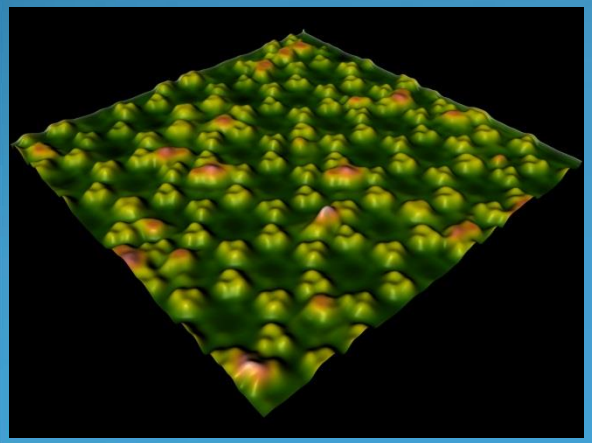
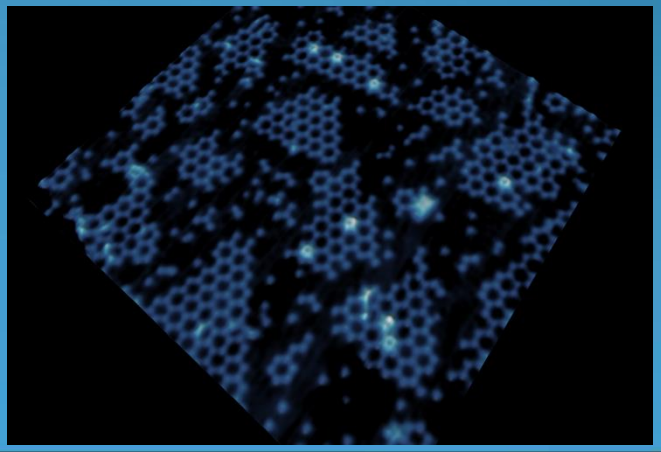
Nanotechnology : Changing the World at the Nanoscale

Dr. Esmeralda Yitamben

African School of Fundamental Physics (ASP 2024)
Marrakech, Morocco
16 July 2024





UNDER THE HIGH PATRONAGE OF HIS MAJESTY KING MOHAMMED VI

Kingdom of Morocco
Ministry of Higher Education, Scientific Research and Innovation

THE EIGHTH BIENNIAL AFRICAN SCHOOL OF FUNDAMENTAL PHYSICS AND APPLICATIONS (ASP2024)

Co-organized by Cadi Ayyad University and Mohammed V University at Faculty of Science Semlalia, Marrakesh, Morocco

April 15th–19th and July 7th–21st, 2024

ASP MISSION

To increase capacity development in fundamental physics and related applications in Africa. The ASP has evolved to be much more than a school. It is a program of actions with directed ethos toward physics as an engine for development in Africa

SCIENTIFIC PROGRAM

▸ TOPICS

- Nuclear & Particle Physics
- Medical and Radiation Physics
- Applied and Industrial Physics
- Theoretical and Computational Physics
- Space Physics, Astrophysics & Cosmology
- Physics for Sustainable Development
- Condensed and Materials Physics Biophysics
- Capacity Development and Retention Discussion
- Physics Education, Outreach and Communication

▸ ACTIVITIES

- Outreach for Secondary Schools April 15th–19th, and July 15th–19th, 2024
- Physics lectures, tutorials and hands-on experimentation for students, July 7th–21st, 2024
- Workshop for High School Teachers, July 8-12, 2024
- ASP Forum, July 13th, 2024

INTERNATIONAL ORGANIZING COMMITTEE (IOC)

B. Acharya (ICTP and King's College London), K. Assamagan (BNL), C. Darve (ESS), F. Ferroni (INFN), M. Laassiri (BNL)

INTERNATIONAL ADVISORY COMMITTEE (IAC)

