# Prototyping in Mechanical Engineering

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# Class 2: Materials

## Space Shuttle *Challenger* disaster

From Wikipedia, the free encyclopedia

*Not to be confused with Space Shuttle Columbia disaster.*

The **Space Shuttle *Challenger* disaster** was a fatal incident in the United States' space program that occurred on January 28, 1986, when the Space Shuttle *Challenger* (OV-099) broke apart 73 seconds into its flight, killing all seven crew members aboard. The crew consisted of five NASA astronauts, and two payload specialists. The mission carried the designation STS-51-L and was the tenth flight for the *Challenger* orbiter.

The spacecraft disintegrated over the Atlantic Ocean, off the coast of Cape Canaveral, Florida, at 11:39 a.m. EST (16:39 UTC). The disintegration of the vehicle began after a joint in its right solid rocket booster (SRB) failed at liftoff. The failure was caused by the failure of O-ring seals used in the joint that were not designed to handle the unusually cold conditions that existed at this launch. The seals' failure caused a breach in the SRB joint, allowing pressurized burning gas from within the solid rocket motor to reach the outside and impinge upon the adjacent SRB aft field joint attachment hardware and external fuel tank. This led to the separation of the right-hand SRB's aft field joint attachment and the structural failure of the external tank. Aerodynamic forces broke up the orbiter.

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# Class 2: Materials

MATERIALS PERFORMANCE

NEWS TOPICS RESOURCES VIDEOS ADVERT

Home / Failed Anchor Rods on the San Francisco-Oakland Bay Bridge: A Corrosion Discussion

Case Histories | Materials Selection & Design

## Failed Anchor Rods on the San Francisco-Oakland Bay Bridge: A Corrosion Discussion

By *Norm Moriber, Technical Editor, and Kathy Riggs Larsen, Editor* on 5/4/2020 1:44 PM

The iconic San Francisco-Oakland Bay Bridge (Bay Bridge) is an 8.4 mile (13.5 km) structure that connects Oakland and San Francisco, California. In October 1989, the Loma Prieta earthquake caused the upper deck of the bridge's East Span to collapse, which resulted in a major construction project that began in 2002 to replace it. Beneath the new East Span road decks at the eastern end of the bridge's Self-Anchored Suspension (SAS) span, there are seismic devices known as bearings and shear keys. The bearings allow the road decks to move slightly during an earthquake, while the shear keys prevent the decks from moving too much.

On March 1, 2013, workers began tensioning the 96 ASTM A354 Grade BD rods fabricated in 2008 for two of the East Span's four shear keys. Shortly after that, it was discovered that 32 of the 96 rods had fractured. Engineers and metallurgists determined the bolts had cracked due to hydrogen embrittlement (HE), which occurs when excess hydrogen, a susceptible material, and tension are present.

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# Movie Break!

# Today's Agenda

- ~~Why are materials important?~~
- Material selection criteria
- Metals
- Plastics / Polymers
- Ceramics
- Composites

# Material Selection Criteria

# Material Selection

- Application specific
- May require multiple materials
  - Coatings on steel
  - Insulation
- May require compromise
- Common things to consider:
  - Price
  - Weight
  - Strength
  - Durability
  - Corrosion
  - Heat
  - Electrical
  - Chemical
  - Other?

# Material Selection: Price

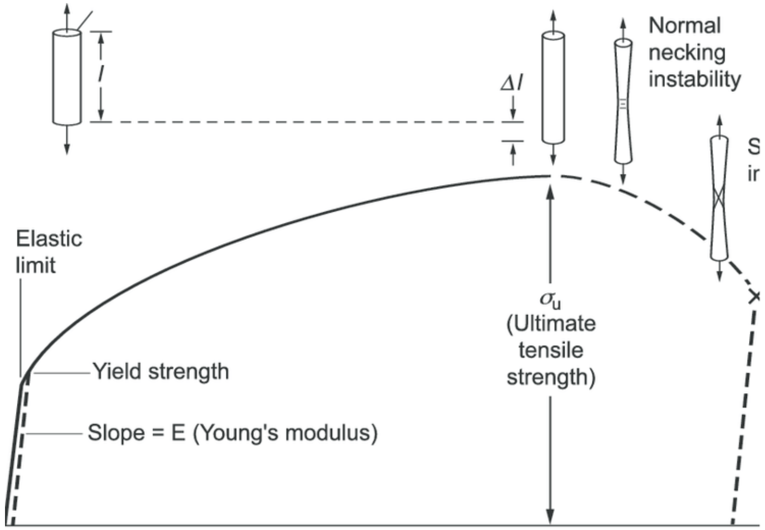
- If you can't afford it, you can't build it
- Materials have the single greatest impact on product price

# Material Selection: "Weight"

- Density
- "Strength to weight ratio"
- Hollow objects

# Material Selection: “Strength”

- Rigidity
- “Strength to weight ratio”
- Tensile strength
- Compressive strength

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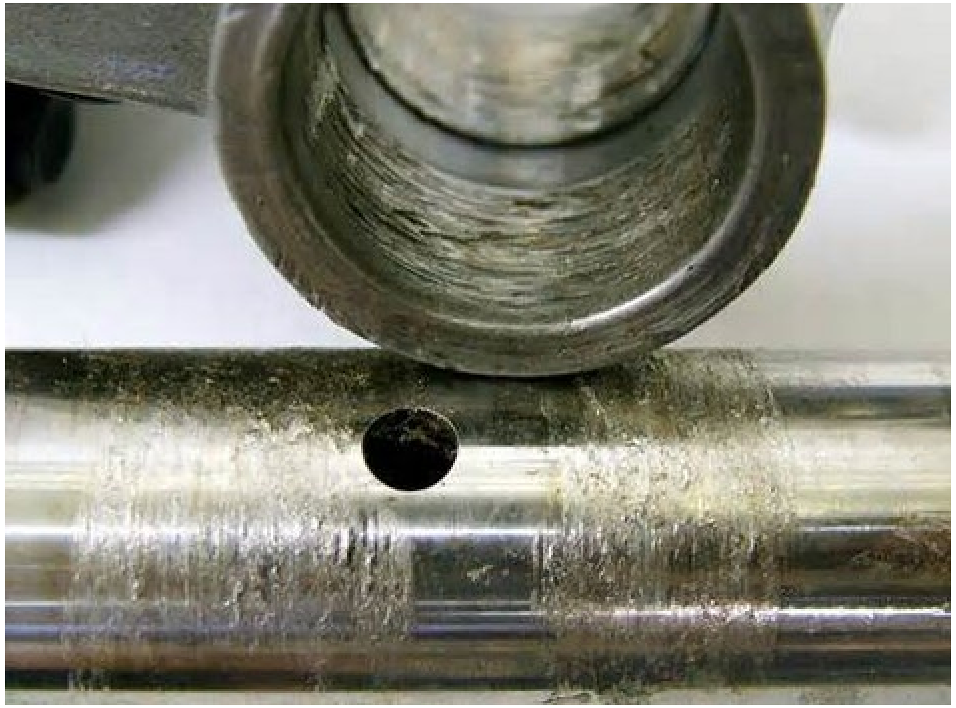
# Material Selection: Durability

