MS4SSA Materials Project-Based and Robotics Modules

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Inspiring Young People and a New STEM Culture: Battlecry WPI/Africa

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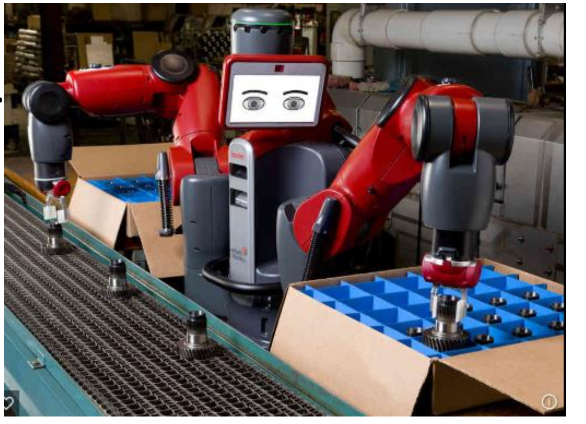
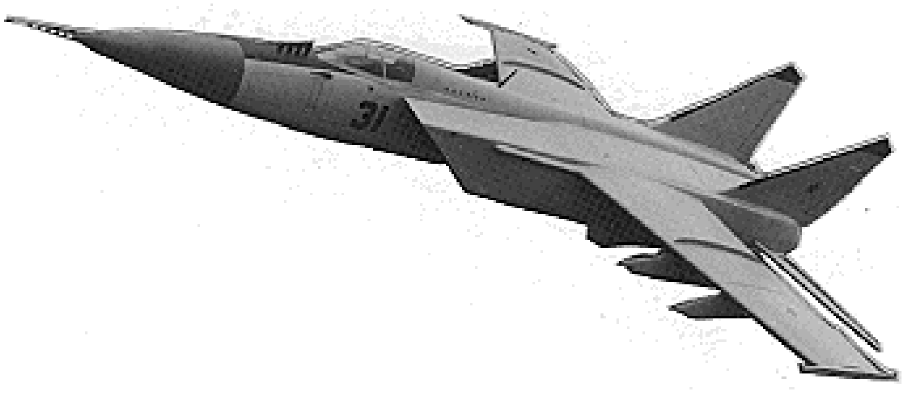
Materials – The Major Driver

- Science and technology are the major engines of development
- Materials have always been a major driver in technological change…
  - Alloys
  - Semiconductors
  - Polymers
  - …

Hard materials

Soft materials





The Evolution of Engineering Materials

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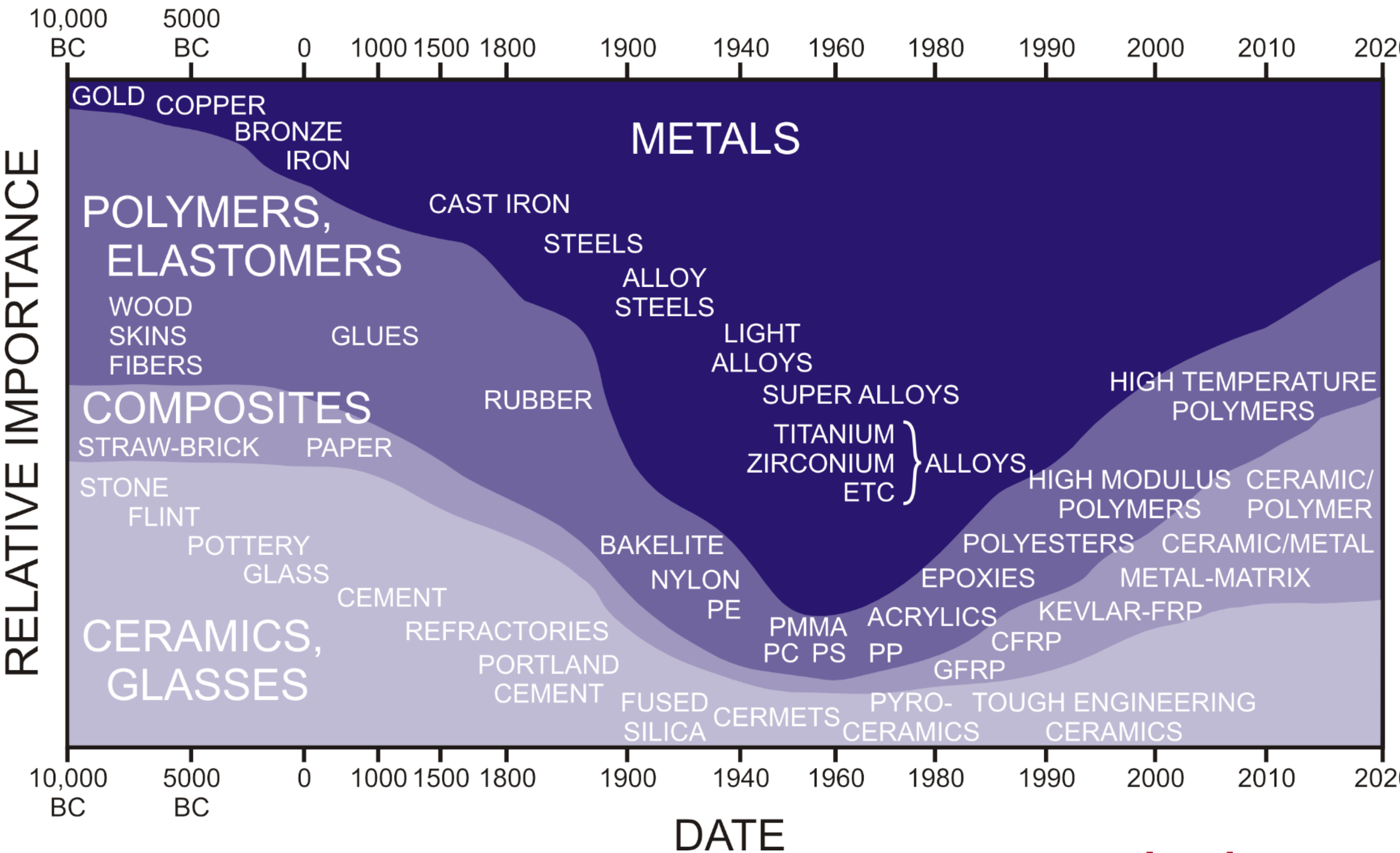
What is in the future?



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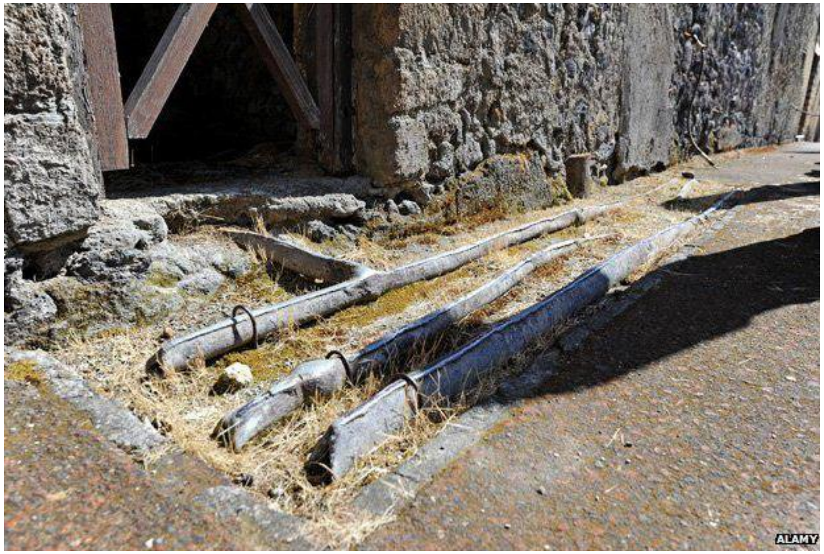
Lead

- First discovered in Turkey more than 8000 years ago
- Easy to smelt due to low melting point
- Used essentially as the "plastic" material of the past
- Applications in lead pipes (the word plumber comes from Greek plumbum)
- Major issues with toxicity of lead – harmful to children and adults e.g. lead in wines
- Applications in radioactive shielding



http://www.bbc.com/news/magazine-29568505

Uranium

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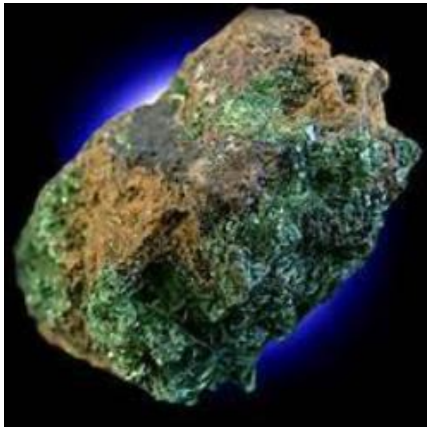
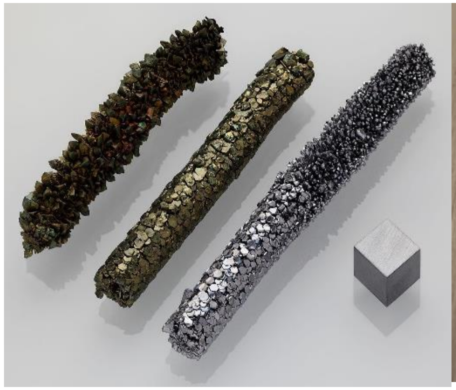
- Large amount of energy released when uranium splits
- The divisive element with many implications for nuclear power
- Largest naturally occurring element on Earth
- Breaks apart to shoot out alpha particles (bundles of 2 neutrons and 2 protons)
- Forms thorium and then protactinium and then lead
- Supplies internal heat for Earth’s magnetic field and plate tectonics
- Key element for nuclear power plants and weapons
- Abundant in Niger



Vanadium

- Vanadium is an important alloying element
- Used as an alloying element in ferrous materials for several centuries
- Sword of Damascus was developed based on alloying with V
- Henry Ford used it to make the body of his model T car lighter and stronger in 1908
- More recent applications in giant batteries

From Ford Motor Company via Wikipedia



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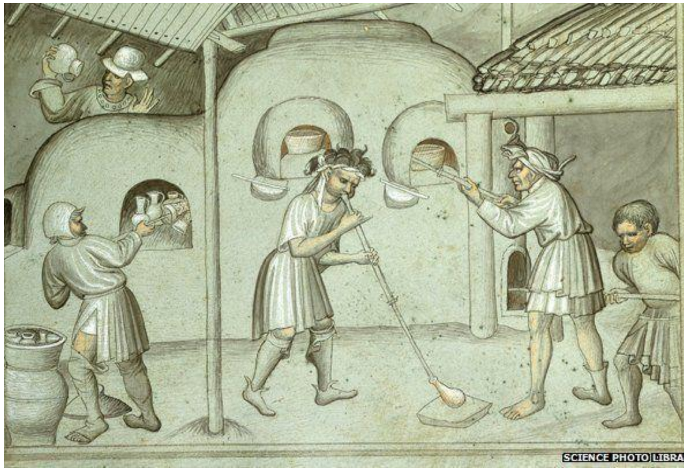
Silicon

- One of the most abundant elements on earth
- Present in sand and stones
- Origin of silicon revolution was of course…glass
- Glassmaking was developed more than a million and a half years ago
- Glass making then evolved from glass blowing to fiber optics
- The basis of silicon micro-chips



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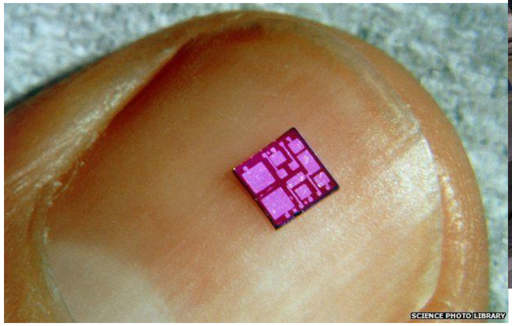

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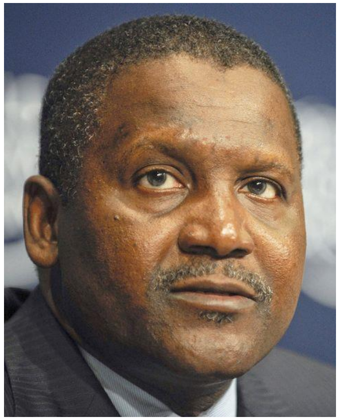
http://ichef-1.bbci.co.uk/news/624/media/images/76679000/jpg/_76679579_manufacturing_solar_panels-spl.jpg

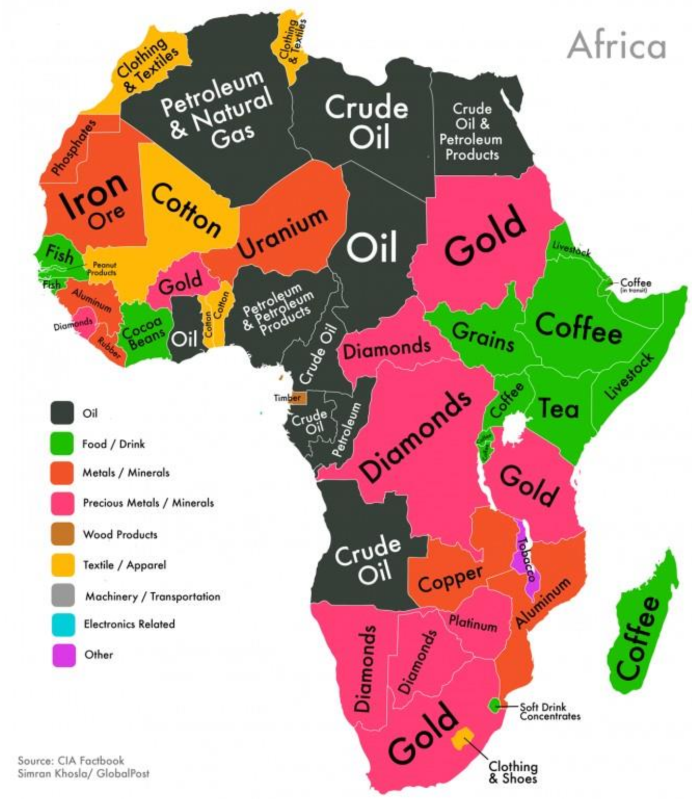
From Artisanal Mining to Wealth

- **Africa has a rich array of minerals and materials resources**
- **Artisanal Mining (Small-Scale)**
  - Difficult conditions
  - Limited profits
- **Industry (Mid- to Large-Scale)**
  - Africa’s richest man (Aliko Dangote) manufactures cement from African raw materials
  - Value addition to people, minerals and natural products



