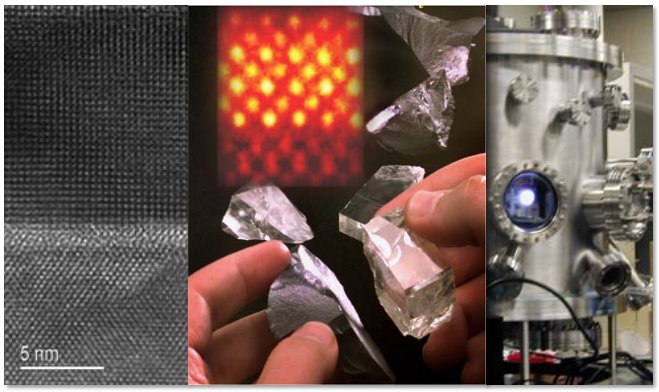
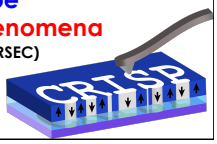
Materials Science and Engineering

Interdisciplinary with HUGE potential



Christine Broadbridge & Heather Edgecumbe
Center for Research on Interface Structures and Phenomena
an NSF-funded Materials Research Science & Engineering Center (MRSEC)
Yale University • Southern CT State University



Materials and Manufacturing Teacher Institute 2013

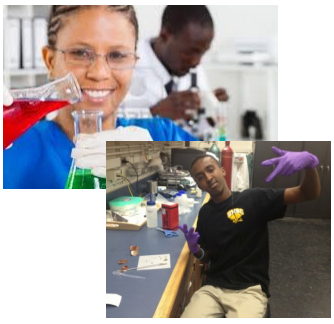
Introduction

What is materials science*?

- A branch of science that focuses on materials; interdisciplinary field impacting the physical, life & engineering sciences.
- Relationship of material properties to its structure, performance and processing.

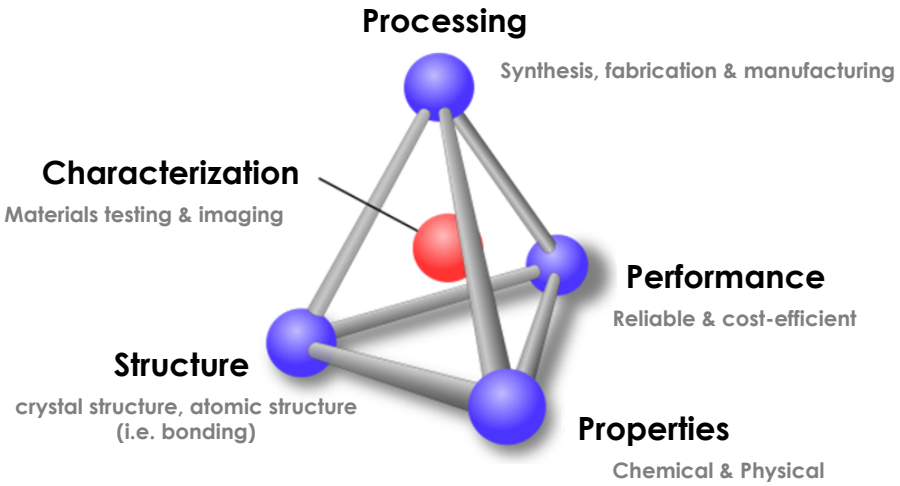
What is a materials scientist?

- A person who uses his/her knowledge of science and engineering to exploit structure - property relationships for practical use.
  - Goal: Take raw materials & make finished products



*Materials Science and Engineering [MSE]

Materials Science and Engineering



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What are Materials?