- Distinct from strength
- Galling
- Repeated use
- “Resilience”



# Material Selection: Corrosion

- More on this in the metals section

# Material Selection: Heat

- Thermal insulators
- Thermal conductors
- Thermal expansion / dimensional change
- Melting point
  - Flow temperature in thermoplastics
- Specific Heat Capacity

# Material Selection: Workability

- How easy is it to make stuff out of?
  - Machinable
  - Weldable
  - Formable
  - Moldable

# Material Selection: Electrical

- Electrically conductive
- Electrically insulating
- Magnetic properties
- Static discharge potential

# Material Selection: Chemical

- Solubility
- Chemical resistances

**Solvent Compatibility**

| Solvent | ABS | LDPE | HDPE | PC | PMP | PP | PS | PTFE |
|---|---|---|---|---|---|---|---|---|
| Acetaldehyde | D | C | B | C | C | C | D | A |
| Acetic Anhydride | C | D | D | D | B | B | D | A |
| Acetone | D | C | C | D | A | A | D | A |
| Acid, Hydroflouric | C | A | A | D | A | B | D | A |
| Acid, Trifluoroacetic | D | D | C | D | D | D | D | A |
| Acid, Acetic Dilute 50% | A | A | A | B | A | A | B | A |
| Acid, Hydrochloric 37% | C | A | A | D | B | D | C | A |
| Acid, Nitric | B | C | B | B | A | D | C | A |
| Acid, Sulfuric | D | B | A | C | B | C | C | A |
| Alcohol, Ethyl | A | B | A | B | B | B | B | A |
| Alcohol, Isobutyl | A | A | A | B | A | A | B | A |
| Alcohol, Methyl | D | A | A | B | A | A | C | A |
| Alcohol, n-Butyl | A | A | A | C | B | A | B | A |
| Alcohol, Propyl | B | A | A | D | - | A | A | A |
| Ammonium Hydroxide | B | B | A | - | B | B | B | A |
| Aniline | D | B | B | B | B | B | D | A |
| Aqua Regia | D | D | C | D | D | D | D | A |
| Benzaldehyde | B | B | A | C | B | A | D | A |
| Benzene | D | D | D | D | B | B | D | D |
| Carbon Tetrachloride | D | B | C | D | D | B | D | A |
| Caustic Soda (NaOH) | B | B | A | D | A | A | A | A |
| Chlorobenzene | D | D | C | D | C | D | D | A |
| Chloroform | D | C | C | D | D | B | D | A |
| Cyclohexane | A | C | C | D | D | C | D | A |
| Esters | D | B | B | D | B | B | D | A |
| Ether | D | D | C | C | D | D | D | A |
| Ether, Diethyl | D | A | D | D | D | D | D | A |
| Ether, Isopropyl | B | A | A | A | A | D | A | A |
| Ethtyl, Methyl | D | A | B | D | D | B | D | A |
| Hexane | D | D | B | C | C | B | D | A |
| Hydrazine | B | - | - | D | D | C | D | A |
| Hydrogen Peroxide | B | D | A | A | A | A | B | A |
| Methylene Chloride | D | D | C | D | C | C | D | A |
| Petroleum Ether | B | B | A | A | - | A | B | A |
| Phenol | D | D | D | D | D | D | C | A |
| Sodium Hydroxide | B | B | A | D | A | B | A | A |
| Tetrahydrofuran | D | C | B | D | C | B | D | A |
| Toluene | D | C | B | D | C | C | D | A |
| Trichloroethylene | D | D | C | D | D | D | D | A |
| Trimethylpentane | D | C | C | D | C | C | D | A |
| Xylene | D | D | C | D | C | C | D | A |

| | |
|---|---|
| A | No Effect, excellent compatibility |
| B | Minor Effect, good compatibility |
| C | Moderate Effect, fair compatibility |
| D | Severe Effect, not recommended |
| - | No data available |

# Material Selection: Other

- Safety
- Biocompatibility
- Optical properties
- Aesthetics
- Flammability
- Hydrophobicity
- Other other stuff

# Material Selection: Other

- Safety
- Biocompatibility
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# Today's Agenda

- ~~Why are materials important?~~
- ~~Material selection criteria~~
- Metals
- Plastics / Polymers
- Ceramics
- Composites

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# Metal

# Metal

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# Metal

- What is metal?
- Properties
  - Electrically conductive
  - Thermally conductive
  - Ductile
  - Malleable
  - Sectile
  - Alloyable
- Fabrication
  - Covered next week

| Group → ↓ Period | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | H | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | He |
| 2 | Li | Be | | | | | | | | | | | | | | | | | | | | | | | | | B | C | N | O | F | Ne |
| 3 | Na | Mg | | | | | | | | | | | | | | | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| 4 | K | Ca | | | | | | | | | | | | | | | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| 5 | Rb | Sr | | | | | | | | | | | | | | | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |
| 6 | Cs | Ba | La | Ce | Pr | Nd | Pm | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | Po | At | Rn |
| 7 | Fr | Ra | Ac | Th | Pa | U | Np | Pu | Am | Cm | Bk | Cf | Es | Fm | Md | No | Lr | Rf | Db | Sg | Bh | Hs | Mt | Ds | Rg | Cn | Nh | Fl | Mc | Lv | Ts | Og |

**Metal** Metalloid Nonmetal *Unknown properties* **Background color** shows metal–metalloid–nonmetal trend in the periodic table

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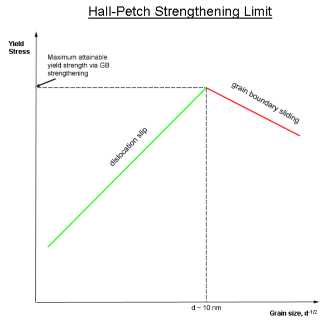
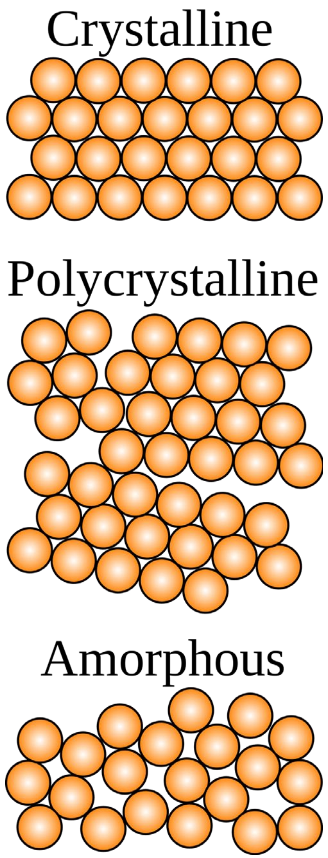
# Metal Grains