The Materials of Africa

- Africa is a continent that is rich with mineral/material deposits
- These include minerals that are rich in gold, uranium, chromium, platinum and copper



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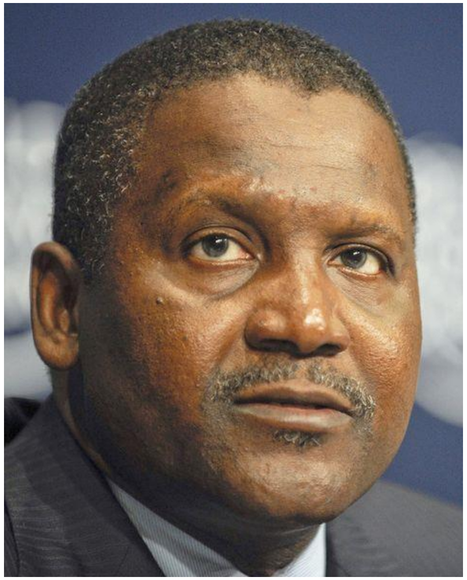
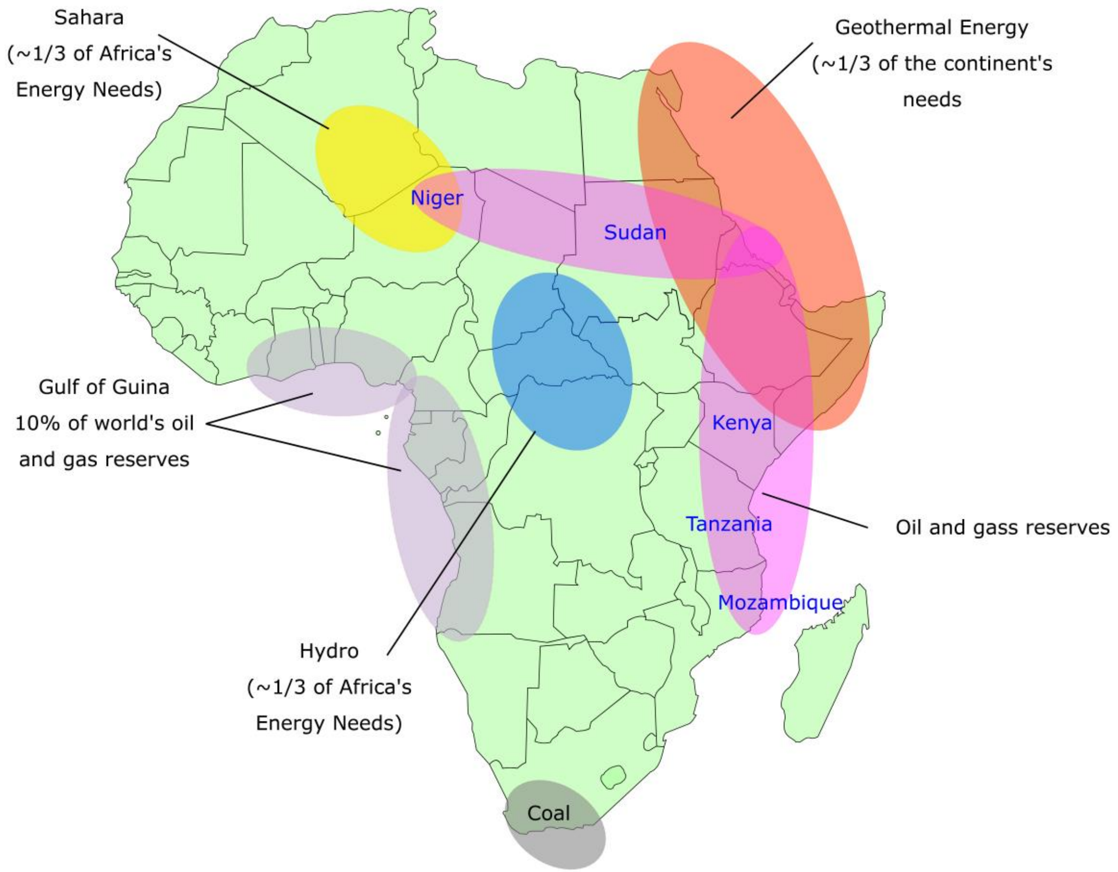


Africa's Richest Man- Aliko Dangote
(Biggest Producer of Cement)

https://en.wikipedia.org/wiki/Aliko_Dangote

The Energy Sources of Africa

- Africa is rich in energy resources
- The energy resources of Africa include
  - Fossil fuels
  - Solar energy
  - Hydro power
  - Wind energy
  - Geothermal energy
- These can be harnessed to produce and store energy in rural/urban areas
  - Energy generation
  - Energy storage



Background and Introduction to Materials Science and Engineering Modules

- Africa is rich in mineral and materials resources
- However most students in Africa have never heard about materials science and engineering
- Hence most of their knowledge of math and science is abstract and not connected to the materials opportunities around them
- Furthermore most students do not know much about how to add value to natural resources through materials processing
- There is therefore a need to introduce students to materials science and engineering modules
- Such modules could increase the pipeline of future materials scientists and engineers or applied scientists and engineers

Materials Science and Engineering

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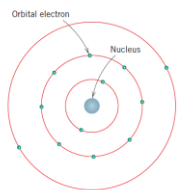
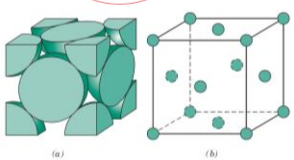
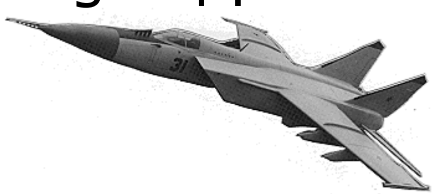
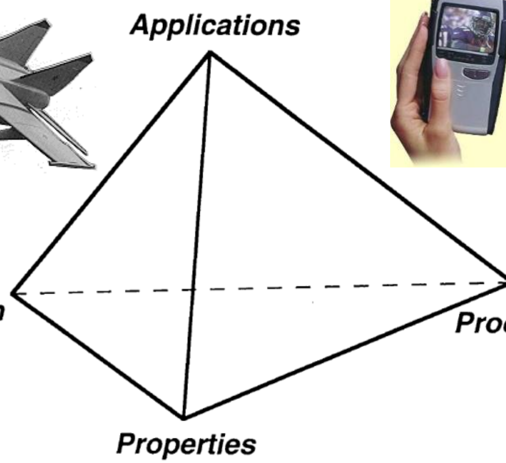
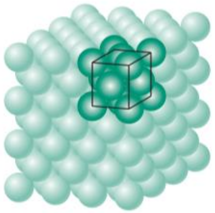
- Science: Knowledge-driven exploration of materials
- Engineering: Application-driven development of materials

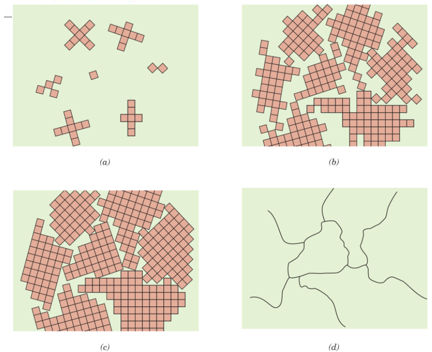


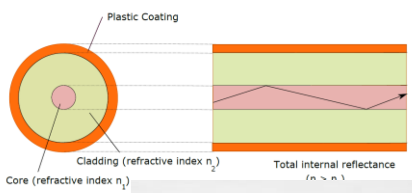


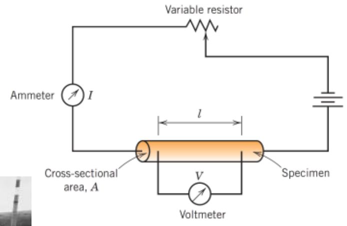


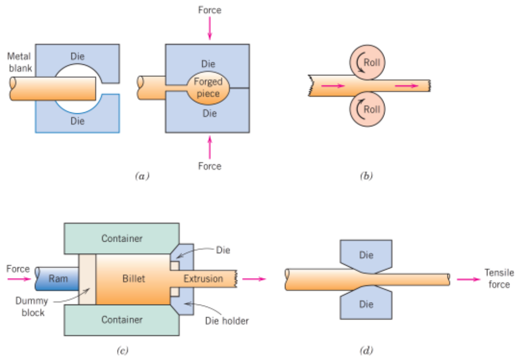












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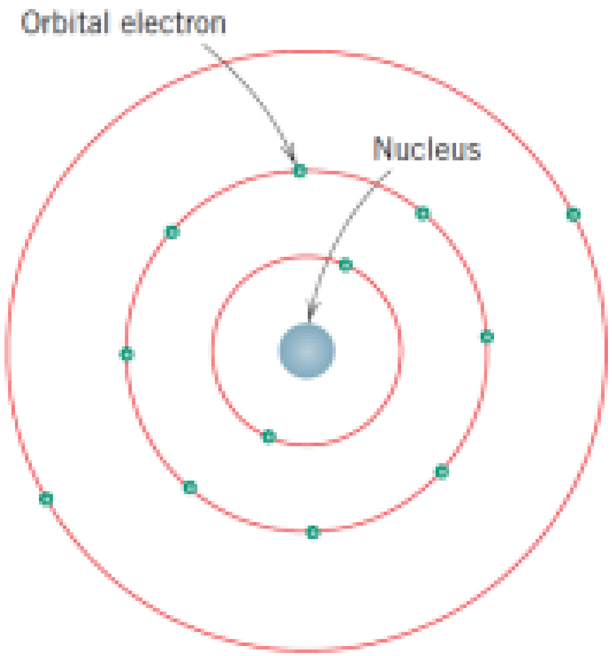
Project-Based Materials Science and Engineering Modules

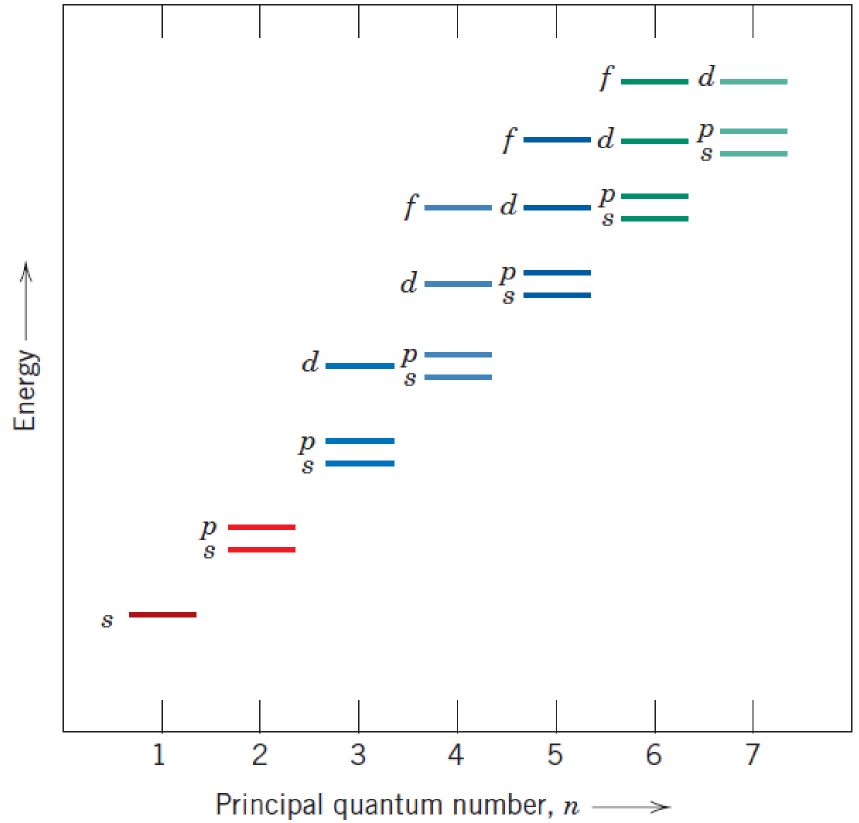
- WPI Team (Materials Science & Engineering), ASM International, MPI, Pete Gange and Robotics Team
  - Projects to promote creativity, understanding and problem solving
  - Modules for the teaching of materials science and engineering in African primary and secondary schools
- The initial modules are presented at a level that can be taught to students in secondary school
- The modules include lecture materials, homework questions, quizzes, answer keys and project-based modules
  - Lecture materials (structure, properties, processing, materials selection and design)
  - Interdisciplinary project-based approach to solving African problems (clean water, clean energy)

Outline of MS4SSA Lecture Modules

- Introduction to materials science and engineering
- Crystal structure and crystallography
- Materials processing and characterization
- Introduction to mechanical properties
- Plasticity and deformation
- Fracture and fatigue
- Phases and phase diagrams
- Materials and their mechanical properties
- Electrical properties of materials
- Biomaterials and bio-inspired design
- Materials selection and design
- Project-based modules – renewable energy/clean water/housing/transportation

Atomic Structure





Bohr model

wave-mechanical model

(Adapted from Callister, William D., and David G. Rethwisch. "Materials science and engineering: an introduction. " Vol. 7. New York: Wiley, 2007.)