N. Blackburn (BNL), M. Campanelli (UCL), D. Charlton (University of Birmingham), S. Connell (University of Johannesburg), A. Dabrowski (CERN), T. Ekelof (Uppsala University), J. Ellis (King's College London), L. Elouadrhiri (TJNAF), E. G. Ferreiro (USC), H. Gao (BNL), J. Govaerts (UCL), J. Gray (ASP), B. Heinemann (DESY), H. Holtkamp (SLAC), J. Huston (MSU), O. Ka (UCAD), Y. K. Kim (Chicago), D. Kobor (UASZ), S. C. Lee (Academia Sinica), B. Masara (SAIP), H. Montgomery (TJNAF), S. Muanza (CNRS-IN2P3), R. Nemutudi (iThemba LABS), M. Nxumalo (NRF), F. Quevedo (University of Cambridge), L. Rivkin (PSI & EPFL), L. Serafini (INFN), H. Severini (Oklahoma), P. Skands (Monash), E. Tsesmelis (CERN), L. Vacavant (CNRS-IN2P3), Z. Vilakazi (Witwatersrand), H. B. White Jr. (Fermilab), J. Yu (UTA)

LOCAL ORGANIZING COMMITTEE (LOC)

A. Adahchour (UCA), A. Arhrib (UAE), A. Belhaj (UM5), D. Benchekroun (UH2C), Z. Benkhaldoun (UCA), A. Boskri (UCA), H. Bouabid (UM5), M. Daoud (UIT), L. B. Drissi (UM5), M. Gouighri (UIT), Y. Hassouni (UM5), A. Hoummada (AH2ST), A. Jabiri (UCA), T. Khalla (UCA), Y. Khoulaki (UH2C), A. Lahbas (UM5), B. Manaut (UMSB), M. Ouchrif (UMP), R. Sebihi (UM5)

CHAIRS

Mohamed Chabab (UCA)
Farida Fassi (UM5)

https://www.africanschooloffphysics.org/asp2024/

Scan me

designed by

A little about me …

IBM Research

Argonne NATIONAL LABORATORY

Sandia National Laboratories

Merck

Western Digital

Outline

- What is nanotechnology?
- What is its current impact?
- What is its future impact?
- Nanotechnology in Africa

What is Nanotechnology?

- Exploring and exploiting unique phenomena occurring at the atomic, molecular, and supra-molecular scale to create materials, devices, and systems with new and useful properties and function.
- Scale ➔ 1 – 100 nm
- Highly interdisciplinary
- Potentially disruptive technology

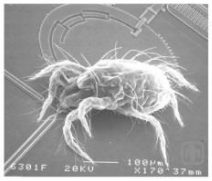
10^{7} meters

10^{-1} meters

10^{-9} meters

The Scale of Things – Nanometers and More

Things Natural



Dust mite

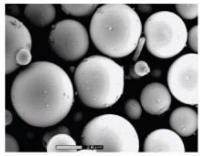
200 μm

Ant

~ 5 mm

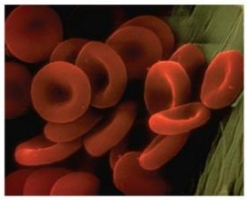
Human hair

~ 60-120 μm wide



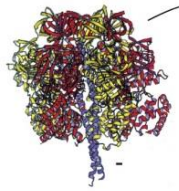
Fly ash

~ 10-20 μm

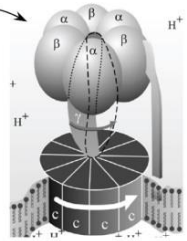


Red blood cells

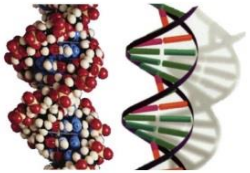
(~7-8 μm)