- Metal crystals appear as "grains"
- Grains have a significant impact on material properties
  - Large grains reduce "creep"
  - Smaller grains increase "yield strength"
- Grain size can be controlled by processing
  - Work hardening
  - Annealing
  - Quenching







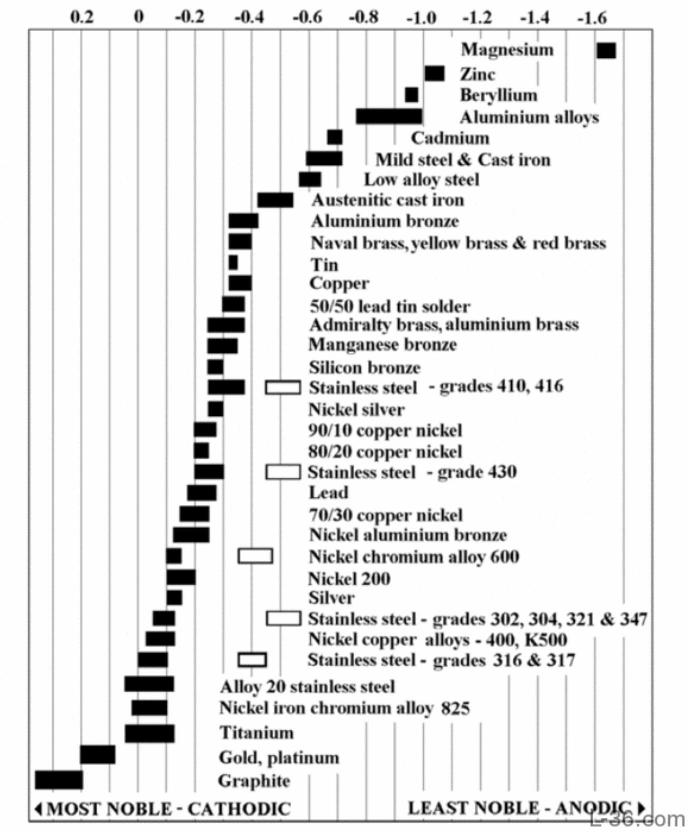
# Metal Oxidation

- Most metals oxidize
  - Noble metals don't
  - Everything else does
- Rust
  - Iron(III) oxide
  - Ferrous metals
- Self-limiting oxides
  - Aluminum
  - Titanium
  - Chromium*
  - Nickel*

| | | | | | |
|---|---|---|---|---|---|
| 25 Mn Manganese | 26 Fe Iron | 27 Co Coblat | 28 Ni Nickel | 29 Cu Copper | 30 Zn Zinc |
| 43 Tc Technetium | 44 Ru Ruthenium | 45 Rh Rhodium | 46 Pd Palladium | 47 Ag Silver | 48 Cd Cadmium |
| 75 Re Rhenium | 76 Os Osmium | 77 Ir Iridium | 78 Pt Platinum | 79 Au Gold | 80 Hg Mercury |
| 107 Bh Bohrium | 108 Hs Hassium | 109 Mt Mietnerium | 110 Ds Darm-stadtium | 111 Rg Roentgenium | 112 Cn Copernicium |

# Metal Oxidation

- Galvanic Corrosion
  - Dissimilar electric potentials
  - In electrical contact
  - In a water-based (aqueous) solution
- Stainless and brass joined in seawater

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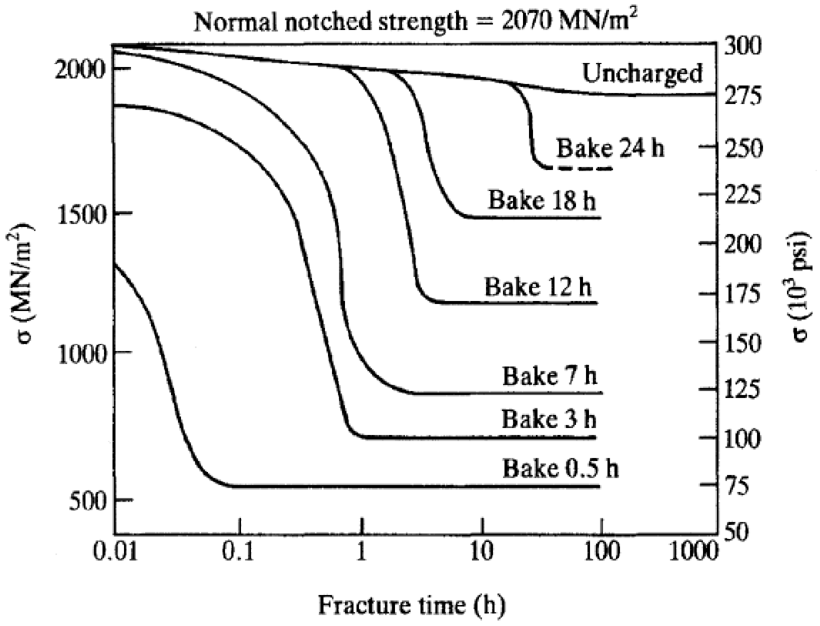
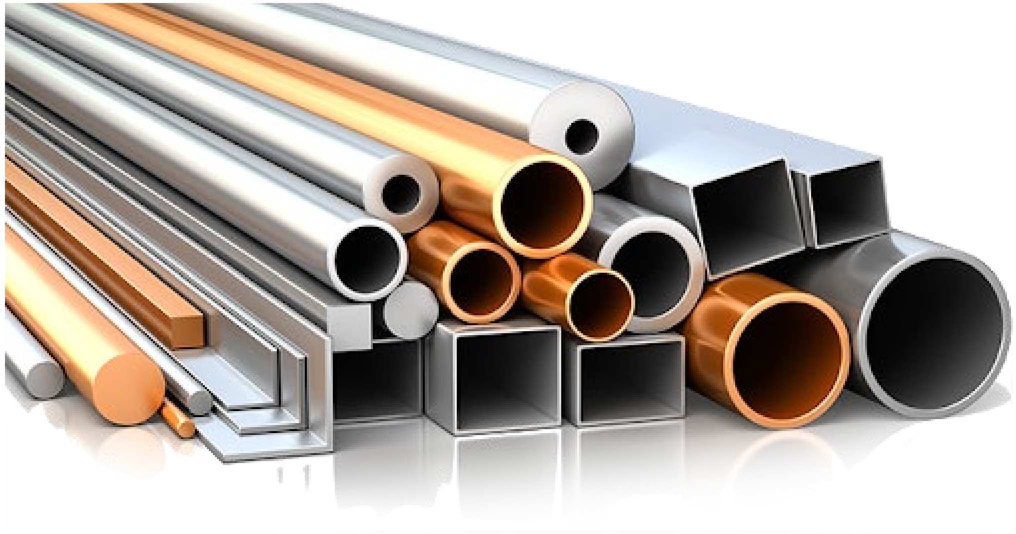
# Hydrogen Embrittlement




