>
<td>Bk</td>
</tr>
<tr>
<td>Cf</td>
<td>Es</td>
</tr>
<tr>
<td>Fm</td>
<td>Md</td>
</tr>
<tr>
<td>No</td>
<td>Lr</td>
</tr>
</tbody>
</table>
## Material Comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>Metals</th>
<th>Ceramics</th>
<th>Polymers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements</td>
<td>Metals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composition</td>
<td>Elements &amp; Compounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>Crystalline</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bonding</td>
<td>Metallic</td>
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<td>Metals &amp; Nonmetals</td>
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<tr>
<td>Composition</td>
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<td>Compounds or Mixture of Compounds</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
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<td>Crystalline or Amorphous</td>
<td></td>
</tr>
<tr>
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<td><strong>Composition</strong></td>
<td>Elements &amp; Compounds</td>
<td>Compounds or Mixture of Compounds</td>
<td>Mostly Compounds</td>
</tr>
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<td>Crystalline</td>
<td>Crystalline or Amorphous</td>
<td>Mostly Amorphous</td>
</tr>
<tr>
<td><strong>Bonding</strong></td>
<td>Metallic</td>
<td>Ionic &amp; Network Covalent</td>
<td>Covalent with Weak Intermolecular</td>
</tr>
</tbody>
</table>
Natural Polymers
Natural Polymers
Artificial Polymers

Rayon

200X
Polymer History
1839

Charles Goodyear
1907

Dr. Leo Baekeland

Bakelite- the first synthetic plastic.
Radios, telephones and electrical insulators were made of Bakelite in the past due to its insulating and heat-resistant properties.
Used X-ray crystallography to discover the chemical structure of cellulose—a long chain molecule.
Staudinger’s classic paper “Uber Polymerization” presented the world the development of the modern polymer theory.
1927

Large scale production of polyvinyl-chloride (PVC) resins begins.
1930

Polystyrene is invented.
Styrofoam
1938

Wallace Carothers of Dupont company produces nylon.
Nylon
1941

Polyethylene is produced.
Polyethylene
1970

James Economy develops Ekonol.
Ekonal

A moldable polymer that has no observable melting point!

Leads to the development of liquid crystal polymers 1 year later.
1971

Aramid
Aramid

Kevlar
1976

Polymer/plastic industry passes steel as the nation’s most widely used material.
Now we use more plastic than steel, aluminum and copper combined!
Carbon-Fiber
Plastics Usage in Cars

Automotive Usage (lbs.)

Year

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Usage (lbs.)</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>200</td>
<td>250</td>
</tr>
</tbody>
</table>
Strongest Material?

![Bar chart comparing the strength of different materials in GPa (log scale)].

- Carbon Nanotubes: 200
- Graphite Fibers: 4.7
- Aramid (Kevlar): 3.4
- Stainless Steel: 1.5
Carbon Nanotube Application

Anti-Ballistic Materials
Bullet-proof jackets stop bullets from penetrating by spreading the bullet's force.

Targets can still be left suffering blunt force trauma, perhaps severe bruising or, worse, damage to critical organs.
Scientists use the elasticity of carbon nanotubes to not only stop bullets from penetrating but to actually rebound their force.
A polymer that transforms into a fireproof ceramic.
HIPS Coating

Hybrid Inorganic Polymer System

Withstand temperatures over 1000ºC!
Lithium-ion Battery Fires
2011

Touchscreens
Touchscreens that contain carbon nanotubes can be made of low-priced renewable raw materials.
Flexible plastic electronics!

2011
The bilayer dielectric is made of a fluorinated polymer known as CYTOP.
The bilayer dielectric is also made with a High-k metal oxide layer.
Alone, each substance has its drawbacks but together, each substance retains its benefits and their drawbacks are cancelled out!
Medical Applications

Longevity Highly Crosslinked Polyethylene Surface

Linear Wear (Laboratory Testing)

mm/million cycles

<table>
<thead>
<tr>
<th>Material</th>
<th>Linear Wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal-On-Longevity Highly Crosslinked Polyethylene</td>
<td>.001</td>
</tr>
<tr>
<td>Metal-On-Metal</td>
<td>.004</td>
</tr>
<tr>
<td>Ceramic-On-Ceramic</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

1. Data on file at Zimmer, Inc.
The NanoTech Institute recently announced the development of artificial muscle tissue that is 100 times stronger than natural human muscles.