Classification of materials:

- **Metals** (Al, Ni, Cu, etc. // good conductors)

- **Ceramics/Glasses** (Al_2O_3, glass //good insulators)

- **Polymers** (plastic, rubber, proteins // synthetic, natural)

- **Composites** (combination of 1-3; i.e. carbon fiber)

Advanced materials, i.e. semiconductors, biomaterials, smart materials, and nano-engineered materials

Materials engineering – fabrication and application of new materials

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The impact of Materials Science

- Materials have defined the progression of humankind: **Stone** Age, **Bronze** Age, **Iron** Age
- Today's age: **Silicon** Age, **Information** Age

metals • ceramics • semiconductors • polymers
composites • smart materials

New generation of materials created by pushing the boundaries of science/innovation

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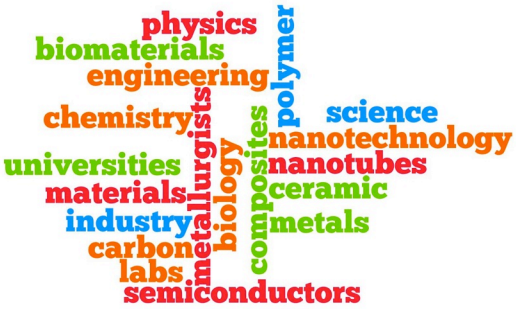
What do Materials Scientists do?

- Investigate how materials are made, figure out how they can be changed and improved, and engineer entirely new materials.



Materials science is an interdisciplinary field with many applications

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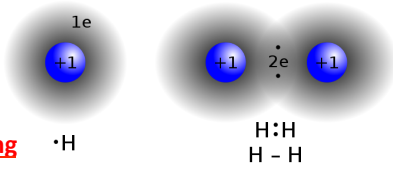
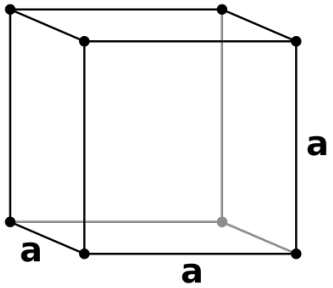
What is structure?
Atomic Structure – 10^{-10} m

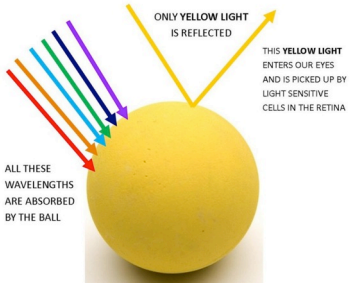
- Pertains to atom electron structure and atomic arrangement
- Atom length scale
  - ➢ Includes electron structure – **atomic bonding**
    - ionic
    - covalent
    - metallic
    - secondary bonding (Van der Waals)
  - ➢ Atomic ordering – **crystal structure**
    - Crystalline
    - Polycrystalline
    - Amorphous
  - ➢ Long range (metals), short range (glass)





What is a property?

- **A material's response to an external stimuli – physical and chemical**
  - – Mechanical
  - – Electrical
  - – Chemical
  - – Optical
  - – Magnetic



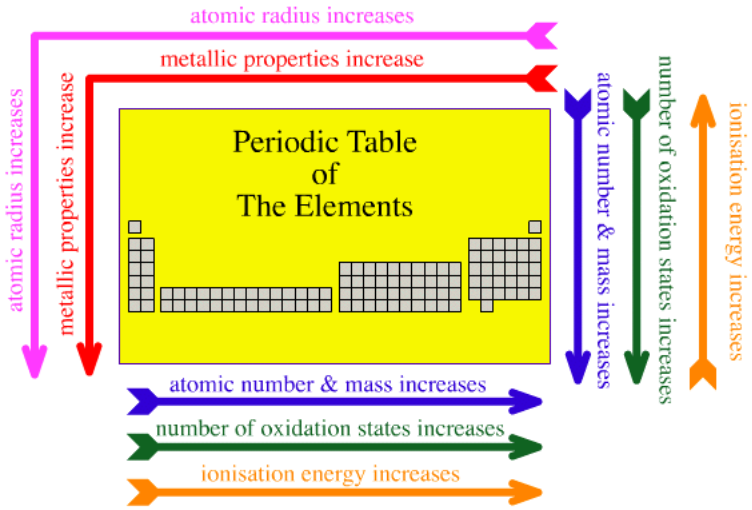
Optical: Stimuli = light [EM radiation]