- Hydrogen infiltrates the crystal lattice
- Typically from $H_2O$-based electrochemistry
- Not typically too worrisome for most projects (unless you're building a bridge)

# Metal: Ferrous vs. non-ferrous

VS



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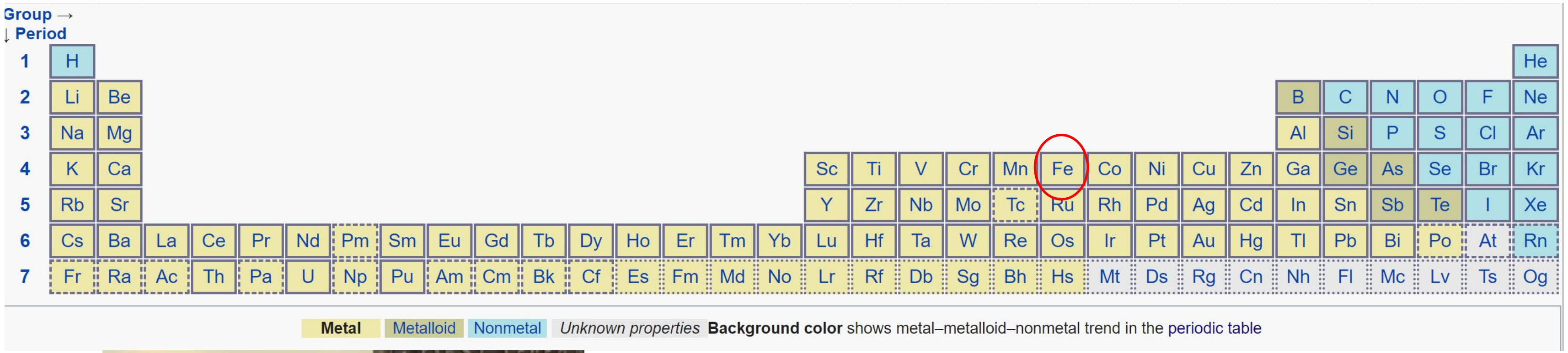
# Metal: Ferrous

- “Iron Age”
- Cast iron
- Wrought iron
- Vibration absorbing

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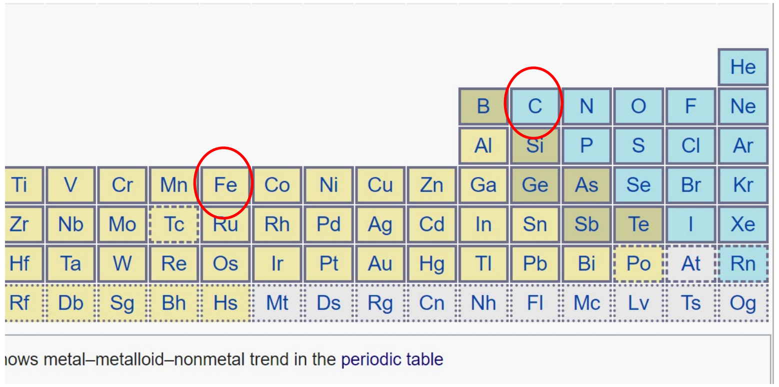
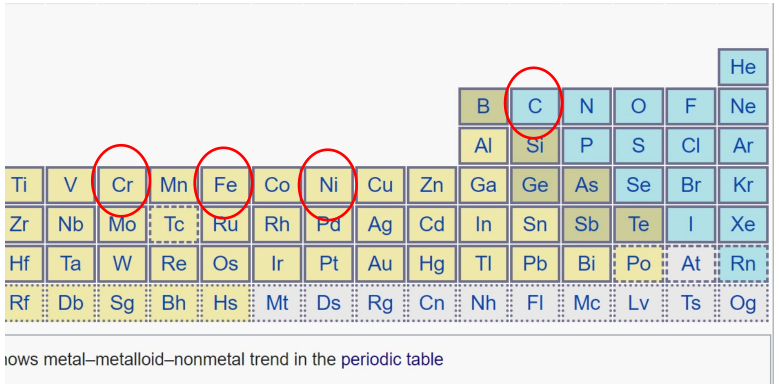
# Metal: Steel

- Iron and carbon
  - Higher carbon (0.6%-1.5%) is usually stronger steel
  - Lower carbon is usually easier to machine/weld
  - SAE 1xxx steels (i.e. 1018)
- Huge variety of steels
  - Alloy Steel
  - Tool Steel
- Rusts unless coated!
  - Galvanized
  - Painted
  - Powder coated
- ISO 4949
- SAE J1086



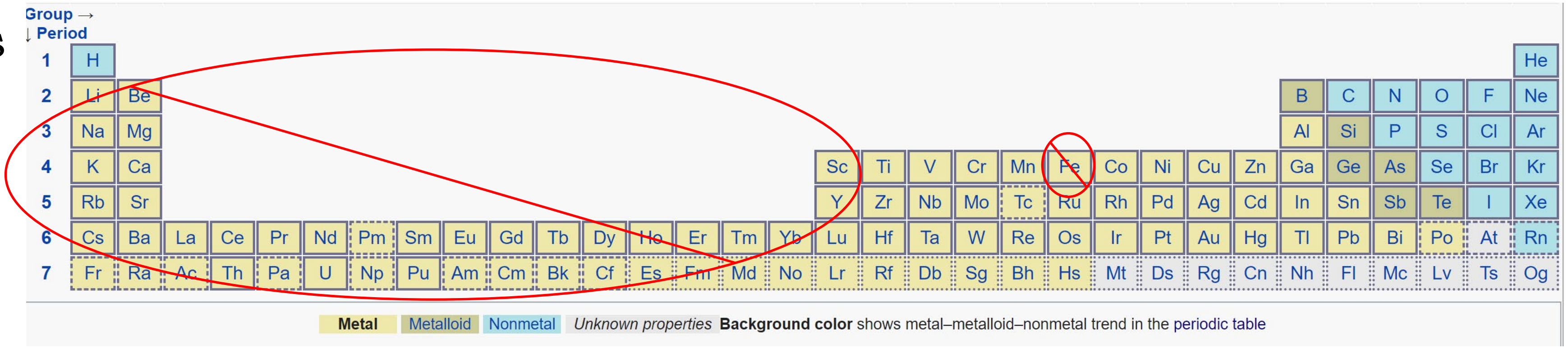
# Metal: Stainless steel

- Iron, carbon, chromium, nickel
  - Martensitic vs. Austenitic
  - Can be non-magnetic
- Huge variety of stainless
  - 304 (aka 18-8, 18% chromium + 8% nickel)
  - 316 (food safe and high corrosion resistance)
  - 416
- Difficult to machine
  - Work hardening
- Difficult to weld
- ISO 4949
- SAE J1086