~10 nm diameter

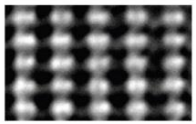


ATP synthase



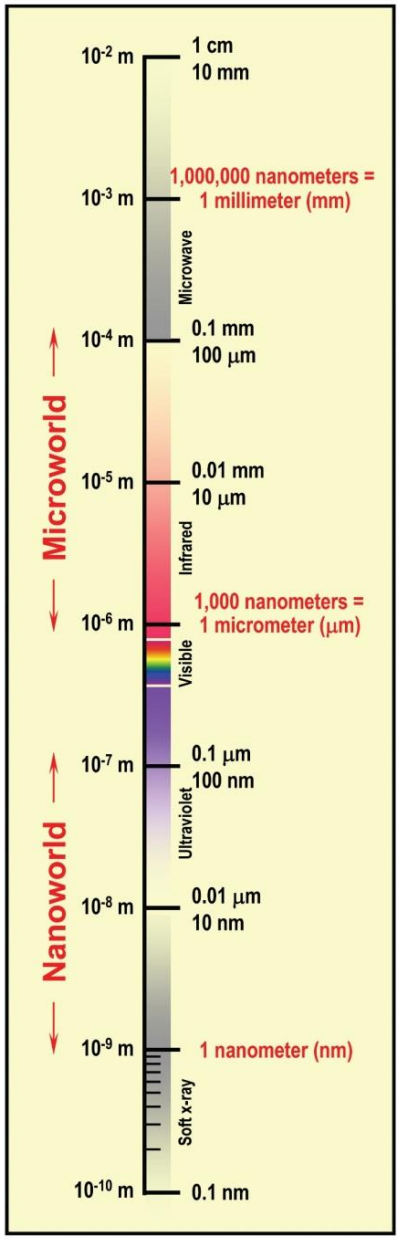
DNA

~2-1/2 nm diameter

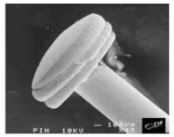


Atoms of silicon

spacing 0.078 nm

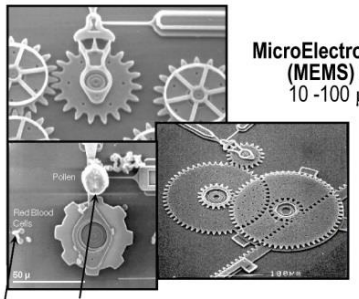


Things Manmade



Head of a pin

1-2 mm

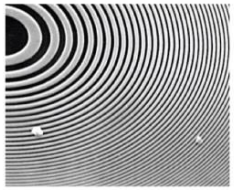


MicroElectroMechanical (MEMS) devices

10 -100 μm wide

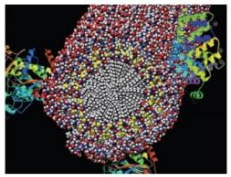
Pollen grain

Red blood cells



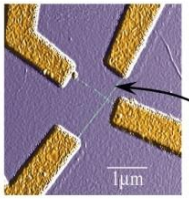
Zone plate x-ray "lens"

Outer ring spacing ~35 nm

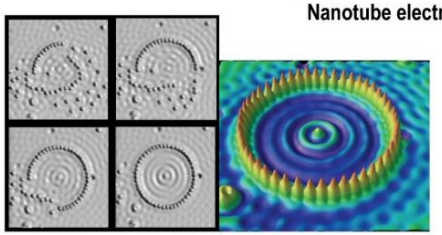


Self-assembled, Nature-inspired structure

Many 10s of nm

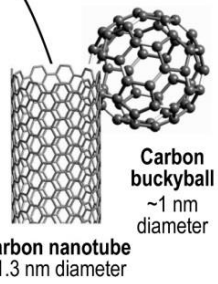


Nanotube electrode



Quantum corral of 48 iron atoms on copper surface positioned one at a time with an STM tip

Corral diameter 14 nm



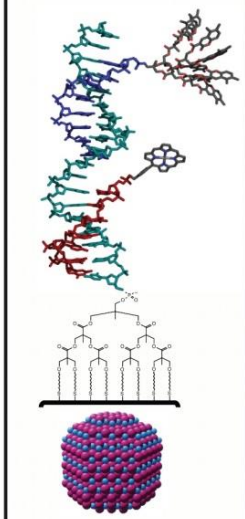
Carbon buckyball

~1 nm diameter

Carbon nanotube

~1.3 nm diameter

The Challenge



Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.

Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 05-26-06, pmd

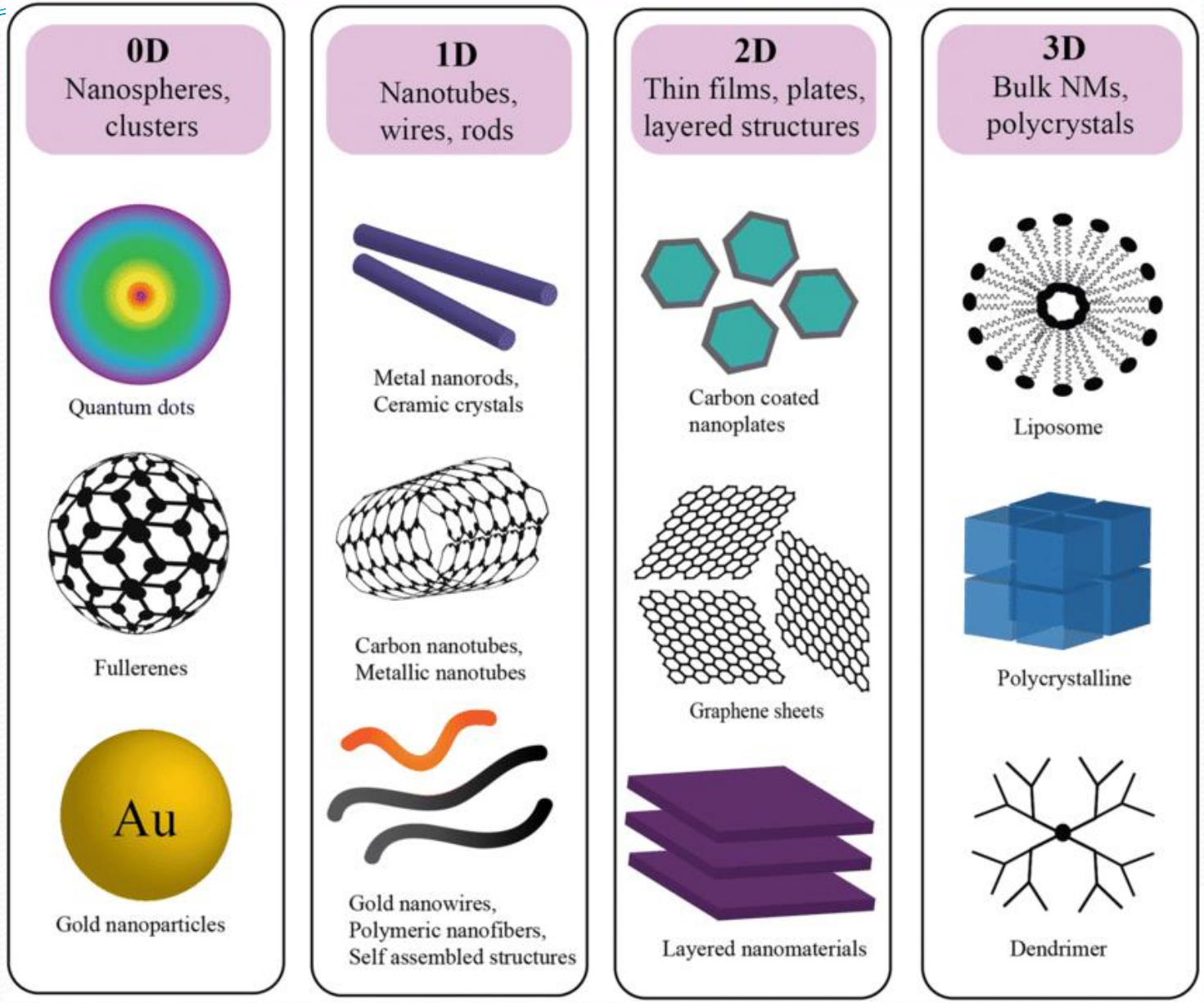
National Nanoscale Initiative, Department of Energy , Office of Science

A Little More on the Scale of Things

- A sheet of paper is ~ 100,000 nm thick;
- A human hair is ~ 80,000 – 100,000 nm wide;
- Hemoglobin, which carries oxygen through the bloodstream is 5 nm in diameter;
- A strand of human DNA is ~ 2.5 nm in diameter;
- A single gold atom is ~ 1/3 nm;
- 1 nm is approximately as long as your fingernail grows in 1s.

National Nanotechnology Initiative
http://www.nano.gov/nanotech-101/what/nano-size

NMs classification based on dimensionality



Poh, T.Y., Particle and Fibre Toxicology 15 (1), 2018

Pre-modern Examples of Nanotechnology

The Lycurgus cup (Rome) at the British Museum, 4th century

Polychrome lustreware bowl (Iraq) at the British Museum, 9th Century

Stained glass window in a church in Europe in the 11th century

Maya warrior, The Cleveland Museum of Art, 250 – 900 AD

(A)Egyptians produced dye for hair, ACS (2006); (B) Egyptians produced Egyptian blue, ACS(2013)

Ancient stained-glass makers knew that by putting varying, tiny amounts of gold and silver in the glass, they could produce the red and yellow found in stained-glass windows. Similarly, today's scientists and engineers have found that it takes only small amounts of a nanoparticle, precisely placed, to change a material's physical properties.