https:// colour-yourlife.co.uk

Structure/Property Relationships

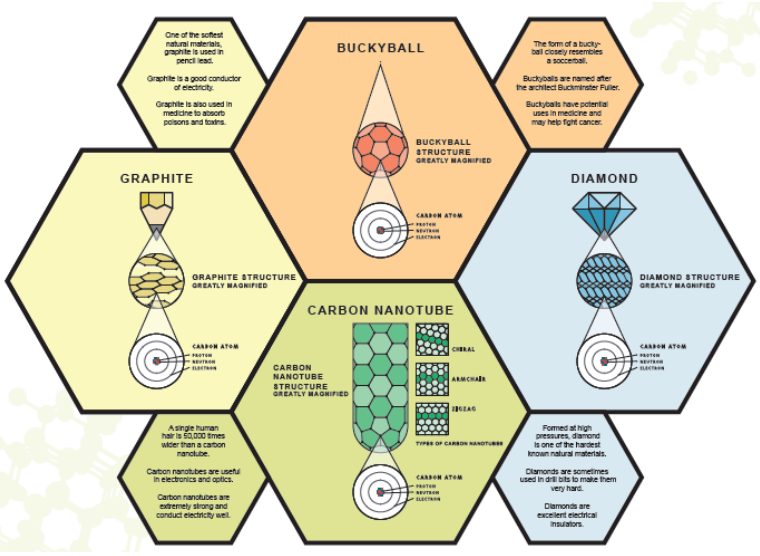
Atomic Structure

- Periodic Table – general trends



Structure/Property Relationships

Crystal structure and bonding



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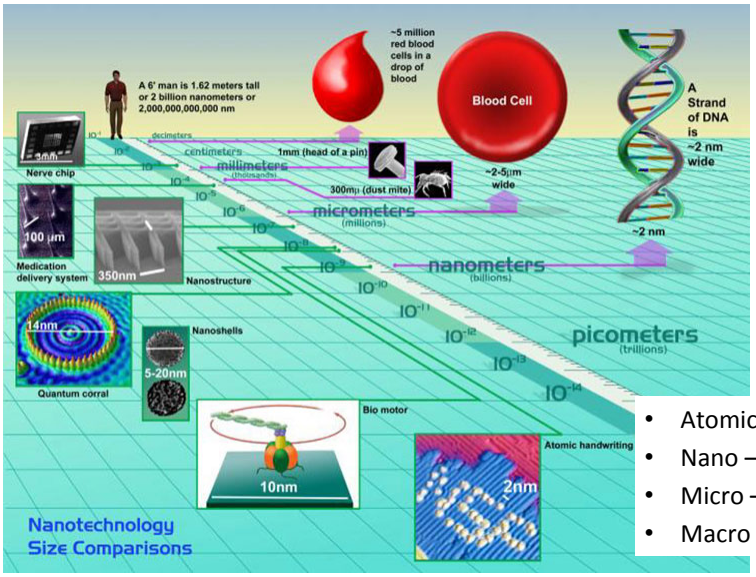
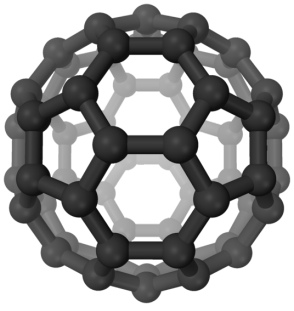
Length Scales of Materials Science



- Atomic – < 10^{-10} m
- Nano – 10^{-9} m
- Micro – 10^{-6} m
- Macro – > 10^{-3} m

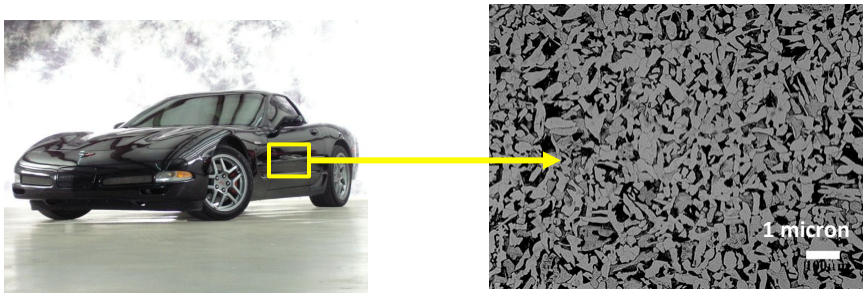
Nano Structure – 10^{-9} m

- Length scale that pertains to clusters of atoms that make up small particles or material features
- Show interesting properties because of large surface area to volume ratio
  - More atoms on surface compared to bulk atoms
  - Optical, magnetic, mechanical and electrical properties change
- How to conceptualize? Your finger nail grows ~1nm every second