# Metal: Non-ferrous

- Everything that's not iron-based




- In depth look at:
  - Aluminum
  - Copper alloys
  - Titanium
  - Others

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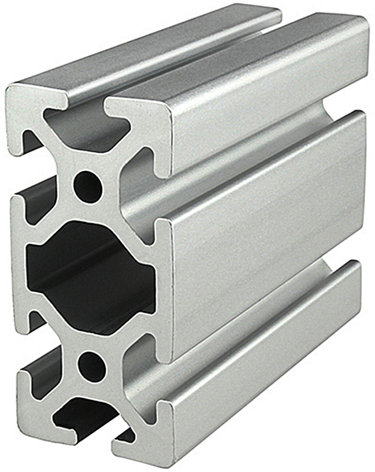
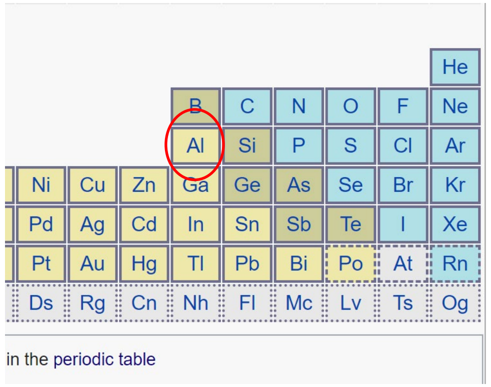
# Metal: Aluminum

- Aluminum is great
  - Easy to machine
  - Harder to weld
  - Very high thermal conductivity
  - Very high electrical conductivity
  - Comes in extrusions
  - Self-limiting oxide
- Grades
  - Different from steel
  - 6061
    - Common use
    - Easy to machine
    - Good all-around
  - 7075
    - High strength
    - “Aircraft aluminum”



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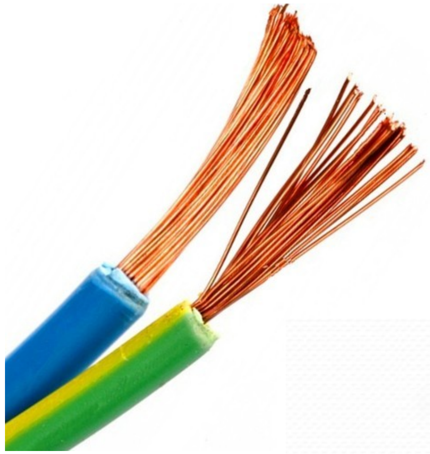
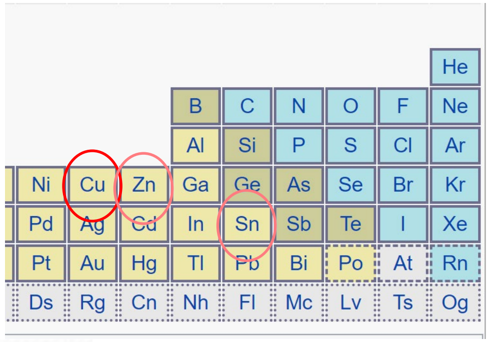
# Metal: Copper Alloys

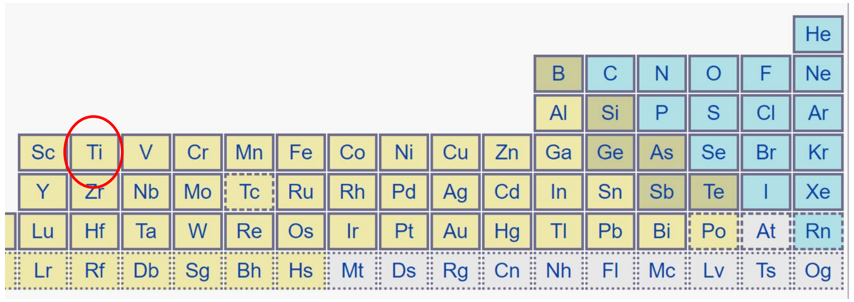
- Copper is a pain in the butt
  - Oxidizes (“patina”)
  - Difficult to machine
  - Difficult to weld
  - Soft, easy to form
  - Very high thermal conductivity
  - Very high electrical conductivity
- Brass
  - Extremely easy to machine and form
  - Harder than copper
  - Acoustically excellent
  - Corrosion resistant
  - Contains zinc
- Bronze
  - Great for bearings
  - “Self-lubricating”
  - Contains tin





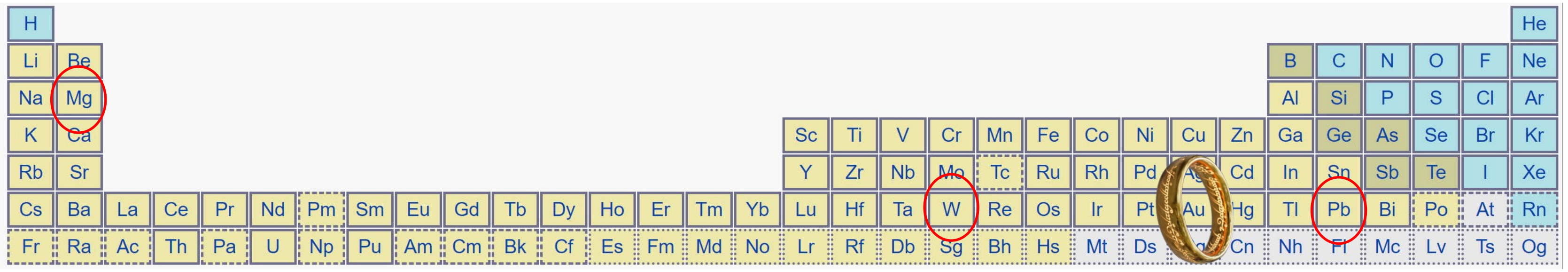

# Metal: Titanium

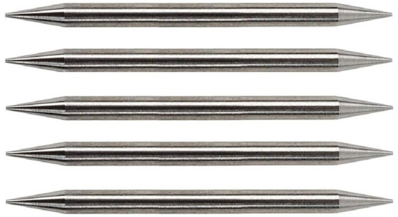
- Titanium is pretty cool
  - More expensive than steel or aluminum
  - High strength : weight
  - Difficult to machine
  - Difficult to weld
  - Very inert naturally forming oxide
  - Biocompatible
  - Lower thermal and electrical conductivity
- Alloys
  - Aluminum
  - Vanadium