Applications: artificial limbs and perhaps even artificial heart tissue.
Cancer Cells

One of cancer's cleverest tricks is its ability to hide from the immune system.
Researchers have developed a polymer implant that attracts and trains immune-system cells to go after cancer.
The macroporous poly-lactide-co-glycolide (PLG) polymeric matrix used in the study has a history of safe use in humans.
The implant could also be used to treat diseases such as arthritis and diabetes, and, potentially, to train other kinds of cells, including stem cells used to repair damage to the body.
Artificial bone marrow that can continuously make red and white blood cells has been created in a University of Michigan lab.
First, scientists create biodegradable scaffolds.
The scaffolds are then seeded with artificial bone marrow cells and osteoblasts, another type of bone marrow cell.
It is designed to function in a test tube.
Antifreeze Protein

A new protein discovered in tiny snow fleas by Queen’s University researchers may lengthen the shelf life of human organs for transplantation.
Construction Applications
Conventional means of internal reinforcement for concrete member in buildings involve steel bars (Rebar).
Fiber Reinforced Polymer (FPR)
Liquid Wood
Liquid Wood

Most plastics are based on petroleum.
Liquid Wood

Produce plastic granulate that can be melted and injection-molded.
Metal Rubber

*Polymer chemists have created a flexible, indestructible material called metal rubber.*
Metal Rubber

*It can be heated, frozen, washed or doused with jet fuel, and still retain its electricity-conducting properties.*
To make metal rubber, chemists and engineers use a process called self-assembly.

The material is repeatedly dipped into positively charged and negatively charged solutions. The positive and negative charges bond, forming layers that conduct electricity.
Uses of metal rubber include electrically charged aircraft wings, artificial muscles and wearable computers.
Industrially Important Polymers

These polymers are produced in high volume at very low cost.
Industrially Important Polymers

About 85% of the world plastics consumption is from just four polymers.
# Industrially Important Polymers

<table>
<thead>
<tr>
<th>POLYMER</th>
<th>MER</th>
<th>APPLICATIONS</th>
</tr>
</thead>
</table>
| Polyethylene (PE)      | \[
\begin{array}{c}
\text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{n}
\end{array}
\]

| Polypropylene (PP)     | \[
\begin{array}{c}
\text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{H} \\
\text{CH}_3
\end{array}
\]

- electrical wire insulation, flexible tubing, squeeze bottles
- carpet fibers, ropes, pipes liquid containers (cups, buckets, tanks)
# Industrially Important Polymers

<table>
<thead>
<tr>
<th>POLYMER</th>
<th>MER</th>
<th>APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polystyrene (PS)</strong></td>
<td><img src="image" alt="Polystyrene Molecule" /></td>
<td>packaging foams, egg cartons, lighting panels, electrical appliance components</td>
</tr>
<tr>
<td><strong>Polyvinyl Chloride (PVC)</strong></td>
<td><img src="image" alt="Polyvinyl Chloride Molecule" /></td>
<td>bottles, hoses, pipes, valves, electrical wire insulation, toys, raincoats</td>
</tr>
</tbody>
</table>
Polymer Formation

Polymerization
Free Radical Polymerization

Two bonds between the two carbons ruptures.

Two free radicals meet, they can form a dimer with a new covalent bond linking the two.
Free Radical Polymerization

- Ethylene

\[
\begin{align*}
\text{polymerization} \\
R-\text{O-}C-C(C-C)C-C-C-C-C(C-C)C-C\text{-O-}R \\
\text{or more simply} \\
\left(\text{H-H}\right)_n \quad n = \text{a very large integer}
\end{align*}
\]

Polyethylene
Lab: Free Radical Polymerization
# Lab: Free Radical Polymerization

## Data Chart

<table>
<thead>
<tr>
<th>NAME</th>
<th>STRUCTURAL FORMULA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vinyl Chloride</td>
<td></td>
</tr>
<tr>
<td>Divinyl Chloride</td>
<td></td>
</tr>
<tr>
<td>Trivinyl Chloride</td>
<td></td>
</tr>
<tr>
<td>PVC</td>
<td></td>
</tr>
</tbody>
</table>
Condensation Polymerization

terephthalic acid

\[
\begin{align*}
\text{O} & \quad \text{O} \\
\text{H} & \quad \text{C}_6\text{H}_4\text{C} \quad \text{O} \\
\text{H} & \quad \text{C} \quad \text{O} \\
\text{H} & \quad \text{H} \\
\end{align*}
\]

glycol

\[
\begin{align*}
\text{H} & \quad \text{C} \quad \text{O} \\
\text{H} & \quad \text{H} \\
\text{H} & \quad \text{C} \quad \text{O} \\
\text{H} & \quad \text{H} \\
\end{align*}
\]

Dacron

\[
\begin{align*}
\text{O} & \quad \text{O} \\
\text{H} & \quad \text{C}_6\text{H}_4\text{C} \quad \text{O} \\
\text{H} & \quad \text{C} \quad \text{O} \\
\text{H} & \quad \text{H} \\
\end{align*}
\]