Microstructure – 10^{-6}

- Larger features composed of either nanostructured materials or periodic arrangements of atoms known as crystals
- Features are visible with high magnification in light microscope.
  - Grains, inclusions other or micro-features that make up material
  - These features are traditionally altered to improve material performance
  - Human hair is ~100 microns in diameter



Macrostructure – 10^{-3} m

- Macrostructure pertains to collective features on microstructure level
- Grain flow, cracks, porosity are all examples of macrostructure features
- Some features can be observed with the naked eye

Classes of Materials

- metals
- polymers
- ceramics/glasses
- composites

Metals

- Metals consist of alkaline, alkaline earth, metalloids and transition metals and are typically crystalline
- Metal alloys are mixtures of two or more metal and nonmetal elements (for example, aluminum and copper, Cu-Ni alloy, steel)
- Bonding: Metallic
  - No particular sharing or donating occurs. Electron cloud is formed (that is, free electrons)
  - Strong bonds with no hybridization or directionality
- Properties:
  - Electrically conductive (free electrons)
  - Thermally conductive
  - High strength – large capacity to carry load over x-section area (stress)
  - Ductile – endure large amounts of deformation before breaking.
  - Magnetic – permanent, temporary
  - Medium melting point

Metal Applications

- Electrical wire: aluminum, copper, silver
- Heat transfer fins: aluminum, silver
- Plumbing: copper
- Construction beams (bridges, sky scrapers, rebar, etc.): steel (Fe-C alloys)

- Cars: steel (Fe-C alloys)
- Consumer goods:
  - soup cans
  - appliances (stainless steel sheet metal)
  - utensils
  - tools
  - Many, many, many more…

- MSE used to = metallurgy [study of metals]

Polymers

- Polymers consist of various hydro-carbon (organic elements) with select additives to create specific properties
- Polymers are typically disordered (amorphous) strands of hydrocarbon molecules.
- Bonding: Covalent-Secondary Bonding Forces
- Properties:
  - ductile: can be stretched up to 1000% of original length
  - lightweight: Low densities
  - medium strength: Depending on additives
  - chemical stability: inert to corrosive environments
  - low melting point
  - disposal can be a concern for the environment

Polymer Applications

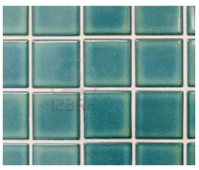
- Car tires: vulcanized polymer (added sulfur)
- Ziploc bags
- Food storage containers
- Plumbing: polyvinyl chloride (PVC)
- Kevlar
- Aerospace and energy applications: Teflon
- Consumer goods:
  - calculator casings
  - TV consuls
  - shoe soles
  - cell phone casings
  - Elmer's Glue (adhesives)
  - contact lenses
  - Many, many. many more…

Ceramics

- Consist of metal and non metal elements
- Typically a mixture of elements in the form of a chemical compound , for example Al_2O_3 or glass
- Different types: crystalline and amorphous ceramics
- Bonding: covalent – ionic
  - Typically covalent. In some cases highly direction covalent bonding
  - Ionic in case of SiO_2 glasses
- Properties:
  - wear resistant (hard)
  - chemical stability: corrosion resistant
  - high temperature strength: strength retention at very high temperatures
  - high melting points
  - good insulators (dielectrics)
  - adhesives
  - good optical properties

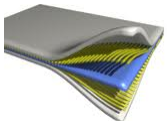
Ceramic/glass Applications

- Window glass: Al_2O_3 – SiO_2 – MgO – CaO
- Aerospace, energy and automotive industry
  - heat shield tiles
  - engine components
  - reactor vessel and furnace linings
- Consumer products:
  - pottery
  - dishes (fine china, plates, bowls)
  - glassware (cups, mugs, etc.)
  - eye glass lenses
  - Ceramic braces