The Periodic Table

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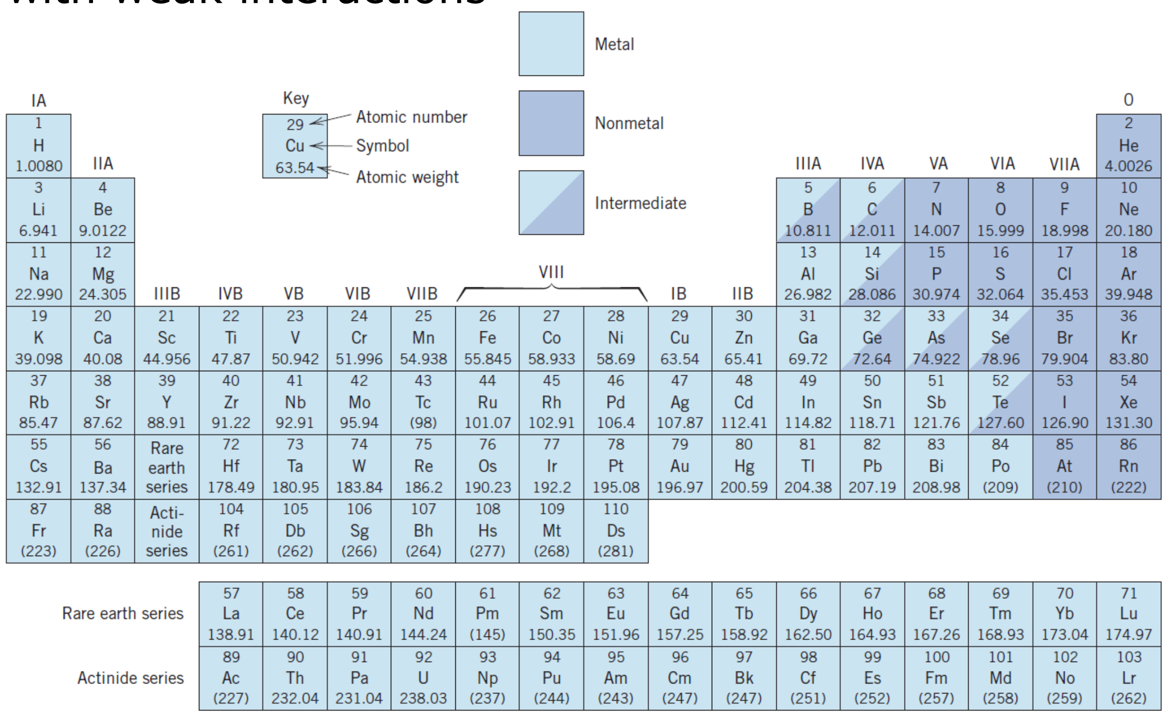
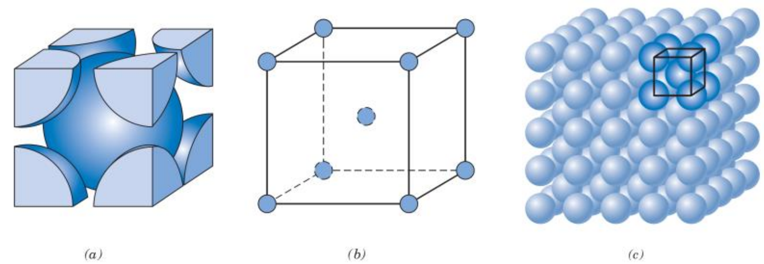
- The periodic table is rich with metallic elements
- Combinations of metals with nonmetals yield ceramics
- Organics are mainly based on covalently bonded carbon structures held together with weak interactions



(Adapted from Callister, William D., and David G. Rethwisch. "Materials science and engineering: an introduction. " Vol. 7. New York: Wiley, 2007.)

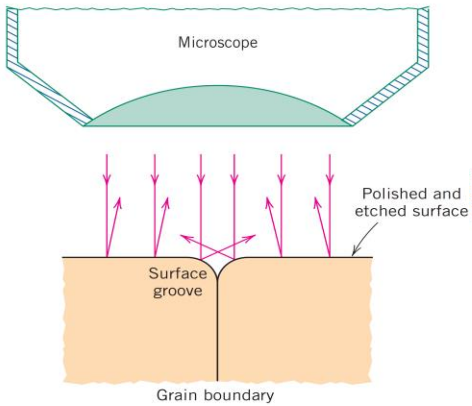
Crystal Structure of Materials

- Repeating units (lego pieces) that can be used to build up the structure of materials
- Seven basic types of crystal systems
  - From cubic to monoclinic
  - Variations in symmetry
- Simple hard sphere ideas can be used to estimate
  - Atomic packing Factor
  - Density

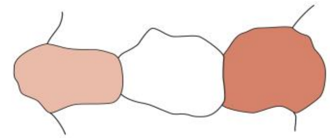


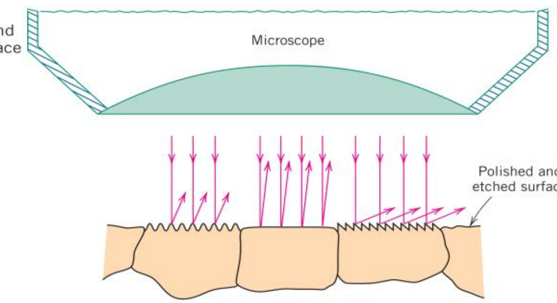
Microscopic Techniques

- Differences in crystallographic orientation affect surface texture at micro- and macroscopic scales.



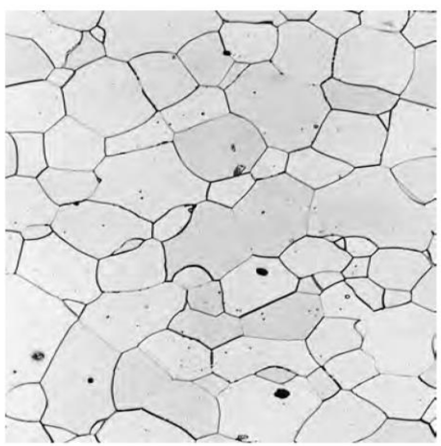
(a)


(a)



(b)

(Adapted from Callister, William D., and David G. Rethwisch. "Materials science and engineering: an introduction. " Vol. 7. New York: Wiley, 2007, Page 99, Figure 4.13)

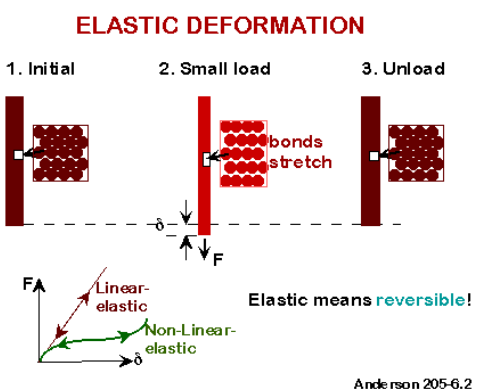

(b)

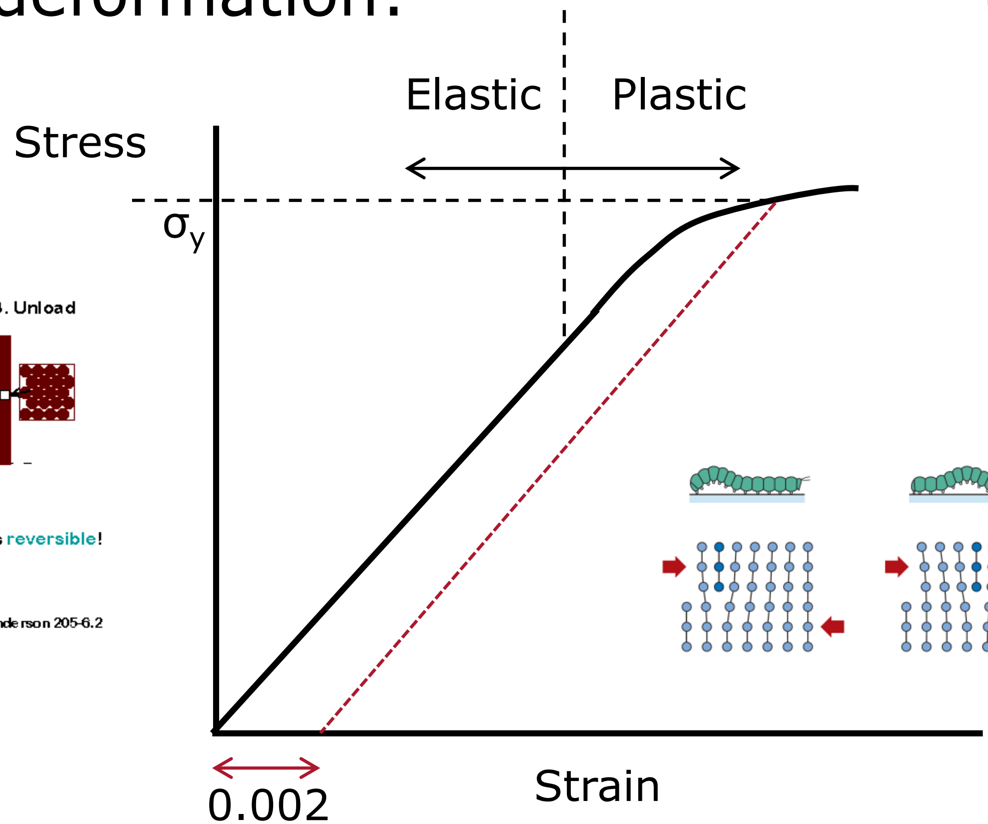

(c)

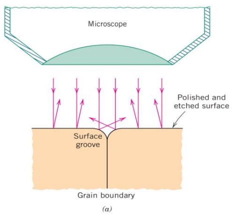
Grains as they might appear when viewed with an microscope.

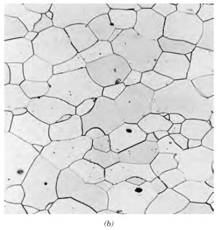
Yield Stress & Deformation

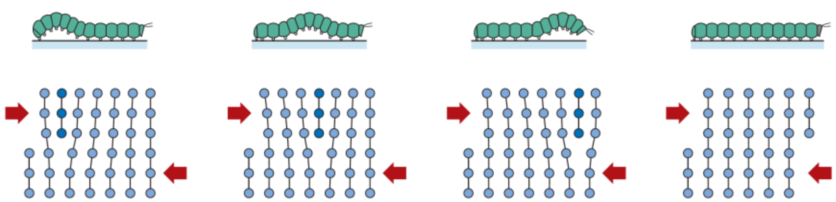
- Associated with the transition from elastic to plastic deformation:





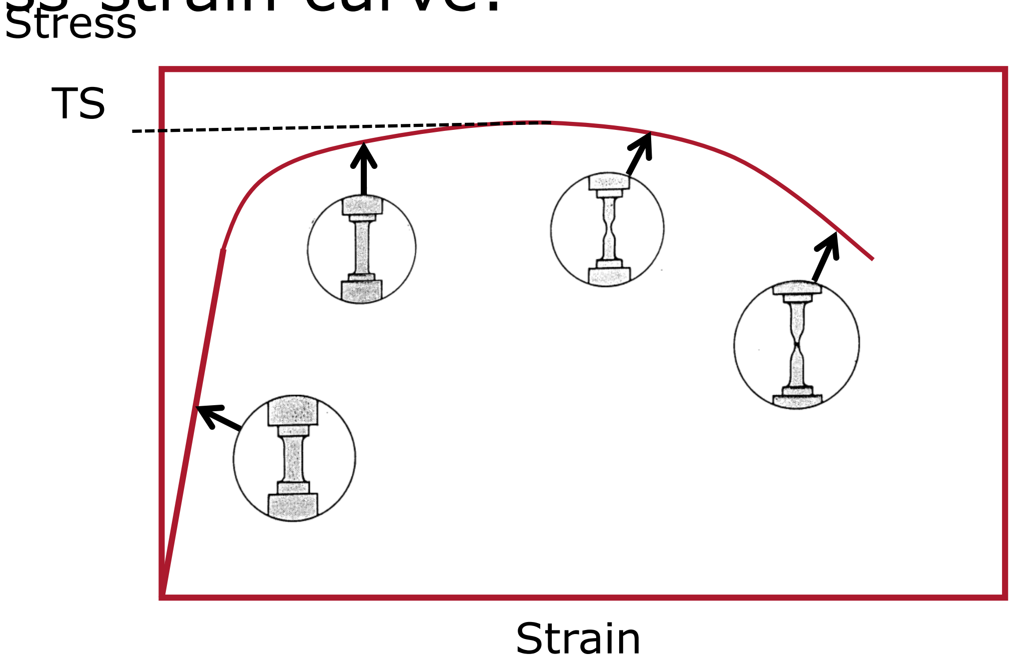






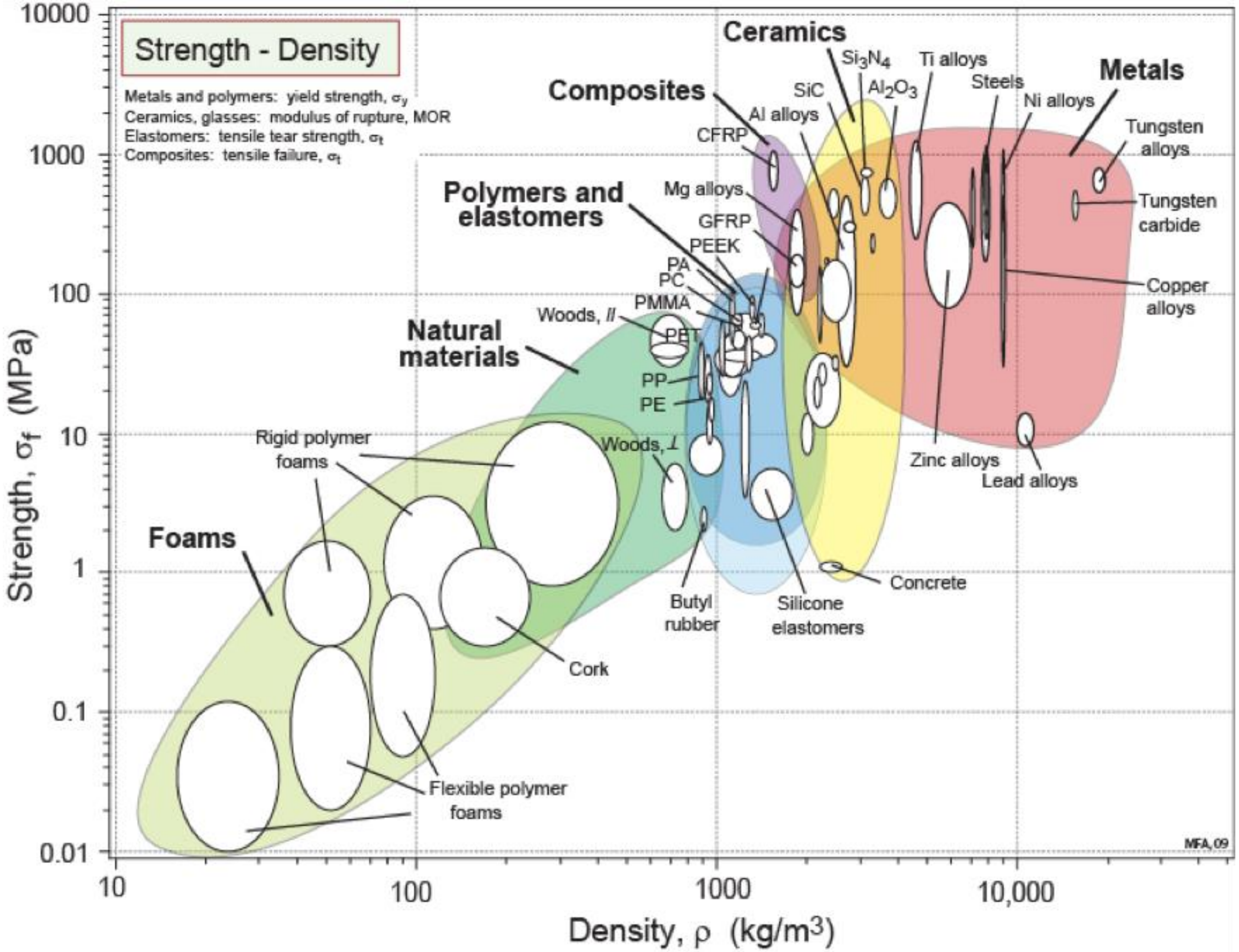
Tensile Strength

- Tensile strength associated with the maximum of the stress-strain curve:



- Not used for design purposes since structures compromised after such large deformations

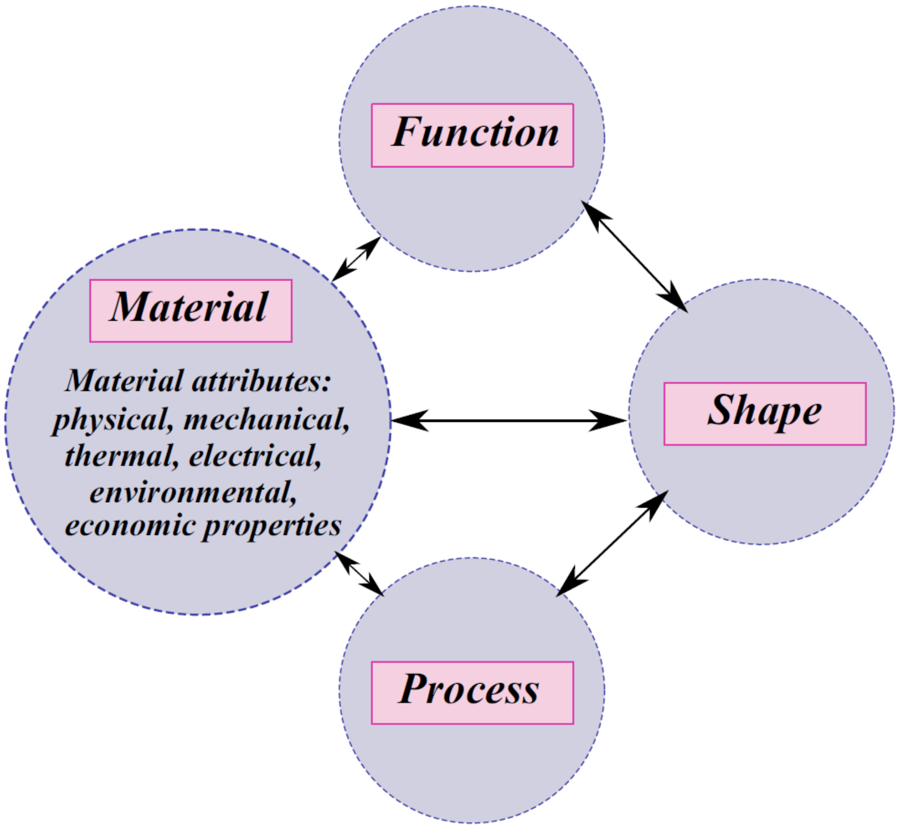
Materials Property Charts



Adapted from Ashby, Michael F. "Materials selection in mechanical design." Metallurgia Italiana 86 (1994): 475-475-

Materials Selection and Design

- "The main problem of materials selection in mechanical design is the interaction between function, material, shape and process."

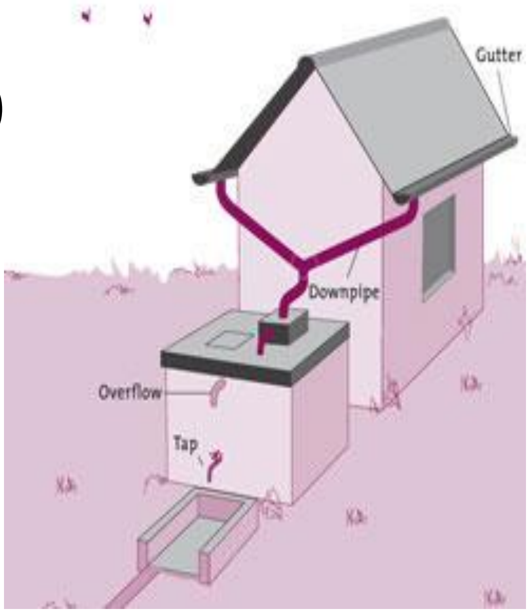


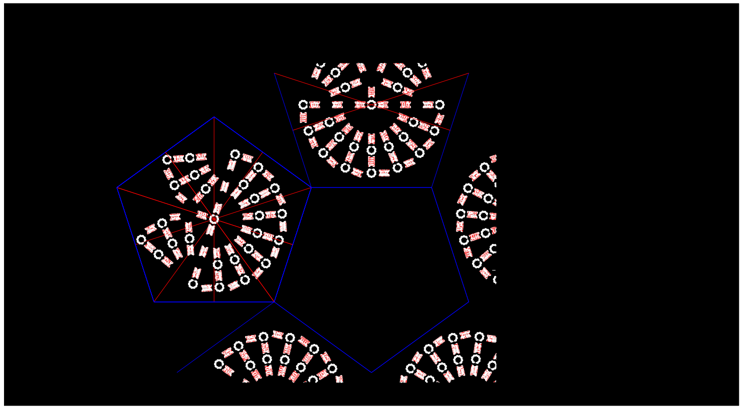
- "Function dictates the choice of both material and shape.
- Process is influenced by the material
- The process determines the shape, the size, the precision and, of course, the cost"

Adapted from Ashby, Michael F. "Materials selection in mechanical design." *Metallurgia Italiana* 86 (1994): 475-475

Projects – Affordable and Sustainable Materials for Buildings

- Features for reducing cost:
  - Low interest loan (PRGF)
  - Subsidized land
  - Ceramic water filters
  - Solar energy
  - Contractor’s profit 24.17%
  - $75/month 30 yr mortgage





Brittle and Ductile Materials

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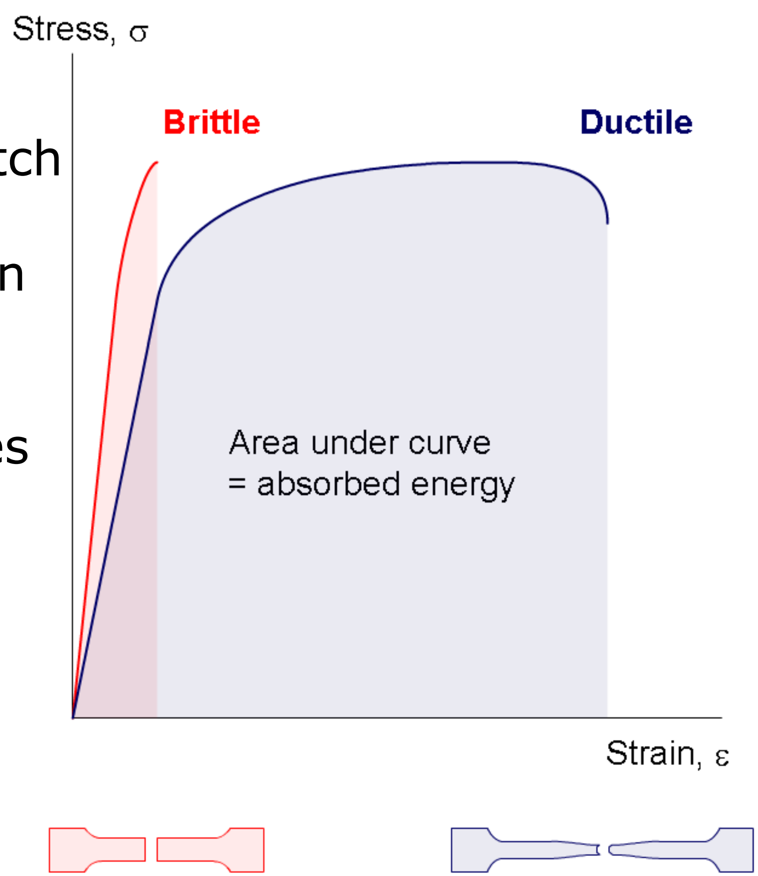
- Energy absorbed by the material up to the point of failure:



- Brittle materials stretch uniformly up to a certain point and then rupture
- A brittle material does not have a plastic region

Ductile materials will withstand large strains before the specimen ruptures

Ductile materials often have relatively small Young's moduli and ultimate stresses

Ductile materials exhibit large strains and yielding before they fail

Project No. 1 - Affordable Housing – The Next Frontier?

- So the real question is whether we can use the same zeal that we use in developing new high tech products to find solutions to global problems of eco-friendly affordable housing?
- As with the other examples – the answer is yes
- However we must adopt a holistic framework that spans the complete range from concepts to reality
  - Non conventional materials
  - Water collection and purification
  - Energy (active and passive solar, wind, hydro, biomass)
  - Integrated rural and urban plans
  - Initial and life cycle costs

Non-Conventional Materials

- Conventional materials represent 70% of the cost of an unaffordable building
- Many of these are imported in developing countries thus making the homes even more unaffordable
- Yet all these countries contain earth, natural fibers, industrial/home/agricultural wastes
- Objective is to develop non conventional materials via intrinsic and extrinsic modification

Typical Matrix and Fiber Materials

Sisal

Polypropylene

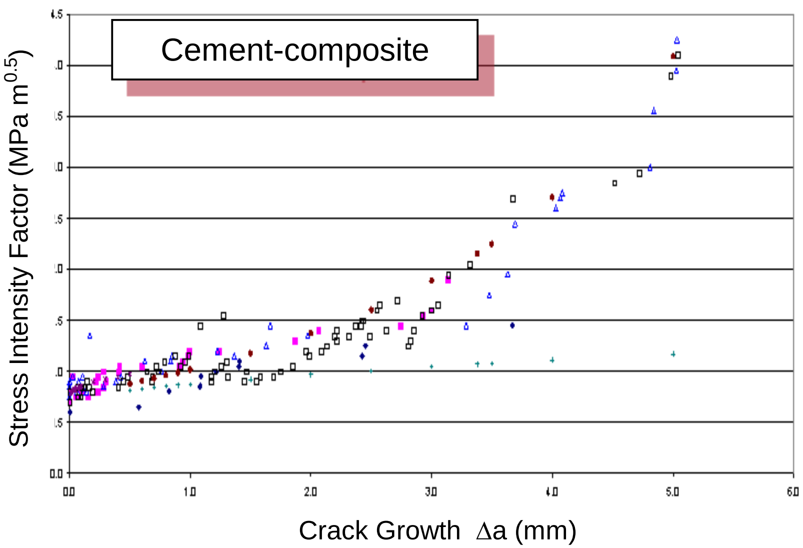
Phylite

Metakaolin

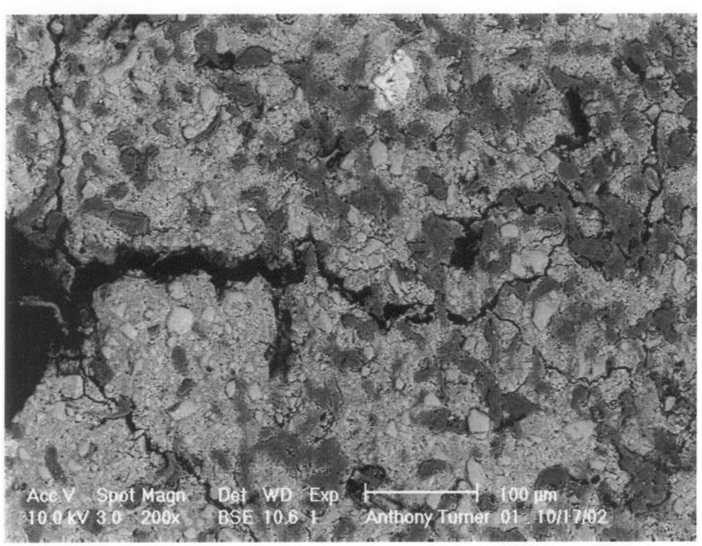
Eucalyptus

Alternative Eco-Friendly Materials

- All countries have industrial and agricultural wastes that can be combined with earth or cement based materials to make building elements
- Examples include straw-reinforced earth, cementitious composites reinforced with natural fibers and polymers reinforced with wood chips
- Such reinforcement gives rise to toughening by crack bridging which increases durability and earthquake resistance of homes and roads