Gold particles in glass

Size*: 25 nm
Shape: sphere
Color reflected:

100 nanometers = 0.0001 millimeter

Silver particles in glass

Size*: 100 nm
Shape: sphere
Color reflected:

200 nm

Had medieval artists been able to control the size and shape of the nanoparticles, they would have been able to use the two metals to produce other colors. Examples:

Size*: 50 nm
Shape: sphere
Color reflected:

Size*: 40 nm
Shape: sphere
Color reflected:

Size*: 100 nm
Shape: sphere
Color reflected:

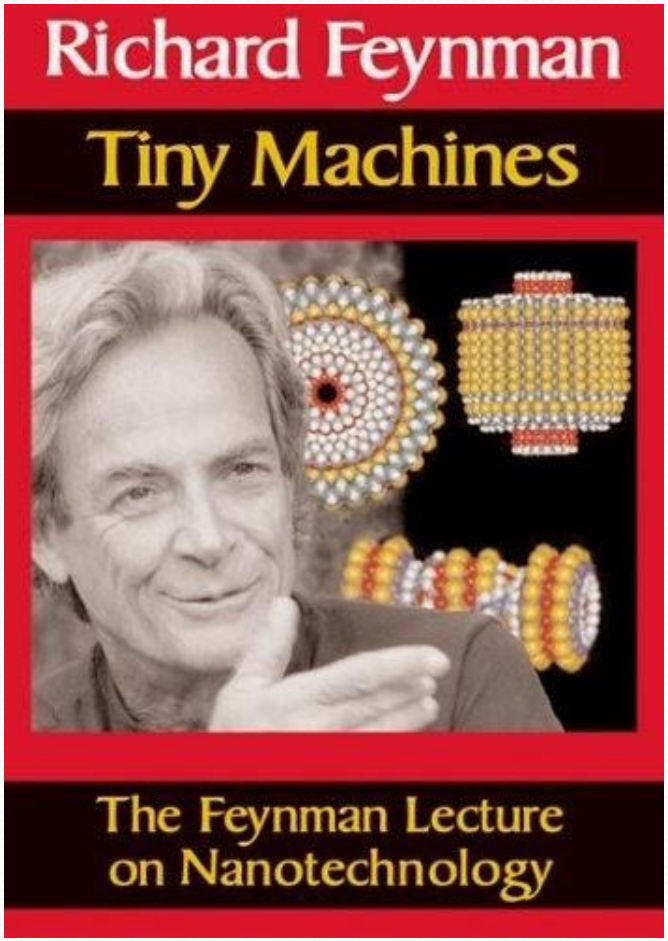
Size*: 100 nm
Shape: prism
Color reflected:

Source: Dr. Chad A. Mirkin, Institute of Nanotechnology, Northwestern University

*Approximate

The New York Times; Images courtesy of the Stained Glass Museum, Britain

Where it all started: "There's plenty of room at the bottom."



"**There's Plenty of Room at the Bottom**" was a lecture given by physicist Richarc Feynman at an American Physical Society (APS) meeting at Caltech on December 29, 1959 This talk inspired the conceptual beginnings of the field decades later.

On the Basic Concept of 'Nano-Technology'