Composites

- A mixture of two different materials to create a new material with combined properties
- Types of composites:
  - Particulate reinforced – discontinuous type with low aspect ratio
  - Whisker/rod reinforced - discontinuous type with high aspect ratio
  - Fiber reinforced - continuous type with high aspect ratio (naturally)
  - Laminated composites - layered structures (surf boards, skate boards)
- Bonding: depends on type of composite (strong-covalent, medium-solid solution, weak-tertiary phase layer)
- Properties: Depends on composites
  - High melting points with improved high temperature strength: ceramic-ceramic
  - High strength and ductile with improved wear resistance: metal-ceramic
  - High strength and ductile: polymer-polymer



Composites: Applications

- Wood: naturally occurring biological material consists of very strong fibers imbedded in a soft matrix
- Plywood: laminated wood for buildings
- Concrete: basements, bridges, sidewalks
- Fiberglass: boats
- Carbon fiber resins: bicycle frames
- Composite decking

Other advanced materials

- **Semiconductors – ceramics**
  - computer chips
  - memory storage devices
  - solar cells
  - image screens
- **Nanomaterials – ceramics, metals, polymers**
  - gold nanoshells
  - quantum dots
  - ferrofluids
  - medical devices

How do we test materials?
Materials Characterization

We use mechanical, chemical and imaging methods

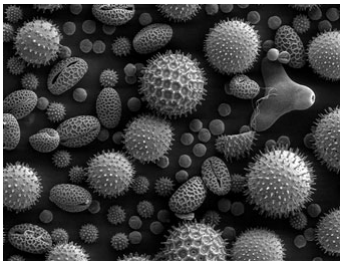
- Mechanical testing gives strength, ductility and toughness material information
  - tensile tests
  - bend tests
  - compressive tests
  - fracture testing
- Chemical testing tells us about composition and chemical stability
  - x-ray diffraction and fluorescence – composition testing
  - corrosion testing
- Microscopy is more of a way to view atomic, nano and microstructures, and gives us insight to structure property relationships
  - light optical microscope – microstructure
  - scanning electron microscope – microstructure and nano structure
  - transmission electron microscope – nanostucture and atomic structure
  - scanning tunneling electron microscope – atomic structures

Mechanical Testing

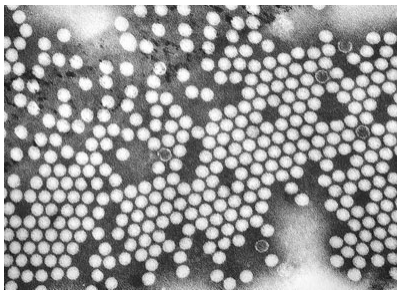
universal testing machines

Imaging Methods

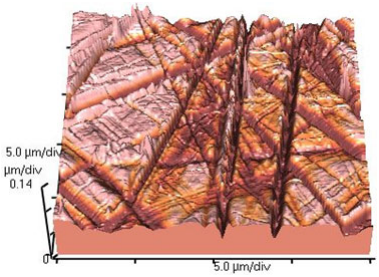
Scanning Electron Microscope



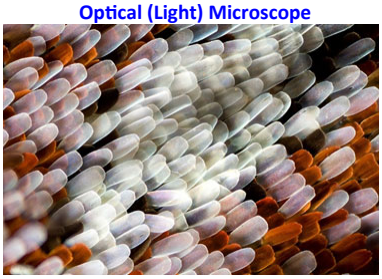
Transmission Electron Microscope



Atomic Force Microscope



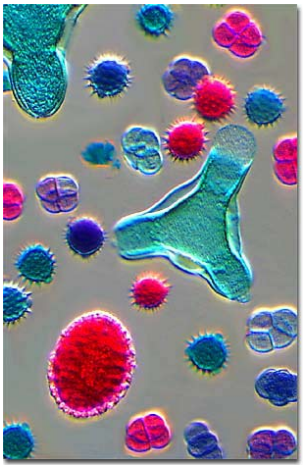
Optical (Light) Microscope



Optical Microscopy

biology and forensics

resolution ~1 μm



Hoffman modulation contrast microscopy [pollen]