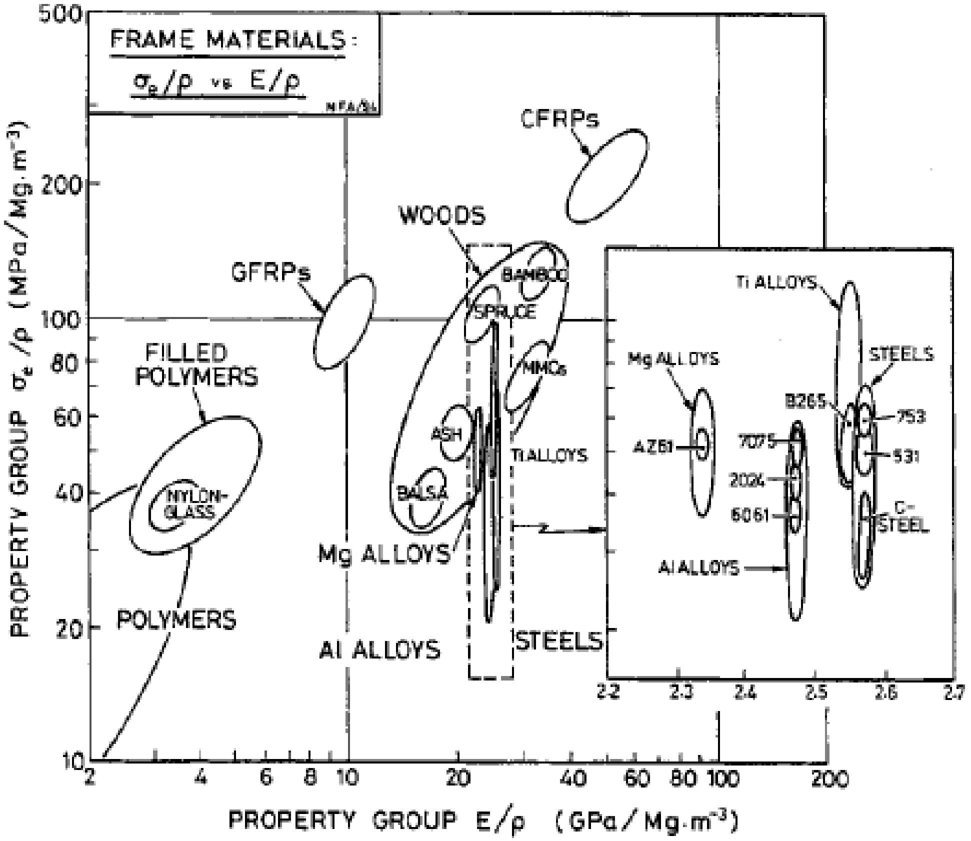


Resistance-curve behavior in natural fiber composites



Backscattered electron image showing cracks and composite bridges. Fibers are seen in dark gray

Background to Bamboo Applications



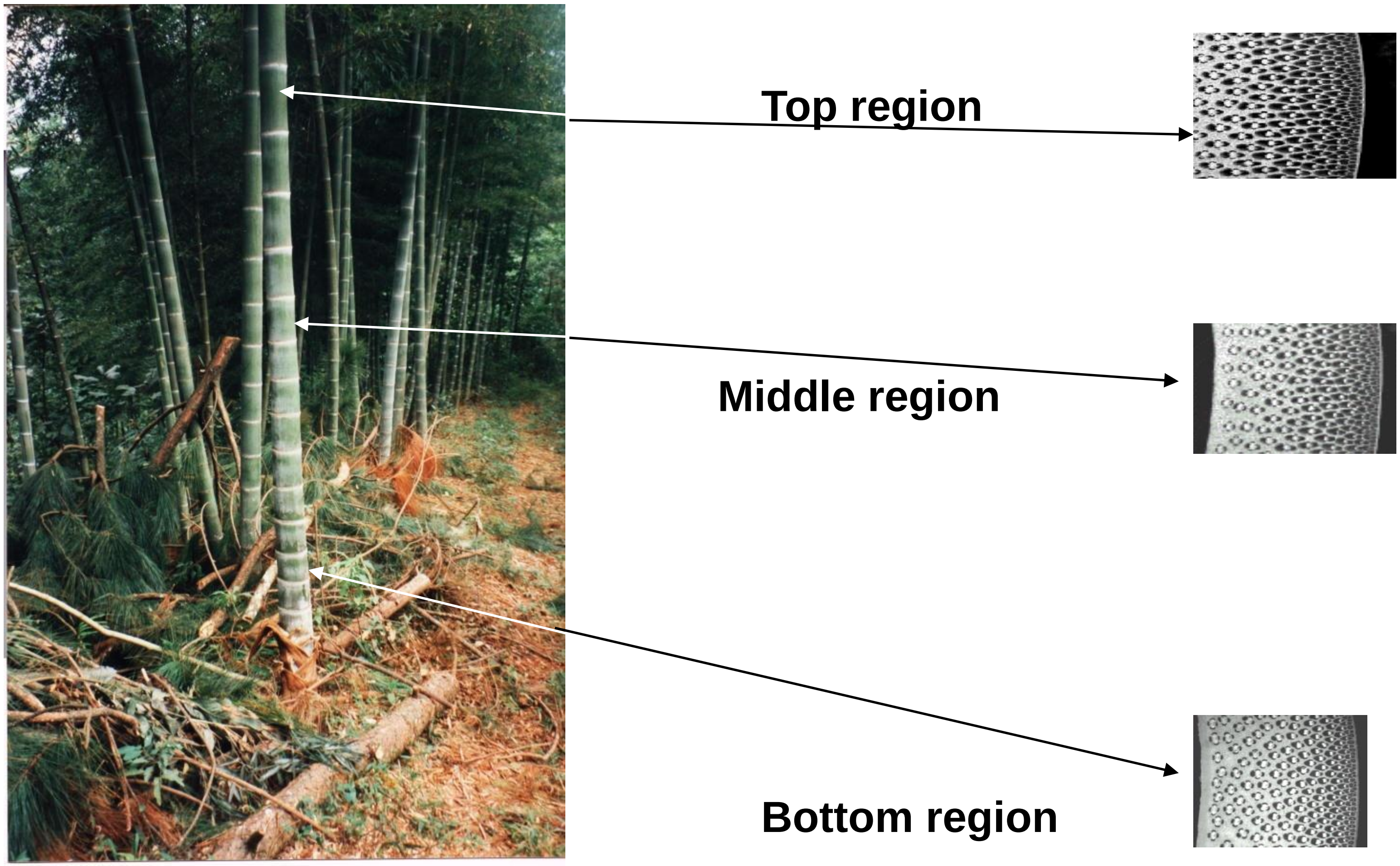
The chart shows that bamboo, which is a very cheap and fast growing material, is the closest material to carbon fiber reinforced plastic in performance for bike frames.

With this information, we felt we could build a high performance bicycle without paying the large expense of having a carbon fiber frame.

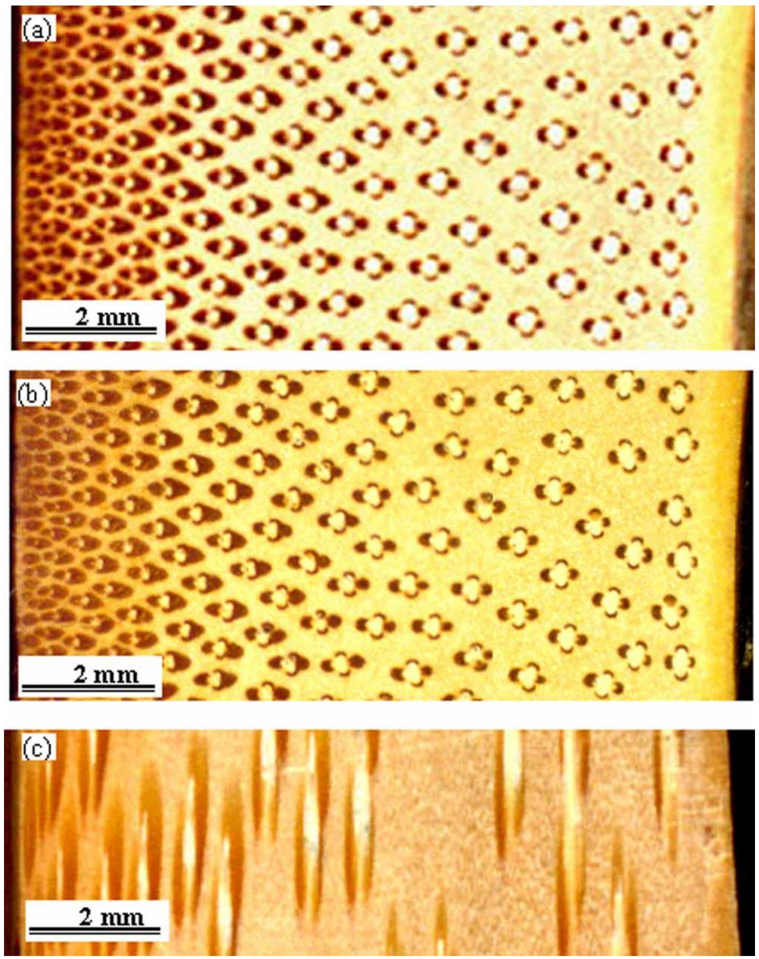
The chart expresses the desire for materials with high Young's modulus and critical stress while having a low density, since in bicycling, light weight is extremely important for high velocity

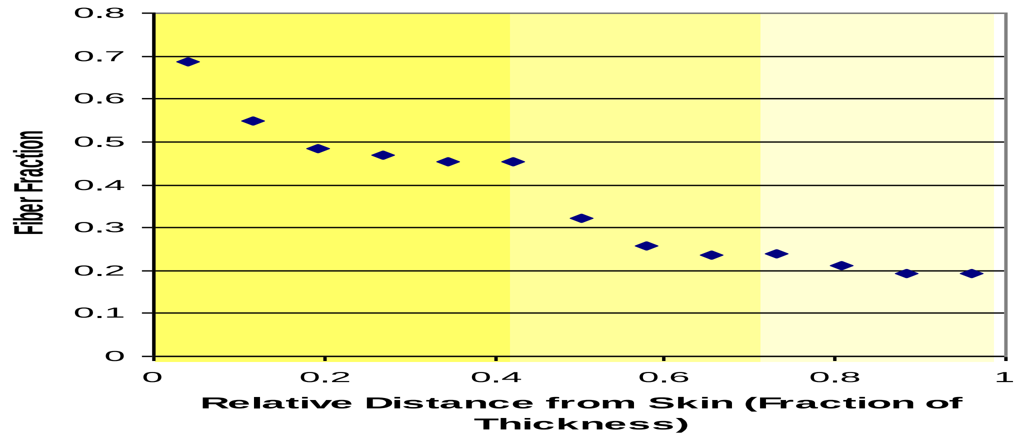
Project - Bamboo Bicycle

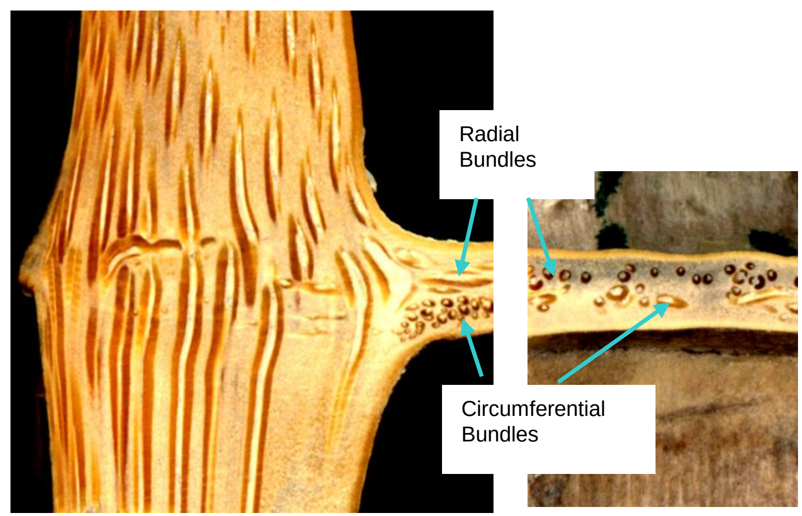
Bamboo as a Material - Plantation of Moso Culm and FGM Cross Section



Scanned Images of Functionally Graded and Intelligentally Adapted Bamboo Structures