# Metal: Others

- Gold
  - Pretty, my precious
  - Very soft
  - Very high conductivities
- Magnesium
  - Extremely light
  - Flammable
- Tungsten
  - Extremely high melting point
  - Extremely difficult to machine/form
  - Tungsten carbide
- Lead
  - Very low melting point
  - Easy to form
  - Cheap
  - High density
  - Toxic
- Superalloys
  - Inconel
  - Nitinol



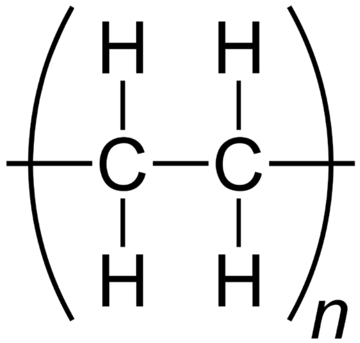
# Today's Agenda

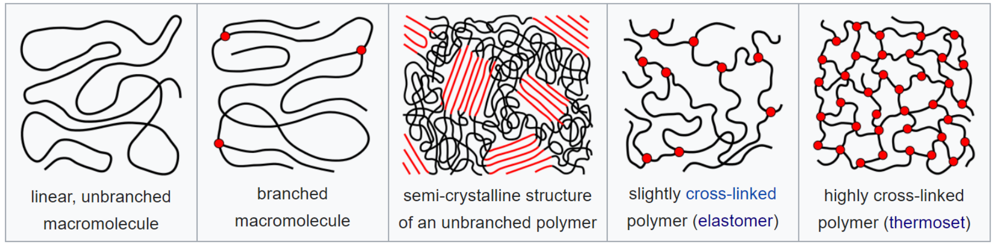
- ~~Why are materials important?~~
- ~~Material selection criteria~~
- ~~Metals~~
- Plastics / Polymers
- Ceramics
- Composites

# Plastics / Polymers

# Plastics: What are they?

- Named for their ability to be formed
- Polymers vs. Plastics
  - I’m using them interchangeably
- Elastomers
- Thermosets
- Thermoplastics



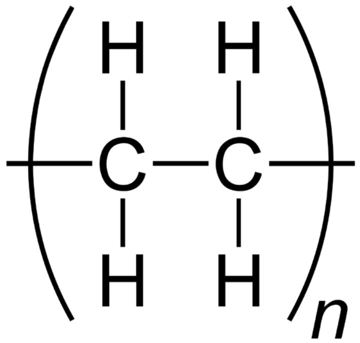



# Plastics: What we'll cover

- Cheap
  - PE
  - Acetal
  - PP
  - Nylon
  - PC
  - Acrylic
  - Others
- Expensive
  - Teflon
  - PEEK
  - Epoxies
- Elastomers
  - Silicone
  - Nitrile
  - Others

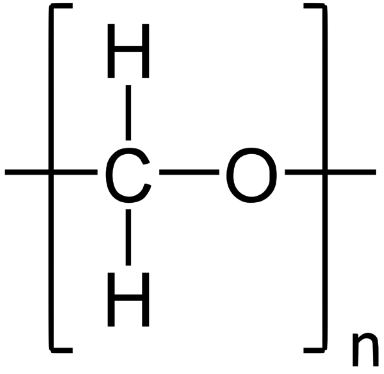
# Plastics: Polyethylene (PE)

- Typically thermoplastic
- Extremely chemically simple
- Extremely common
- Very, very cheap
- Chemical, corrosion resistant
- High impact strength
- Low hardness / rigidity



# Plastics: Acetal (POM)

- Thermoplastic
- Chemically simple
- Cheap
- Good rigidity for a plastic
- Very machinable
- Excellent dimensional stability
- Low friction

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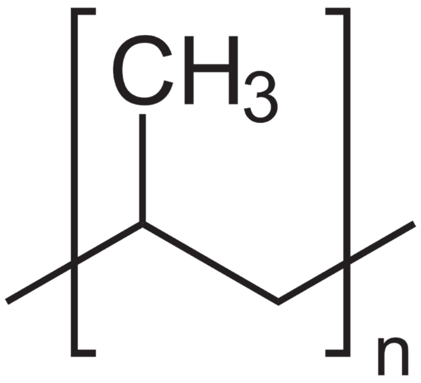
# Plastics: Polypropylene (PP)

- Thermoplastic
- Chemically simple
- Extremely common
- Very cheap
- Chemical, corrosion resistant
- Moldable
- Fatigue resistant
- Flexible

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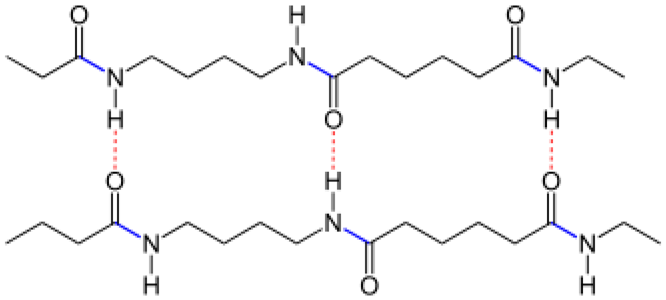
# Plastics: Nylon (polyamide)

- Thermoplastic
- Common
- Cheap
- Used in composites
- High tensile strength



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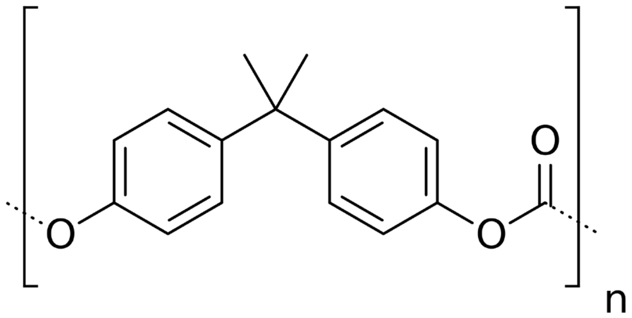
# Plastics: Polycarbonate (PC)