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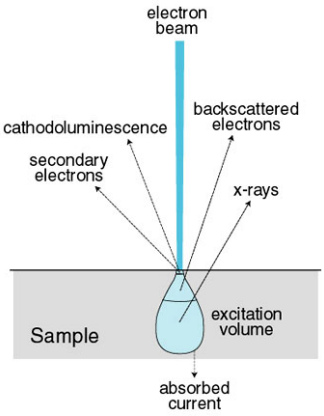
Scanning Electron Microscopy [SEM] Analysis

Resolution < 10 nm



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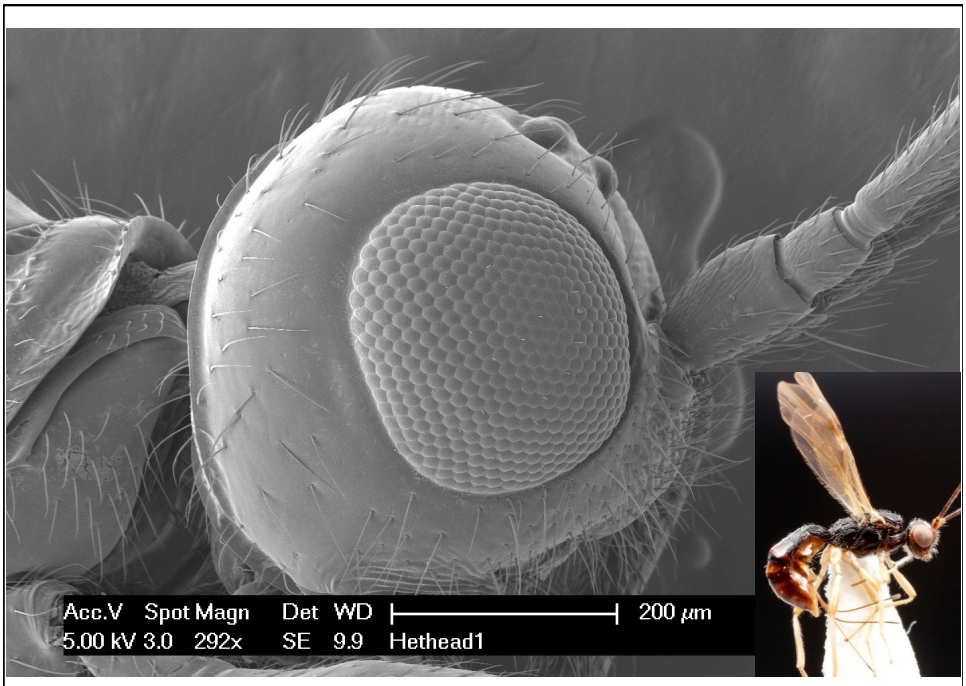

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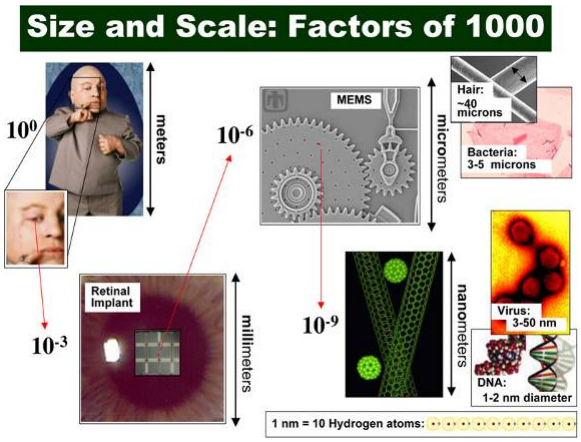
Powers of ten ~ from macro to nano

http://www.mrsec.wisc.edu/Edetc/nanoscale/index.html
Courtesy of Charles Tahan



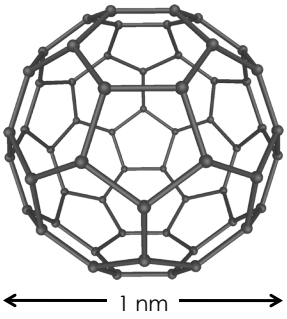
- 1 nm to 100 nm (http://www.nano.gov)
- A human hair is about 100,000 nm in diameter
- A smoke particle is about 1,000 nm
- A Virus is 3 – 50 nm
- DNA is about 1 – 2 nm in diameter
- 10 Hydrogen atoms is 1 nm