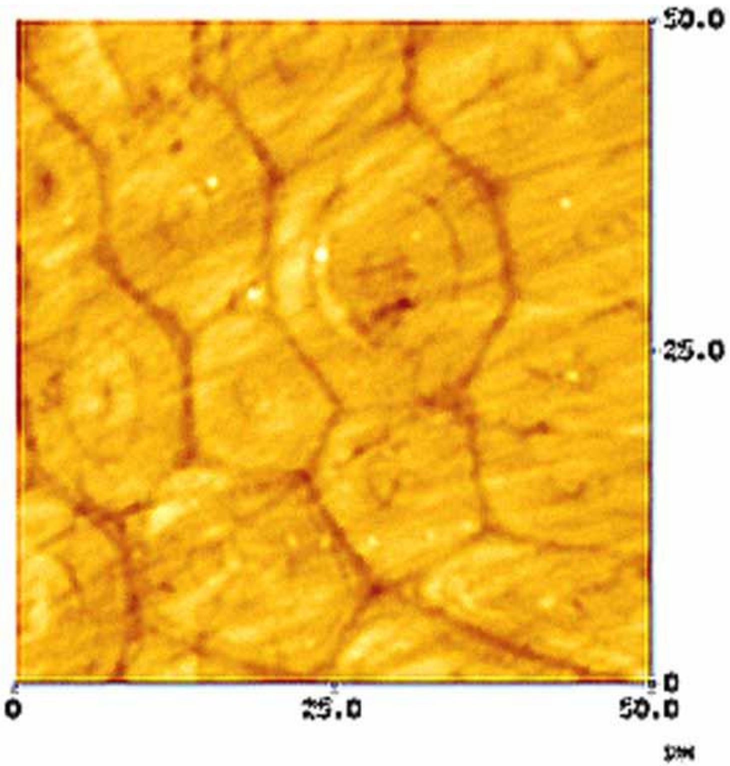




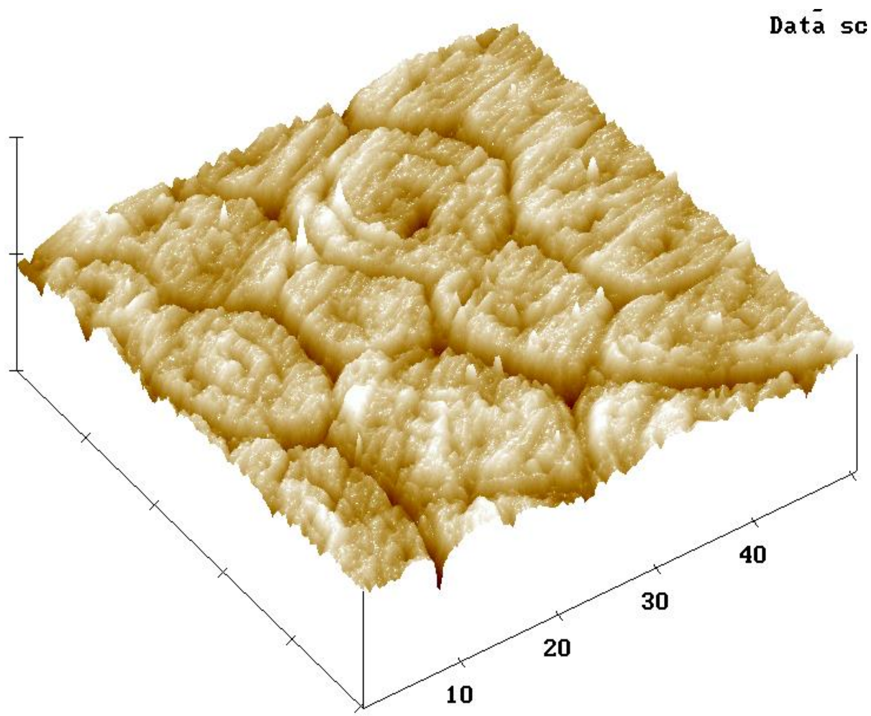
(a) L-R Cross section of the culm wall

(b) L-C Cross section of the diaphragm

AFM Scans of the Fiber Bundles



(a) Surface of vascular bundles in 2-D image



(b) Surface of vascular bundles in 3-D image

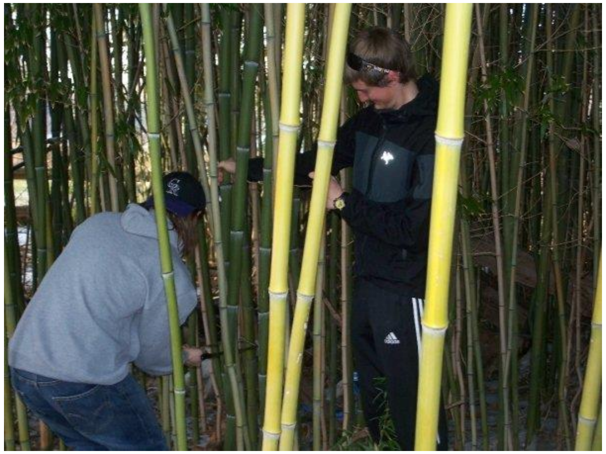
Design Objective

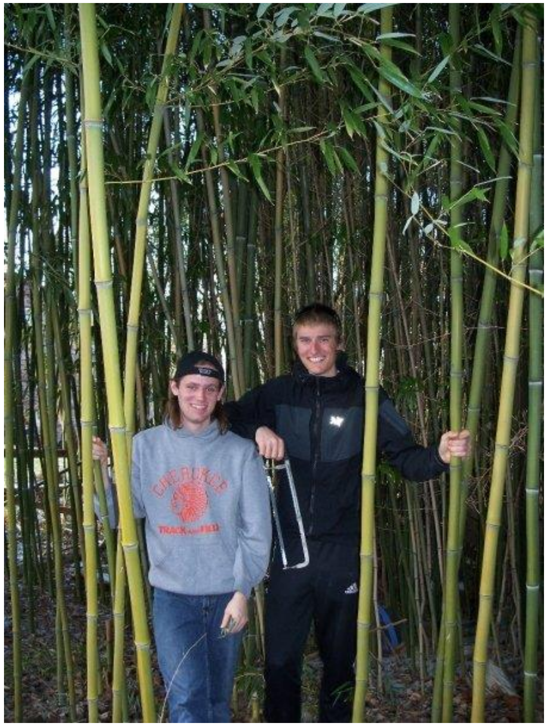
- The objective of this project was to make a bamboo fixed gear bicycle at low cost that would be strong and durable while providing a comfortable ride.

The frame must be light, stiff, and comfortable. The optimization of these three variables is crucial for the design of a successful racing bike or a comfortable road machine.

Gathering the Bamboo

- Bamboo was collected from Pennsylvania along the Delaware River
- When cut down, the bamboo is full of water so experimentation was necessary to determine the best drying technique



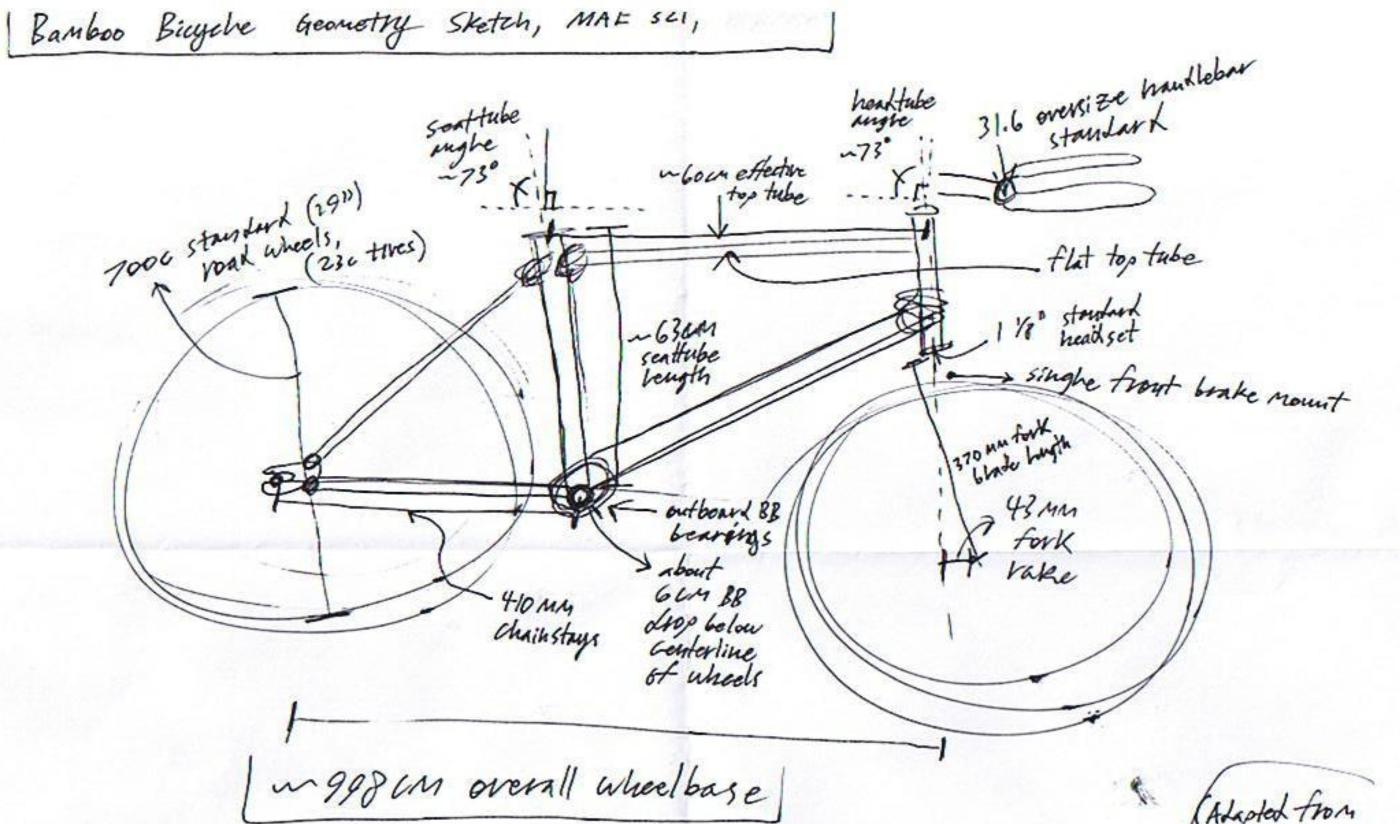


Treating the Bamboo

- Baking the bamboo in an oven helped to remove water but caused cracking at the nodes
- After trying many techniques, we found the most effective approach was to first use a blow torch on the bamboo to seal the nodes and then bake it in an oven.

Testing the baking of bamboo with a fresh piece, a piece that was previously blowtorched, and a fresh piece wrapped in aluminum foil.

Frame Geometry



Notes:
1) 110mm rear hub spacing (track standard)
2) English-thread 68 mm BB shell (standard) from 6061 aluminum
3) 1.5" I.D. headtube, approx. 200mm w/ headset inserted
4) 27.2 O.D. seatube w/ machined aluminum sleeve epoxied. (No front derailleur or)

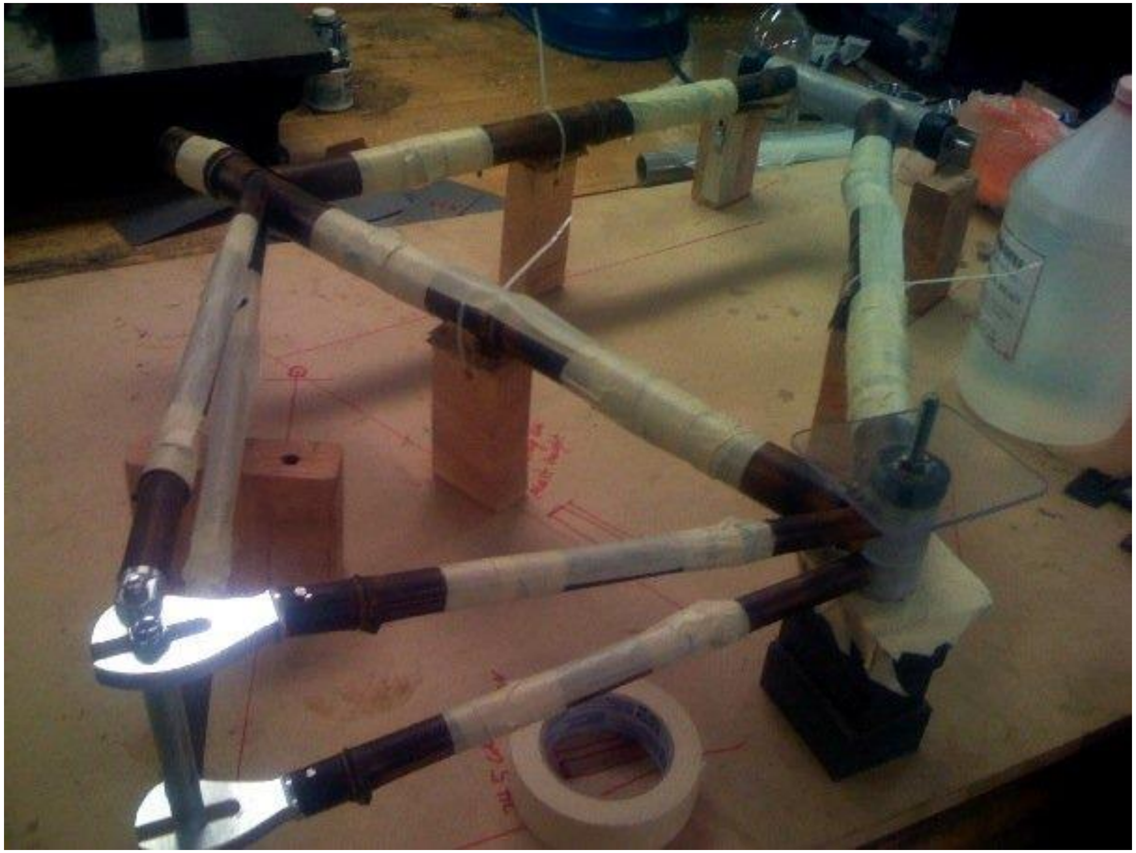
(Adapted from Ibis Silk 61cm road frame geometry) www.ibiscycles.com

Cutting The Bamboo

- The first step was to cut the tubes to a ballpark length to fit the jig
- The tubes were then mitered with a large end mill, roughly the size of the head tube and BB shell to which they mate
- A Dremel was then used to miter the small diameter chainstays and seatstays as well as perfect the miters of the larger tubes

The Jig

- A key piece to putting the frame together was first building a jig
- The jig keeps the tubes together in a specific geometry while being wrapped with carbon tape and epoxy before curing



Wrapping the Tubes

- To connect the tubes together, we used unidirectional carbon fiber tape
- The tape was dipped in an epoxy and wrapped around each joint
- After curing, the joints were extremely sturdy
- Special attention was paid to area going to experience higher stresses, applying extra wrapping

Bamboo Frame Bicycle

WPI

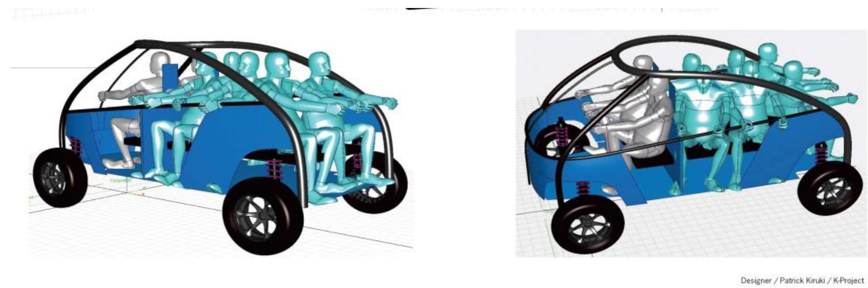
Nick Frey, Will Watts, Douglas Wolf, Tom Yersak