- Thermoplastic
- Optically clear
  - Though will discolor in sun
- Tough, resilient, impact resistant
- “Bulletproof” “glass”





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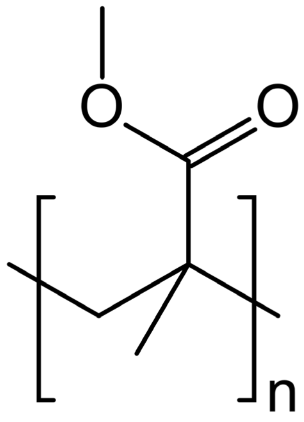
# Plastics: Acrylic (PMMA)

- Thermoplastic
- Very optically clear
  - Can be dyed
- Excellent for laser cutting
- Excellent biocompatibility
- Can be brittle
  - Difficult to machine
- Can be vapor polished
- aka Plexiglass, Lucite, Acrylite

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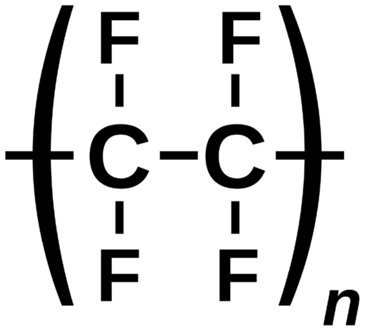
# Plastics: Other common plastics

- Polystyrene – food packaging, foam peanuts
- Polyurethane – foams and packaging materials
- Polyvinyl chloride (PVC) – plumbing and rigid applications
- Acrylonitrile butadiene styrene (ABS) – LEGOs, cases, impact and strength

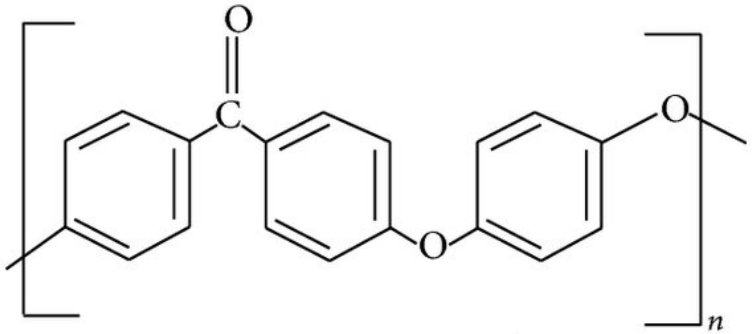
# Plastics: Teflon (PTFE)

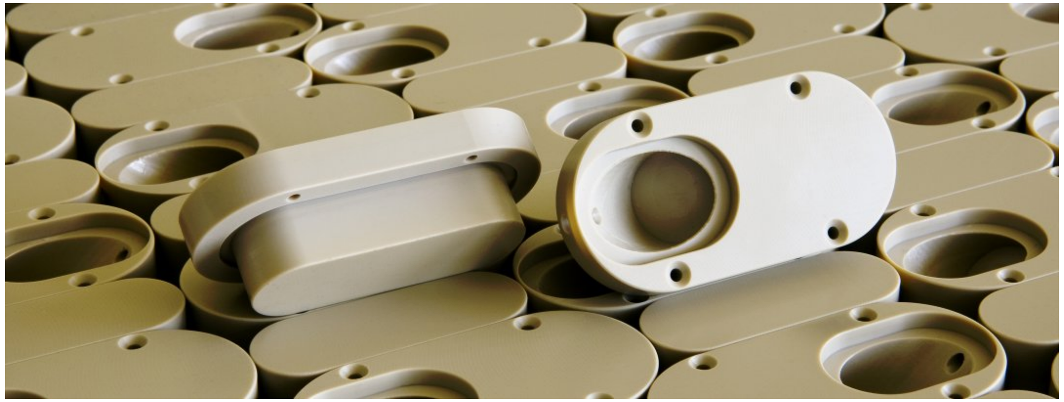
- Thermoplastic
  - High temperature
  - Can release fluorine fumes
- Extremely chemically resistant
- Machinable
  - Watch out, it deforms!
- Extremely expensive
- Extremely low friction
- Extremely hydrophobic
- Biocompatible




# Plastics: PEEK

- Polyether ether ketone
- Thermoplastic
  - High temperature
- Extremely chemically resistant
- Machinable
  - Like a dream
- Extremely expensive
- High rigidity
- Excellent dimensional stability
- Biocompatible



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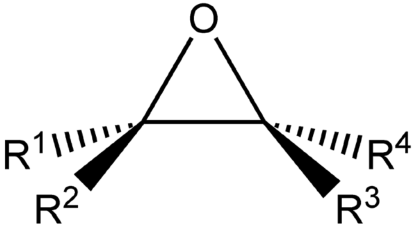
# Plastics: Epoxies

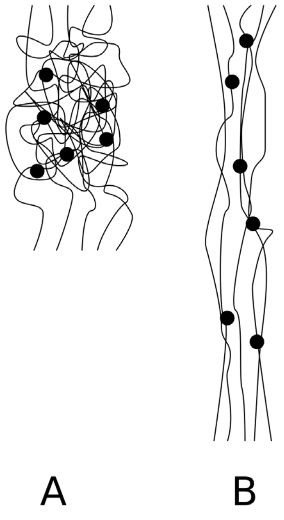
- Thermoset (at long last!)
  - Typically two mixed components
    - Resin
    - Hardener
- Adhesives
  - Extremely high bond-strength
- Self-leveling
  - Flooring
- Composites





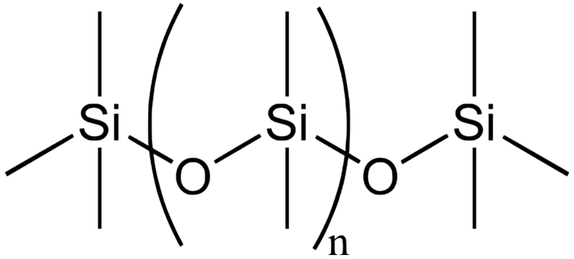
# Elastomers:

- Typically thermosets
  - “Vulcanizing”
- Stretchy
- Bendy
- Rubbery
- Elongation %
  - Up to 700%
- Durometer




# Elastomers: Silicone

- "Synthetic rubber"
- Polymerized siloxane
- Food safe
- Good wear characteristics
- Good chemical resistance
- Temperature resistant
- RTV
  - Room temperature vulcanization
- Biocompatible