+ \text{H}_2\text{O}
Condensation Polymerization
Condensation Polymerization

Protein
Lab: Condensation Polymerization
# Lab: Condensation Polymerization

## Data Chart

<table>
<thead>
<tr>
<th>NAME</th>
<th>STRUCTURAL FORMULA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amine</td>
<td></td>
</tr>
<tr>
<td>Carboxyl</td>
<td></td>
</tr>
<tr>
<td>Amino Acid</td>
<td></td>
</tr>
<tr>
<td>Protein</td>
<td></td>
</tr>
</tbody>
</table>
Which Type Polymerization?

polyacrylonitrile

Carbon Fiber Production

Free Radical Polymerization | Condensation Polymerization
Chain Length Factors
Chain Length Factors

Number of Monomers & Initiators.
Lab: Building Sweet Polymer Chains
Lab: Building Sweet Polymer Chains

Data Chart

<table>
<thead>
<tr>
<th>Bag #</th>
<th>Number of Initiators</th>
<th>Number of Chains</th>
<th>Chain Length (# of Monomers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Degree of Polymerization
Polymer Structure
Polymer Atomic Arrangement

Crystalline

Semi-crystalline

Amorphous
Chain Structures

Branched

Linear

Cross-Linked
Lab: Silly Polymer
Copolymers

- Block Copolymer
- Graft Copolymer
- Random Copolymer

Diacid | Diamine

O

C -(CH₂)₄ - C - NH - (CH₂)₆ - NH -
Nylon

\[
\text{HO-C-COOH} + \text{H}_2\text{N-NH}_2 \\
\text{a dicarboxylic acid} \quad \text{a diamine}
\]

\[
\begin{array}{c}
\text{C-O-C} \\
\text{H} \\
\text{N=N} \\
\text{H}
\end{array}
\]

\[n\]

a polyamide
Polymer Configuration

The *cis* configuration arises when substitute groups are on the same side of a carbon-carbon double bond.

*Trans* refers to the substitutes on opposite sides of the double bond.
Photomobile Polymer
Stereoregularity

Isotactic

Syndiotactic

Atactic = ?
Thermal Transitions

- Glassy State
- Crystalline State
- Rubbery State
- Liquid

Specific Volume vs. Temperature

- T_g: Glass Transition Temperature
- T_f: Fusion Temperature
Elastomers show a high degree of elasticity.
Mechanical Properties

- **Fibre**
- **Rigid Plastic**
- **Flexible Plastic**
- **Elastomer**

Graph showing strain vs. stress for different materials. Points A and B indicate different material behaviors.
Elastomers
Lab: 😊 & 😞 Balls
<table>
<thead>
<tr>
<th>Test Ball</th>
<th>Coefficient of Restitution</th>
</tr>
</thead>
<tbody>
<tr>
<td>😊</td>
<td></td>
</tr>
<tr>
<td>😞</td>
<td></td>
</tr>
<tr>
<td>😊</td>
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<td>😊</td>
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<td>😞</td>
<td></td>
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<tr>
<td>😊</td>
<td></td>
</tr>
<tr>
<td>😞</td>
<td></td>
</tr>
</tbody>
</table>
Lab: Elastomers-The Inside Story
Elastomers

Are usually thermosets but may be thermoplastics.
Response to Heat

Thermoplastic Softens or melts with heat

The polymer chains start to relax as they gain energy. They lose some of their crystallinity.
Thermoplastics can be reformed and recycled.
Lab: Shrink to Fit!
Lab: Shrink to Fit 2!
Lab: Thermoplastics
Lab: Thermoplastics

Data Chart

<table>
<thead>
<tr>
<th></th>
<th>After Heating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Heating</td>
<td></td>
</tr>
<tr>
<td>After Heating</td>
<td></td>
</tr>
<tr>
<td>After Cooling</td>
<td></td>
</tr>
</tbody>
</table>
Response to Heat

Thermoset Sets with chemical reaction
Thermosets

Thermosets are not recyclable and are more brittle.
Polymer Production

Polymers are formed by many low temperature processes.
The polymer is heated to the liquid state and forced through a die under pressure.
Extrusion

This results in an endless product of constant cross section.
Extrusion

60% of all polymers are prepared this way. Examples include: tubing, pipes, window frames, insulated wire.
Film Blowing

The material coming out of the die is blown into a film.
This process is used extensively with polyethylene and polypropylene.

An example is plastic wrap.
Injection Molding

Similar to extrusion, the polymer is heated to the liquid state, but it is prepared in metered amounts.
Injection Molding

The melt is forced into a mold to create the part. It is not a continuous process.
Injection Molding

Many toys are made by injection molding.
Blow Molding

A melted polymer is put into a mold.
Blow Molding

Compressed air is used to spread the polymer into the mold.
Blow Molding

This process is used to make many containers such as plastic soda containers and milk jugs.
Compression Molding

A solid polymer is placed in a mold, the mold is heated and puts pressure on the polymer to form the part.
Reaction Injection Molding

- ISO
- Mix Head
- Metering Lance
- POLY
- Mold