Norio TANIGUCHI
Tokyo Science University
Noda-shi, Chiba-ken, 278 Japan

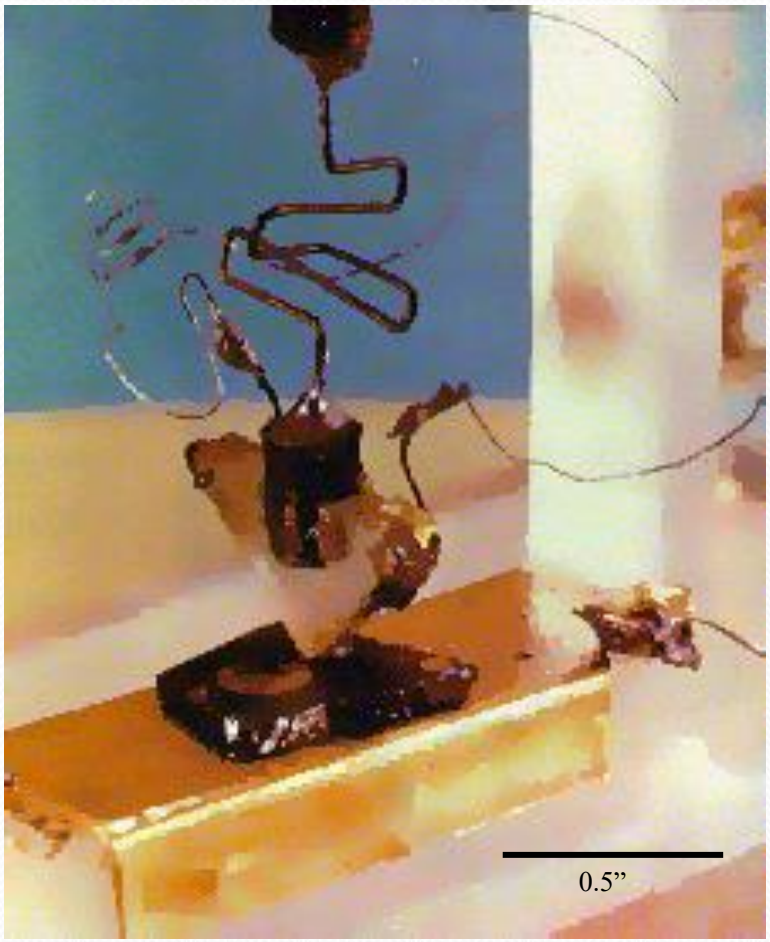
Abstract

'Nano-technology' is the production technology to get the extra high accuracy and ultra fine dimensions, i.e. the preciseness and fineness of the order of 1 nm (nanometer), 10^{-9} m in length. The name of 'Nano-technology' originates from this nanometer. In the processing of materials, the smallest bit size of stock removal, accretion or flow of materialsis probablyof one atom or one molecule, namely 0.1~0.2 nm in length. Therefore, the expected limit size of fineness would be of the order of 1 nm. Accordingry, 'Nano-technology' mainly consists of the processing of separation, consolidation and deformation of materials by one atom or one molecule. Needless to say, the measurement and cont-roll techniques to assure the preciseness and fineness of 1 nm play very important role in this technology.

In the present paper, the basic concept of 'Nano-technology' in materials processing is discussed on the basis of microscopic behaviour of materials andas a result the ion sputter-machining is introduced as the most promissing process for the technology.

Norio Taniguchi first termed the word “Nanotechnology” in 1974, in his paper on ion sputtering: *N. Taniguchi, Proc. Intl. Conf. Prod. Eng. Tokyo Part II, Japan Society of Precision Engineering, 1974, pp 18-23.*

The Beginning: at Bell Labs in 1947



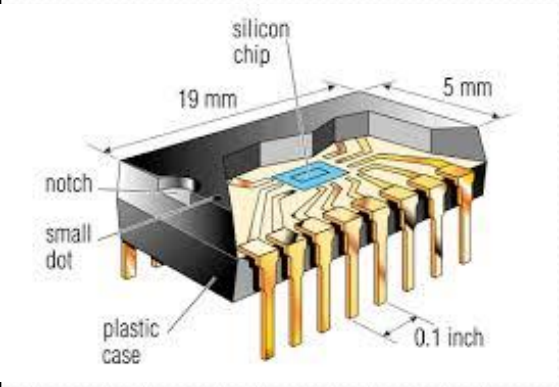
the first transistor made of Germanium

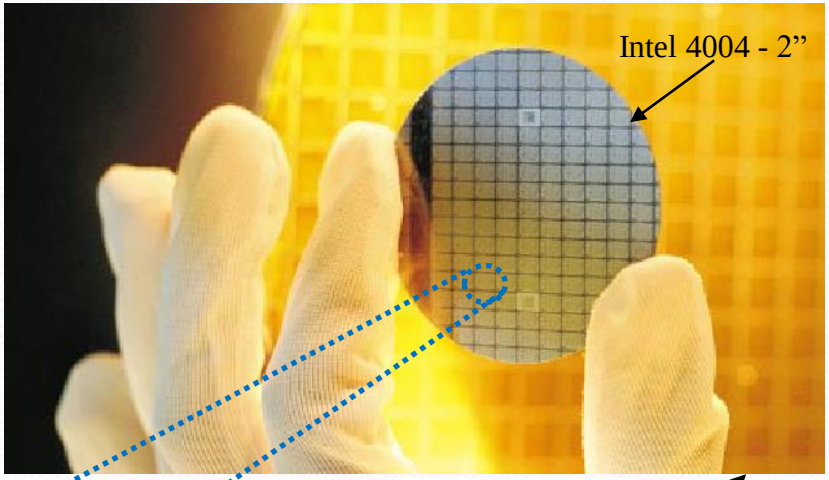
INVENTORS Shockley (*seated*), Bardeen (*left*) and Brattain (*right*) were the first to demonstrate a solid-state amplifier (*opposite page*).