Ezekiel Odeh

Bamboo Applications

Bamboo Racing Bicycles

Pictures by courtesy of Princeton University Website



Bamboo People Mover
Patrick Kiruki

Bamboo Solar Vaccine Refrigerator

Bamboo Wind Turbine
Ting Tan – University of Vermont

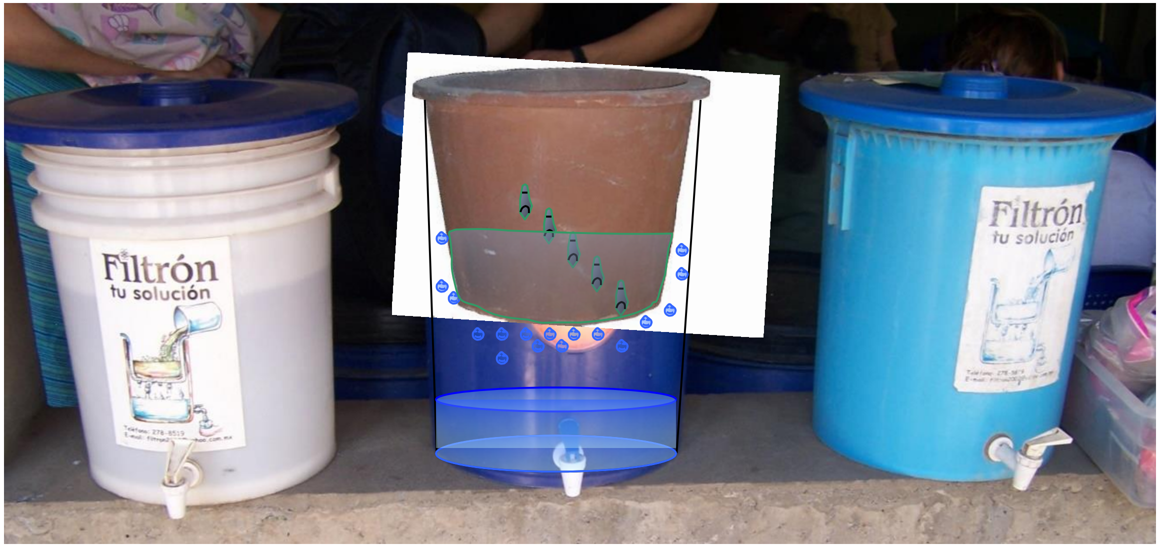
Project-Based Learning: Clean Water Project

- The problem of contaminated water is the single biggest cause of the steep decline in life expectancy in Africa
  - Impact bigger than that of HIV
  - Example of Nigeria
  - 5000 lives lost per day
- Major problem is due to microbial pathogens (E.Coli)
- Other global challenges due to water contamination include chemical contamination (fluoride, arsenic and heavy metals) in Asia, Africa, Latin America
- Holistic approach needed to develop solutions from science to technology &evidence-based policy & entrepreneurship

Water Treatment Methods

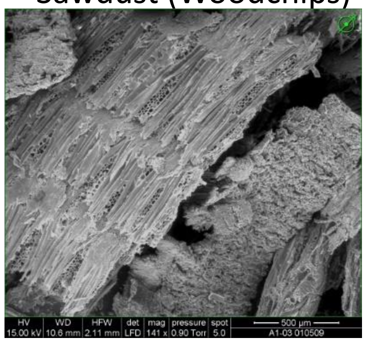
Solutions	Pros	Cons
Boiling Water	- 100% potable if boiled for at least 20 min. - Can be done in the home all year round.	- Requires time to gather fuel (fire wood) - Requires time for heating and cooling - Causes a Change in the taste of water - Method does not remove turbidity
Adding Chlorine	-Effectively kills bacteria -Simple to use -Can be used anytime -Low cost technology	-Effects the taste of water -Must be applied periodically -Does not remove turbidity -Most be purchased and transported
SODIS	-Low cost -Can be large or small -Remove turbidity -Can be us	-Does not work in shade, night or rainy season -Requires 4-6 hours to reach required to heat -Requires Time for water to cool -Change in the taste of the Water. -Does not remove turbidity
Bio Sand Filter	- Can be large or small -Easy to use -Local materials	-Appropriate sand must be available. -Does not remove microbio. contaminants -Time to cultivate bio-sand.
Filtròn Water Filter	- Kills bacteria 99% - Easy to use -One time transportation -No change of taste -Culturally acceptable - Self-encased water Container permits serving. - Made locally -Works all year around 24 hours a day. -Low cost	- Cost, US$ 7.50 to $25.00 (depending on country) - Heavy compared to the other systems. - Fragile, easy to break - Periodic cleaning is required (turbid water clogs the filtering element). - Combustion for the production process - Should be replaced after two years
PuR (P&G)	-Effective -Good for emergencies	-expensive (US $ 4.20 a month) US $0.14 cents a day for 20 liters

Point-of-Use Water Filtration Systems

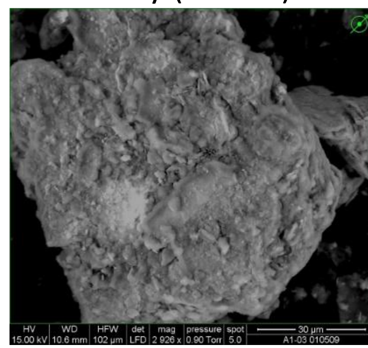


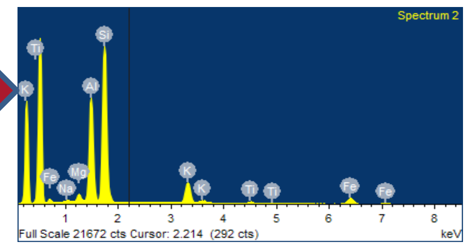
Materials Science: Surface Morphology and Chemical Composition - SEM/EDX

Sawdust (Woodchips)

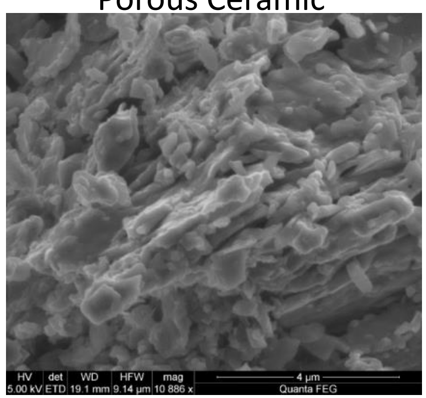


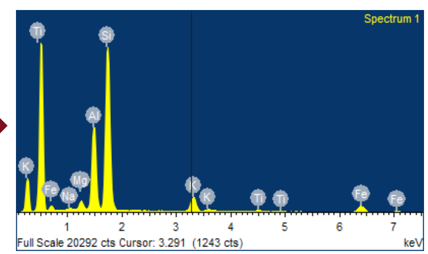
Clay (Redart)

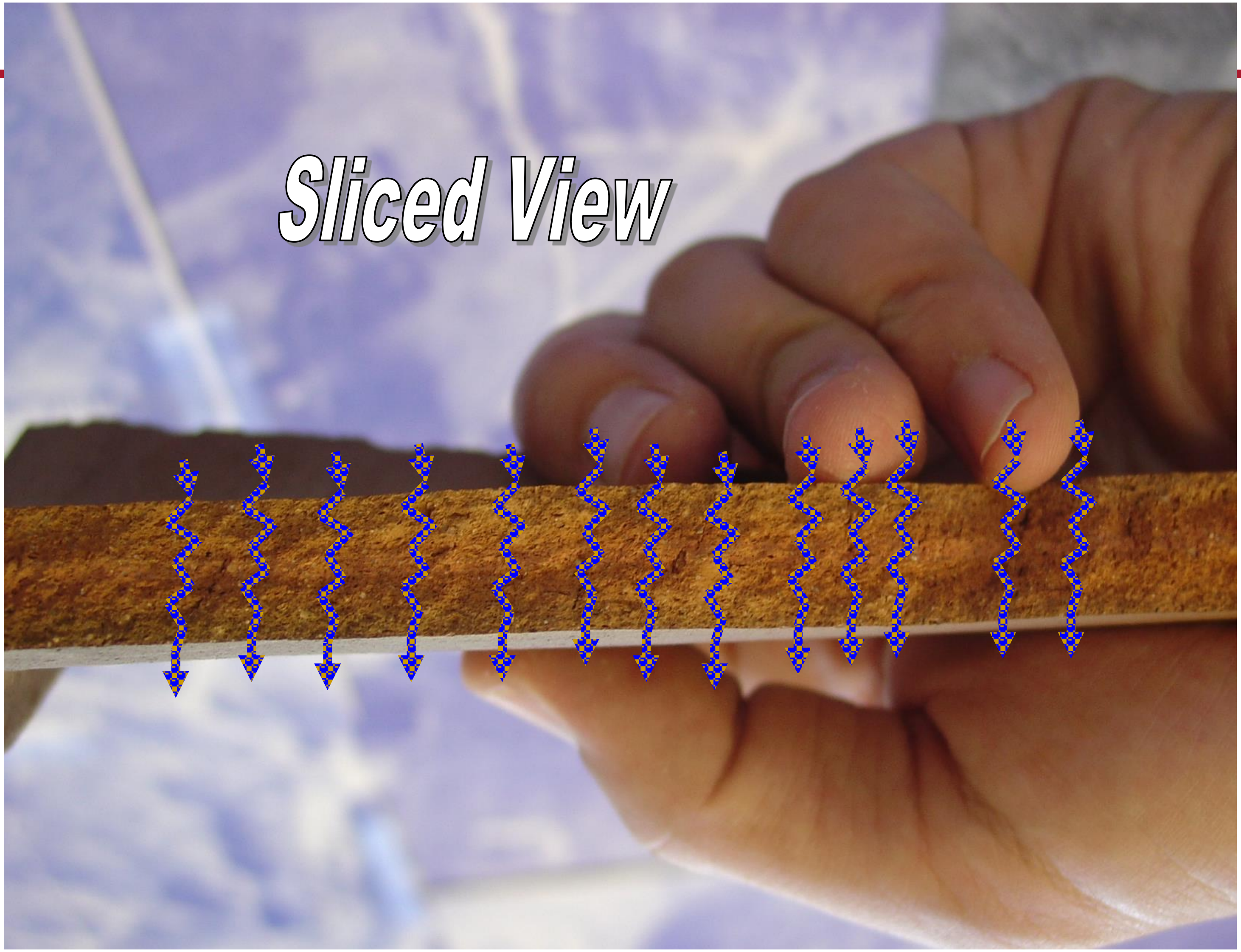




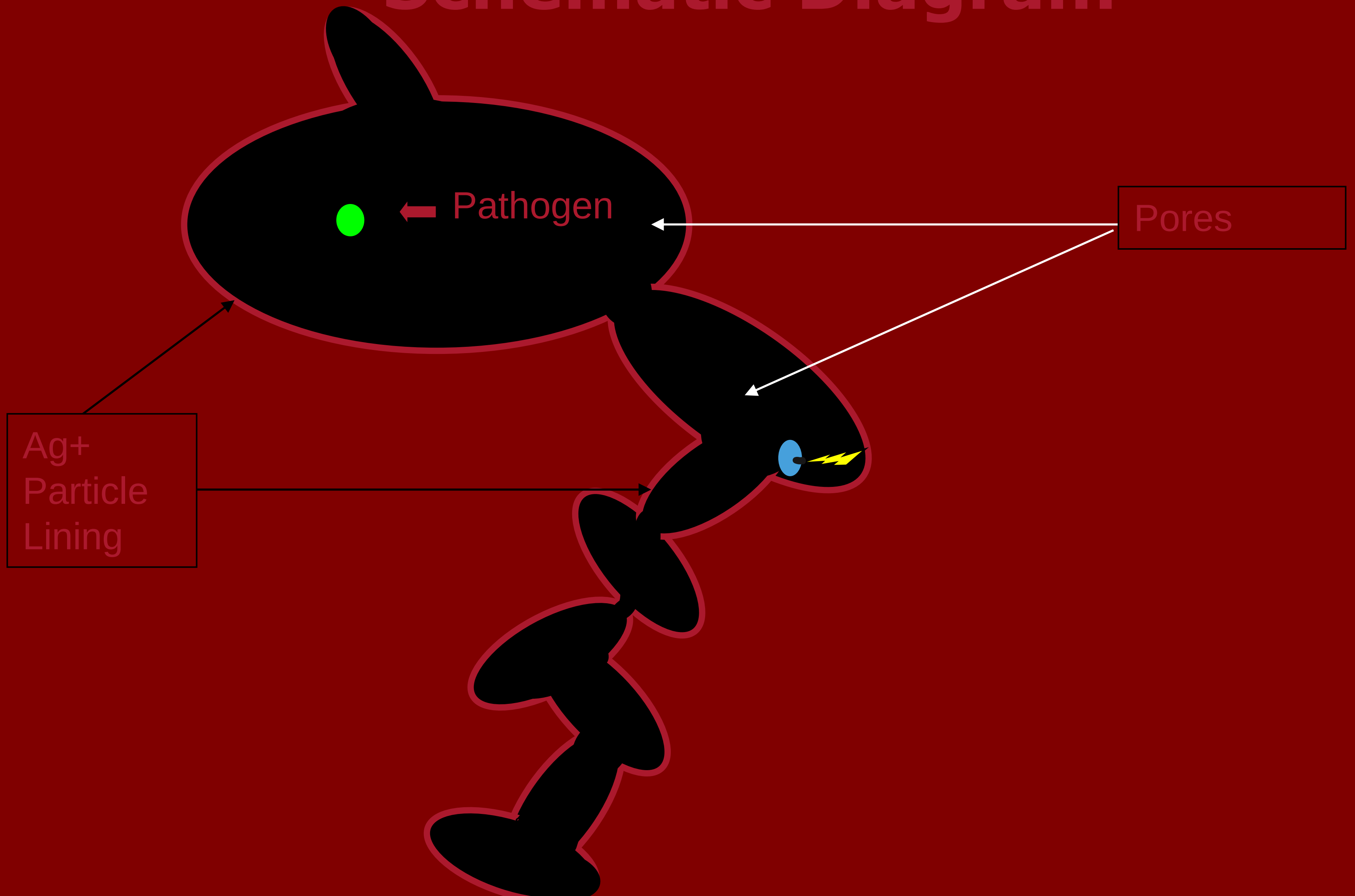
Porous Ceramic






Sliced View

Schematic Diagram



Size Comparison

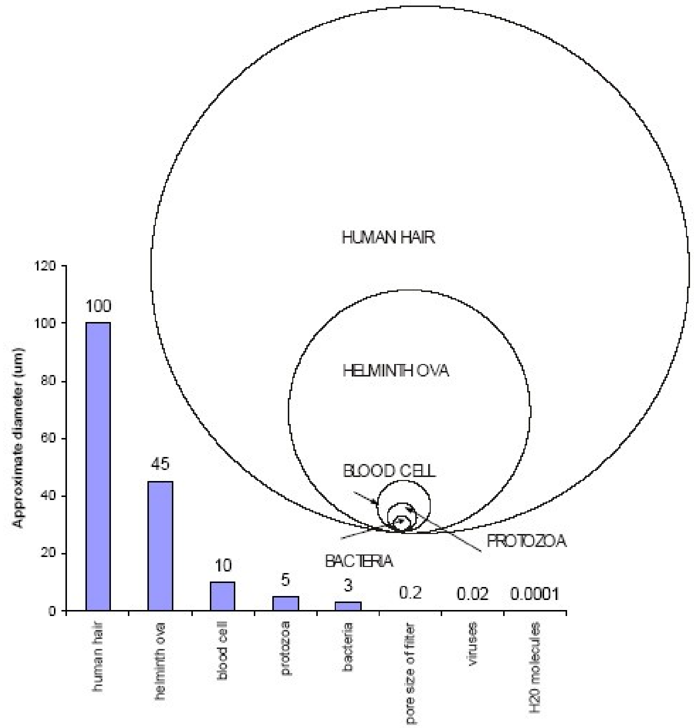


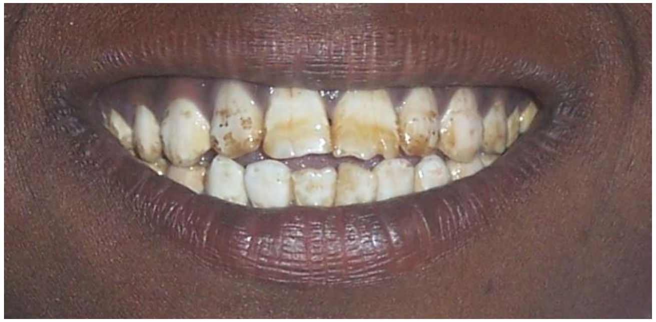
Figure 2. Comparison of relative sizes of various contaminants in water. Based on these, the pore size of the ceramic filter, at 0.2μm, would be about the size of a full stop on this page.