Provide as many examples as possible for students

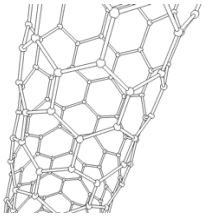
Nanotechnology

Control & manipulation of matter [1-100nm]

Unique phenomenon enable novel applications



C_{60} buckyball
fullerene



C nanotube
cylindrical fullerene
[photovoltaic, solar cell]

Quantum dots
Nanosize semiconductors
[DVD, video games]

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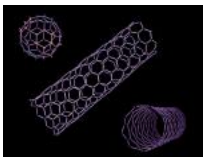
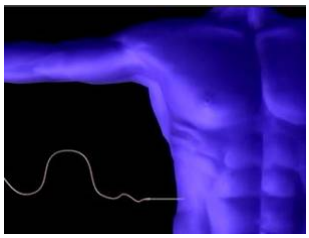
Innovations In Development or Under Investigation

- **Health Care**
  - Chemical and biological sensors, drugs and delivery devices, prosthetics and biosensors
- **Technology**
  - Better data storage and computation
- **Environment**
  - Clean energy, clean air

Thin layers of gold are used in tiny medical devices



Carbon nanotubes can be used for H fuel storage



Possible entry point for nanomedical device

Examples of current commercial products

- Cosmetics (skin care products)
- Tennis balls which last longer
- Wrinkle free fabrics, "nano-fabrics"
- Sunscreen with transparent zinc-oxide

The possibilities are limitless…

Potential Impacts

How might Materials Science and Engineering enhance K-12 education?

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For Discussion -- MSE Connections to the NAE Frameworks

SCIENCE AND ENGINEERING PRACTICES FOR K-12 SCIENCE CLASSROOMS

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

CORE AND COMPONENT IDEAS IN THE PHYSICAL SCIENCES

Core Idea PS1: Matter and Its Interactions
PS1.A: Structure and Properties of Matter
PS1.B: Chemical Reactions
PS1.C: Nuclear Processes

Core Idea PS2: Motion and Stability: Forces and Interactions
PS2.A: Forces and Motion
PS2.B: Types of Interactions
PS2.C: Stability and Instability in Physical Systems

Core Idea PS3: Energy
PS3.A: Definitions of Energy
PS3.B: Conservation of Energy and Energy Transfer
PS3.C: Relationship Between Energy and Forces
PS3.D: Energy in Chemical Processes and Everyday Life

Core Idea PS4: Waves and Their Applications in Technologies for Information Transfer
PS4.A: Wave Properties
PS4.B: Electromagnetic Radiation
PS4.C: Information Technologies and Instrumentation

Summary

Materials Science & Engineering

- A branch of science that focuses on materials; interdisciplinary field composed of physical, life and engineering sciences.
- Relationship of material properties to its structure, performance and processing.
- Interdisciplinary field with huge potential for synergies with the National Academies Frameworks, Next Generation Science Standards & Common Core.

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Role of a Engineer

- Heather Edgecumbe, Principal Manufacturing Engineer
  - B.S. Materials Engineering
    - Boston Scientific, Inc., Fremont, CA
    - Varian Associates, Inc., Palo alto, CA
    - Corometrics, Inc., Wallingford, CT

Role of "Materials" Engineers

- Answer the "needs" of society by utilizing all science professions– Biology, Engineering, Physics, Chemistry *(Interdisciplinary)*
  - Need a plane to fly lighter
  - Need to conduct electricity over long distances
  - Need a ball to bounce higher
  - Need to heal a brain aneurysm
  - Need to see at night

Engineers ask questions to define the need or problem

- What are the desired functions?
  - Design output and specifications
- What are the constraints?
  - technological feasibility
  - cost
  - safety
  - compliance with legal requirements

Engineers are problem solvers

Industry needs students with problem solving skills.