AT&T Archives

In 1956, Schockley, Bardeen, and Brattain were awarded the Nobel Prize in Physics, "for their researches on semiconductors and their discovery of the transistor effect"

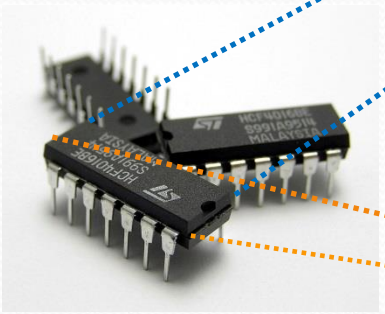
Integrated circuits: The heart of the computer





Intel.com

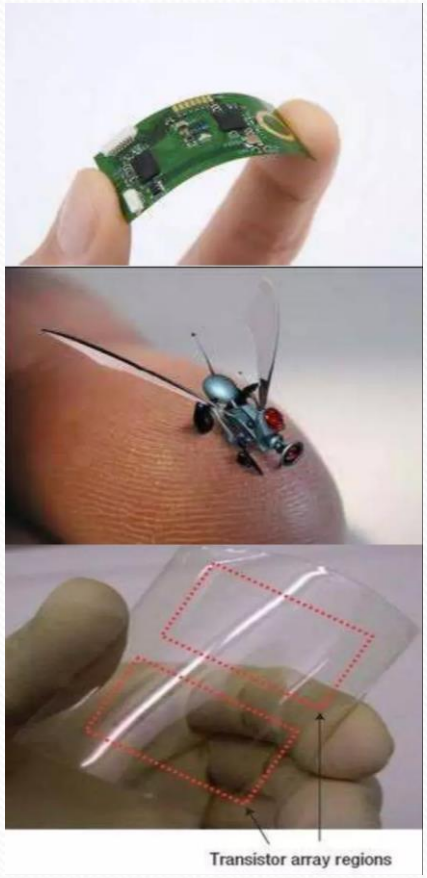
today’s wafers-12”



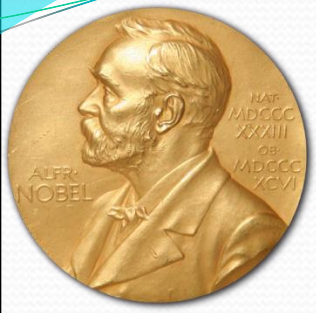
Three 14-pin (DIP14) plastic dual in-line packages containing IC chips packaged chip

Wikipedia.org

modern pc



Visualization? : Nobel Prize in Physics 1986



"for his fundamental work in electron optics, and for the design of the first **electron microscope**"

"for their design of the **scanning tunneling microscope**"