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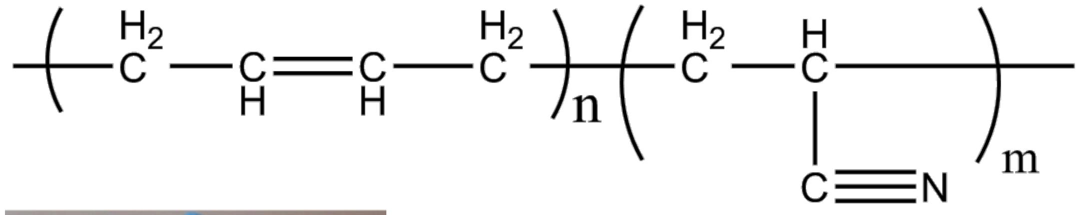
# Elastomers: Nitrile

- "Synthetic rubber"
- Good chemical resistance
  - Oil, fuel, etc.
- Can be self-healing
- aka Buna, Buna-N



# Elastomers: Others

- Natural rubber (aka latex) – cheap, excellent rubberiness
- Viton – Extremely chemically resistant, but expensive

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# Today's Agenda

- ~~Why are materials important?~~
- ~~Material selection criteria~~
- ~~Metals~~
- ~~Plastics / Polymers~~
- Ceramics
- Composites

# Ceramics

# Ceramics: The One Slide

- Engineering ceramics
  - Alumina
  - Silica
- Very difficult to fabricate
- High dimensional stability
- Can be ground and polished
- High chemical resistance
- Good thermal insulators
- Good electrical insulators
  - Capacitors
- High density
- Brittle

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# Ceramics: Glass

- Typically prized for optical clarity
- “Amorphous solid”
- Difficult to fabricate after molten
- Soda-lime glass
  - Silica-based
  - Made from sand
- Borosilicate glass
- Designer glass
  - Gorilla glass

# Today's Agenda

- ~~Why are materials important?~~
- ~~Material selection criteria~~
- ~~Metals~~
- ~~Plastics / Polymers~~
- ~~Ceramics~~
- Composites

# Composites

# Composites & Other Materials:

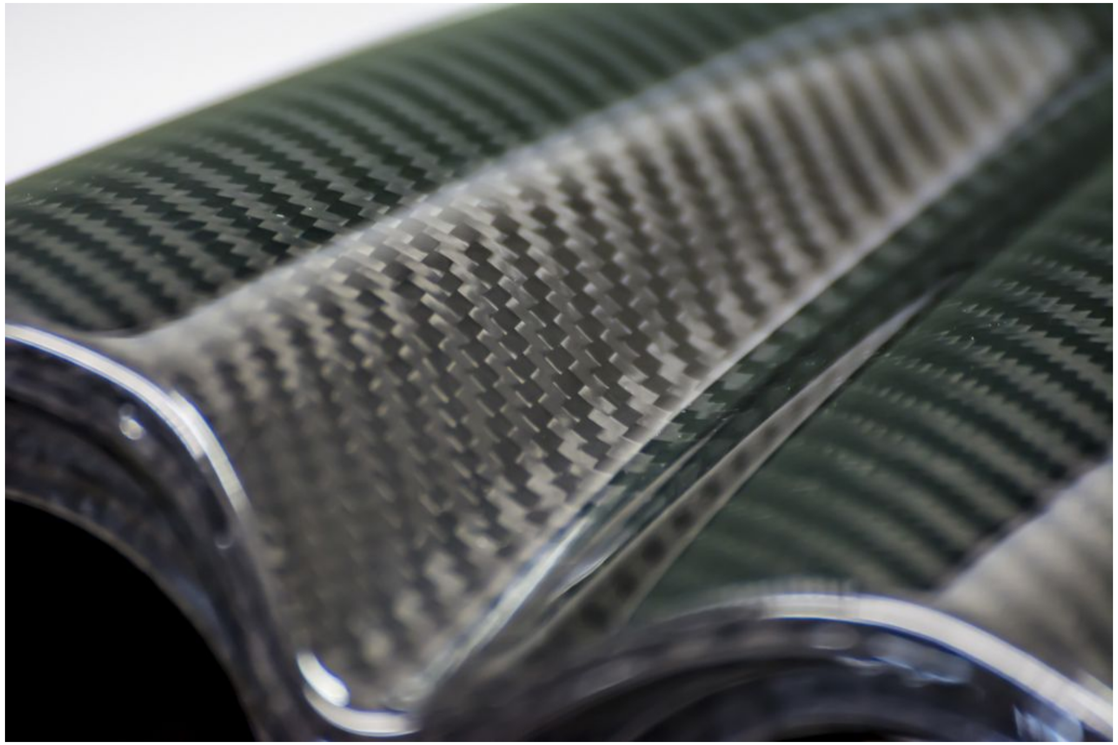
- Multiple materials
  - Matrix
  - Binder
- Examples:
  - Wood
  - Carbon Fiber
  - Fiberglass
  - Textiles
  - Concrete
  - Paper products
  - Me?

# Wood

- Likely eco-friendly
- Cheap
- Easy to cut, but difficult to shape/mold
- Strength varies on species, grain, moisture, treatment, and other factors
  - Bamboo
  - Balsa
  - Old growth redwood
- Hydrophilic and porous, must be 'sealed' to use in contact with liquids.
- Please consult your local carpenter

# Carbon Fiber & Fiberglass

- Extremely light
- Extremely rigid
- Expensive
  - Carbon fiber is more expensive
  - Fiberglass is cheaper
- Difficult to form
- Fiberglass itches



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# Textiles

- Fibers
  - Natural
  - Synthetic
  - Both
- Flexible and strong in tension
- Cheap
- Variety of styles, textures, stre etc.
- Easy to cut
- Does not keep its shape well
- Typically hydrophilic

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# Concrete

- Extremely strong in compression
  - Best when paired with rebar
- Cheap per volume
- High density
- Moldable during pouring
  - Otherwise very difficult to fabricate
- Wear resistant
- May be sealed or painted


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# Paper products

- Cardboard is a great engineering prototyping tool
- Papier mache
- Very cheap
- Very light
- Easy to cut, laser cut, form
- Can be shredded and molded
- Holds paint well
- Hydrophilic


# Today's Agenda

- ~~Why are materials important?~~
- ~~Material selection criteria~~
- ~~Metals~~
- ~~Plastics / Polymers~~
- ~~Ceramics~~
- ~~Composites~~

Engineering is about curiosity.

The best learning is what you teach yourself.

# Resources

- Check out McMaster-Carr for material choices, then Wikipedia/Google

- Shigley's Mechanical Engineering Design – Budynas & Nisbett
- Mechanical Design Handbook – Rothbart & Brown
- Machinery's Handbook – Oberg & Jones
- Art of Electronics – Horowitz & Hill

# Questions? Office Hours!

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