E. coli Filtration Tests of Non-Coated Ceramic Water Filters

Volume Fraction Clay:Sawdust	Test 1	Test 2	Average $\pm$ Range
45:55	99.97	99.85	99.91 $\pm$ 0.06
50:50	99.99	99.93	99.96 $\pm$ 0.03
55:45	99.52	99.84	99.68 $\pm$ 0.16
65:35	99.99	99.99	99.99 $\pm$ 0.00

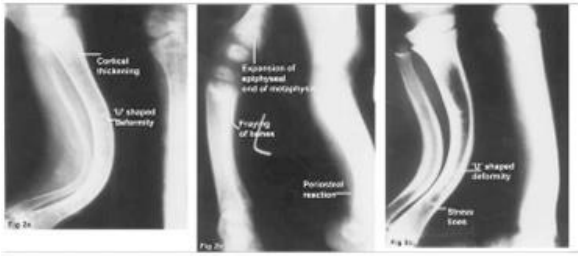
Microbial and Fluoride Removal

- High fluoride content can cause serious health problems[1]
  - Occurs naturally in deep bore holes
  - Groundwater with high fluoride concentrations can be found in many areas of the world, including large parts of Africa, China, Mexico, the Middle East and southern Asia (India, Sri Lanka)[1]
  - Example: A "national health problem" in India
    - 17 out of 32 states and territories have naturally high concentrations of fluoride (UNICEF, 1999). As high as 48 mg /L in Rewari District of Haryana. [2]
    - 60–70 million people in India are at risk
- High fluoride intake causes dental and skeletal fluorosis; osteoporosis; nausea; adverse effect on kidneys
- The question is – can we combine fluoride and microbial removal?



Dental fluorosis: Soft, pitted teeth

Skeletal Deformities: Bihar, India



1: UNICEF Handbook on Water Quality, Released: 16th April, 2008

2: UNICEF 1999 *State of the art report on the extent of fluoride in drinking water and the resulting endemicity in India. Report by Fluorosis Research & Rural Development* Foundation for UNICEF, New Delhi.

Clay/HA Filters for Fluoride Removal

- Hydroxyapatite (HA): $Ca_5(PO_4)_3(OH)$
  - Made from simple acid/base reaction
  - Mechanism of removal involves:
    - Crystal substitution (OH^-/F^-)
    - Fluorite précipitation (CaF_2)
    - Surface sorption
- Redart Clay
  - Previously used to remove bacteria and microbial organism in the form of frustum-shaped filter
- Mixing of Clay with HA
  - “A combo” with the potential to remove both Fluoride and Bacteria
  - Ease of forming
  - Cost
- Strategy
  - Fundamental Study (Adsorption study)
  - Proof-of-concept
    - Disc-shaped filter
    - Frustum-shaped filter

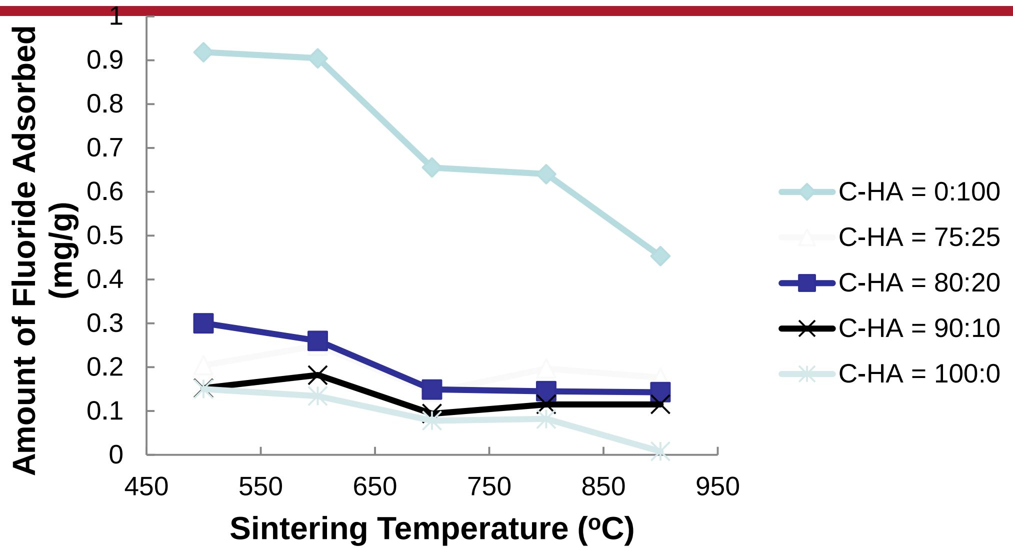
Two simple routes for synthesis of HA:

1. $10\ Ca(NO_3)_{2,}4(H_2O) + 6\ NH_4H_2PO_4 + 14\ NH_4OH = Ca_{10}(PO_4)_6(OH)_2 + 20\ NH_4NO_3 + 50\ H_2O$
2. $10\ Ca(OH)_2 + 6\ H_3PO_4 = Ca_{10}(PO_4)_6(OH)_2 + 18\ H_2O$

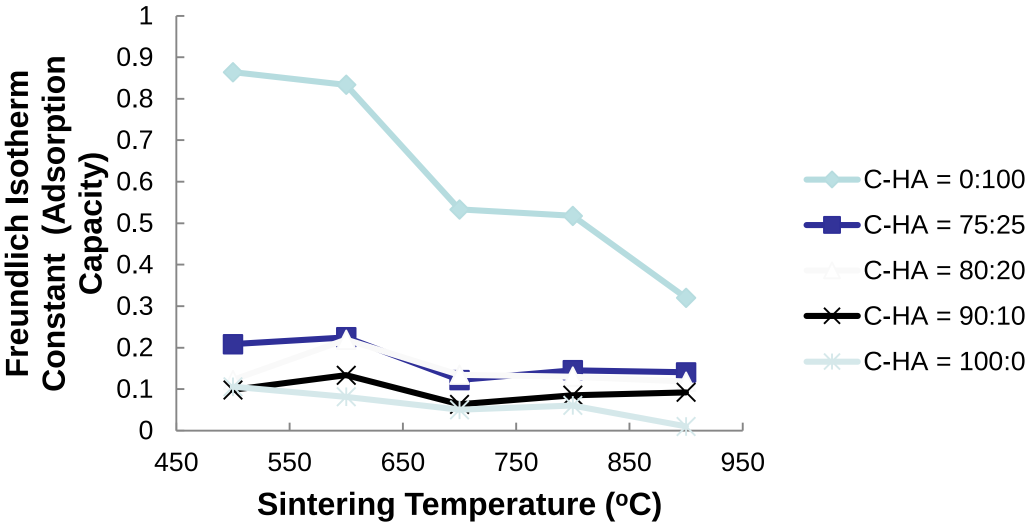
The principal reaction is hydroxyl-fluoride exchange of apatite:

1. $Ca_5(PO_4)_3(OH) + F^- = Ca_5(PO_4)_3(OH_{1-x}, F_x) + (1-x)F^- + xOH^-$
   where x is the degree of fluoridation
2. $Ca_5(PO_4)_3(OH) + 10F^- = 5CaF_2 + (PO^{3-}{}_4)3 + OH^-$

Results



Effect of sintering temperature of the adsorbent on the amount of fluoride that is adsorbed from water with an initial fluoride level of 10mg/L. Results was obtained for other fluoride concentration.

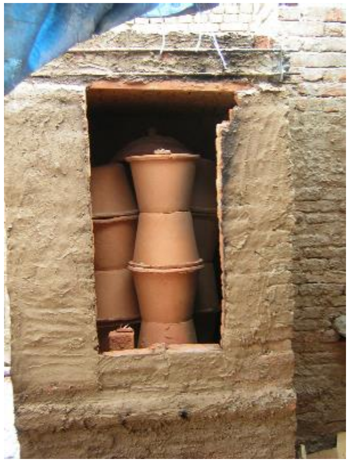


An overall picture of the adsorption capacity of the C-HA adsorbent using the Freundlich isotherm constant

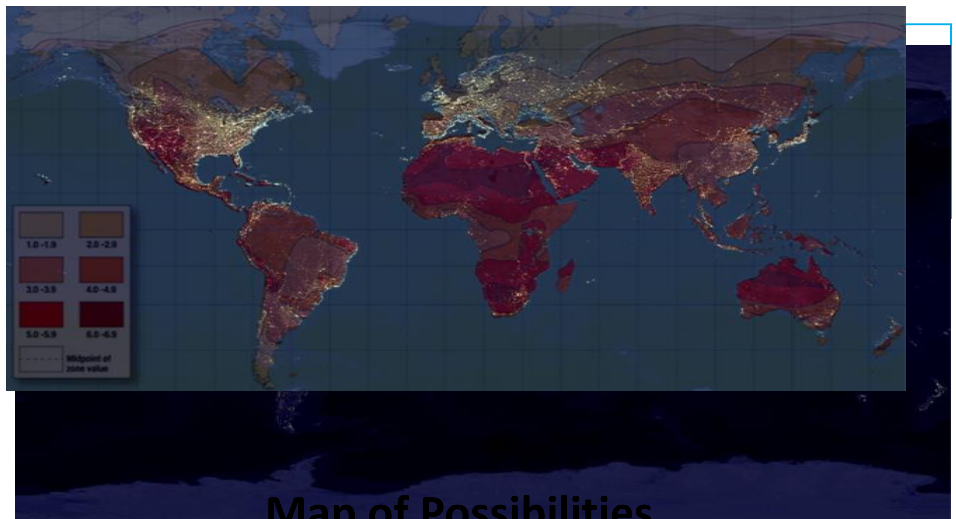
Filter Processing - From Ideas to Markets







Motivating Technological Independence in Africa: Solar Energy



Map of Possibilities

Map of the World at Night

Mpala Project-Based Module

- 49,107 acres of savannah and dry woodland, 1 hour from Nanyuki, on the Laikipia Plateau in North Central Kenya
- MRC staff members and immediate families housed in various community villages
  - Homes were generally a single 20-ft diameter room. People used old bed-sheets to partition the space to create a living room and 1-2 bedrooms. Household sizes ranged from 1-8 persons.
- Because it is in a remote area, access to basic necessities is a challenge.
  - Clean drinking water is available to staff and researchers through boreholes and purified rainwater collection.
  - Electricity, however, is only provided to the research community, through a combination of solar panels and generators

Project-Based Module on Clean Energy

Project-Based Approach

- Identify societal problem and/or developmental need
- Explore possible solutions within a scientific and engineering framework
- Develop and test potential solution
- Propose potential strategies for going from ideas to markets/policy

From Problem to Solutions

Inspiring Young People and a New STEM Culture: Battlecry WPI/Africa

MS4SSA
Math and Science for Sub-Saharan Africa

NEW JERSEY CENTER FOR TEACHING & LEARNING

WPI

THE WORLD BANK

Inspiration for STEM to Young People

- Robotics is a source of inspiration for young people to pursue STEM
- This has been recognized Dean Kamen (WPI Alum) and founder of FIRST Robotics …
  - Alloys
  - Semiconductors
  - Polymers
  - …

| Hard materials

| Soft materials

WPI Robotics Modules

- Project-based extra-curricular program designed to inspire students
- Promote experiential learning and creativity within a team-based friendly competitive framework
- Modules integrate mechanical design, electronics and motors, and computer science
- Scope of Program
  - Mechanisms and motors
  - Programming
  - Three-dimensional printing

Summary and Concluding Remarks

MS4SSA
Math and Science for Sub-Saharan Africa

- This lecture presents an introduction to the MS4SSA materials, project-based and robotics modules
- Project-based approach is proposed to motivate the students to learn and integrate concepts
- Materials science and engineering projects enable students to have better understanding of concepts while applying them to real world problems and opportunities
- Robotics inspire young people to explore STEM fields while developing a culture of intelligent engineering
- Look forward to working with individual African Governments and African Nodes on the implementation of the project-based modules
  - Gambia, Ghana, Ethiopia, Zanzibar, Lesotho, Malawi, Mauritius, Mozambique, Nigeria, Rwanda, Burkina Faso, Benin, Guinea, Senegal, Togo, Niger, Mauritania

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