Technical

Solution: NGSS Engineering Practices

SCIENCE AND ENGINEERING PRACTICES FOR K-12 SCIENCE CLASSROOMS

1. Asking questions (for science) and defining problems (for engineering)
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8. Obtaining, evaluating, and communicating information

Interpersonal

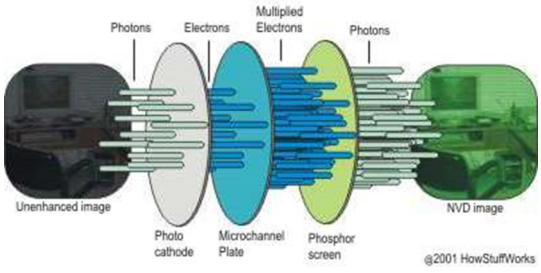
Solution: CCSS Speaking and Listening

Materials Science in Action

- "Need" to see in the dark

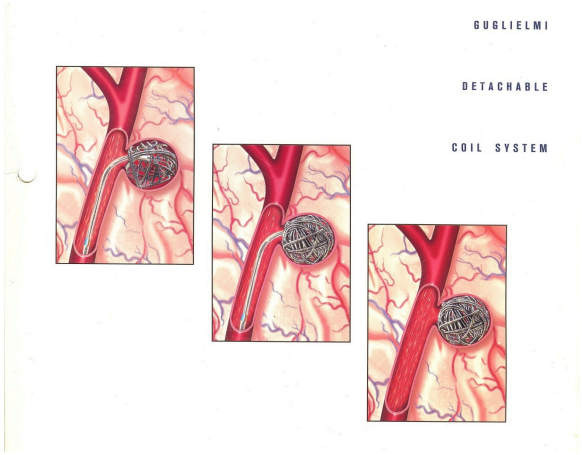
Materials Science in Action

- Night Vision Goggles – Metals, Semiconductors, Glasses, Plastics, Phosphor



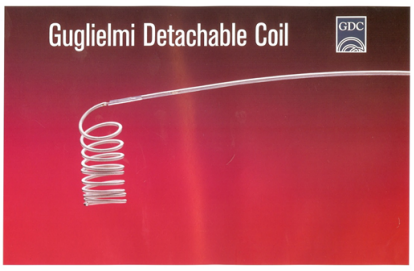
Materials Science in Action

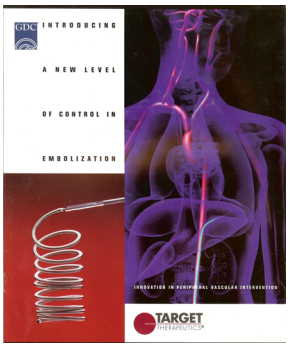
- "Need" to heal a Brain Aneurysm



Materials Science in Action

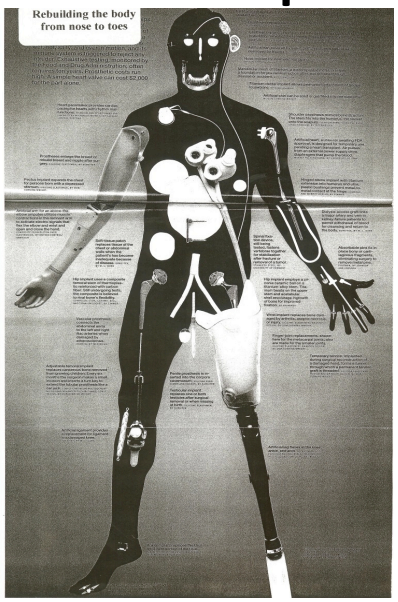
- ***Platinum*** Coils





Career in Materials Science

- A great national need for persons specifically trained to carry out research and development in materials science and engineering.
- A person choosing a career in this field can expect to achieve both financial reward and personal fulfillment.

Appendix

Medical Implants