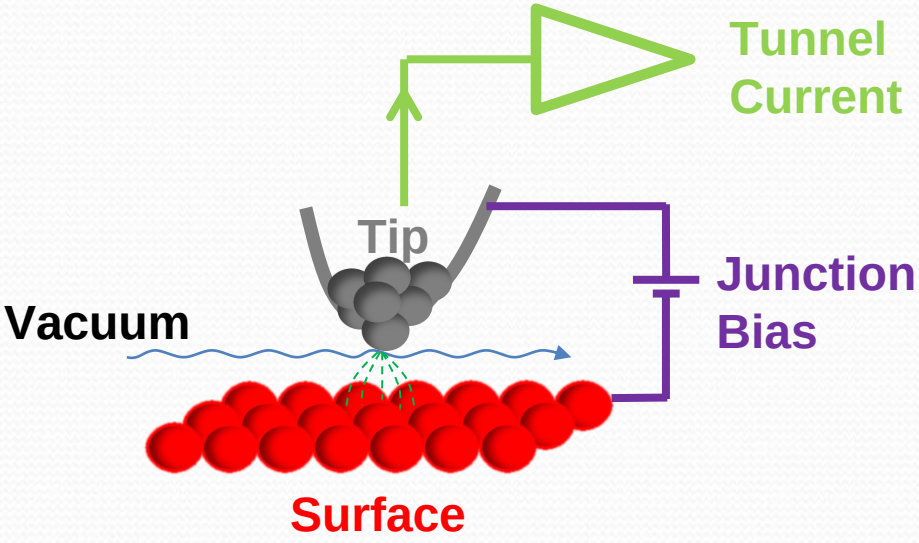
Ernst Ruska

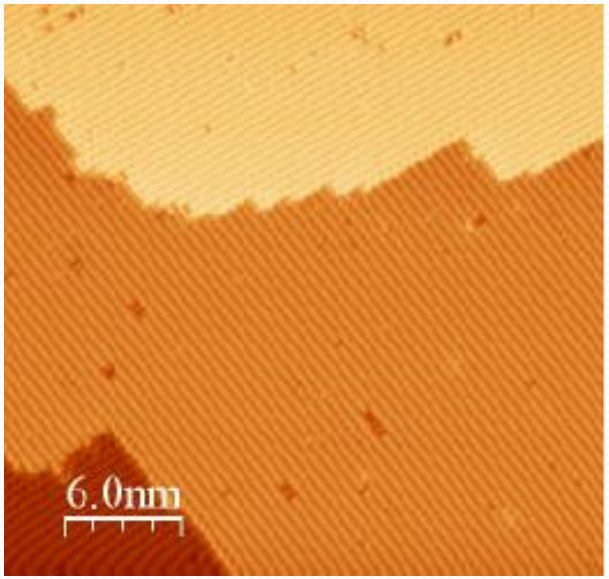
Gerd Binnig

Heinrich Rohrer

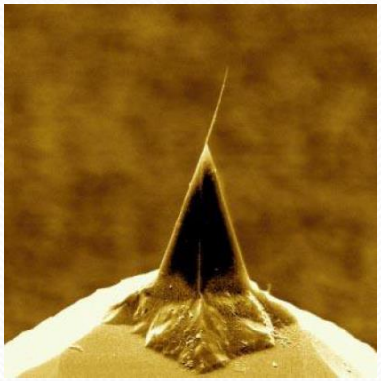
Their work helped visualize individual atoms through the probing of surfaces

Scanning Tunneling Microscopy: A Revolution for Tunneling

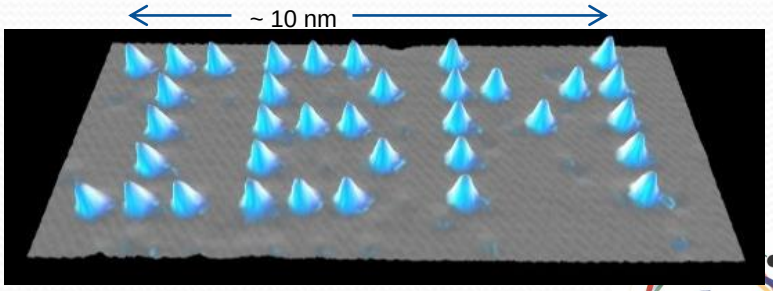




Imaging



STM tip

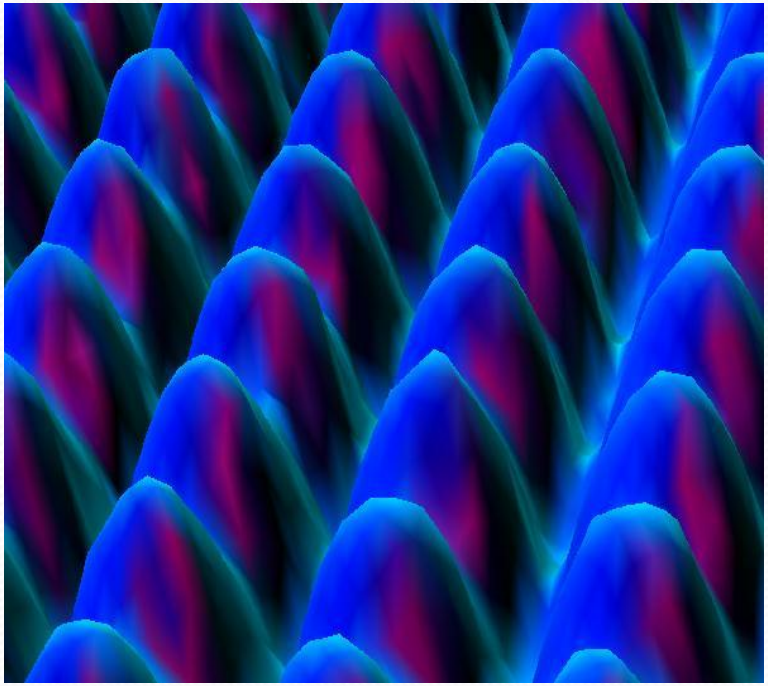


Eigler,D., Nature 344, 524 (1990)

Atomic manipulation

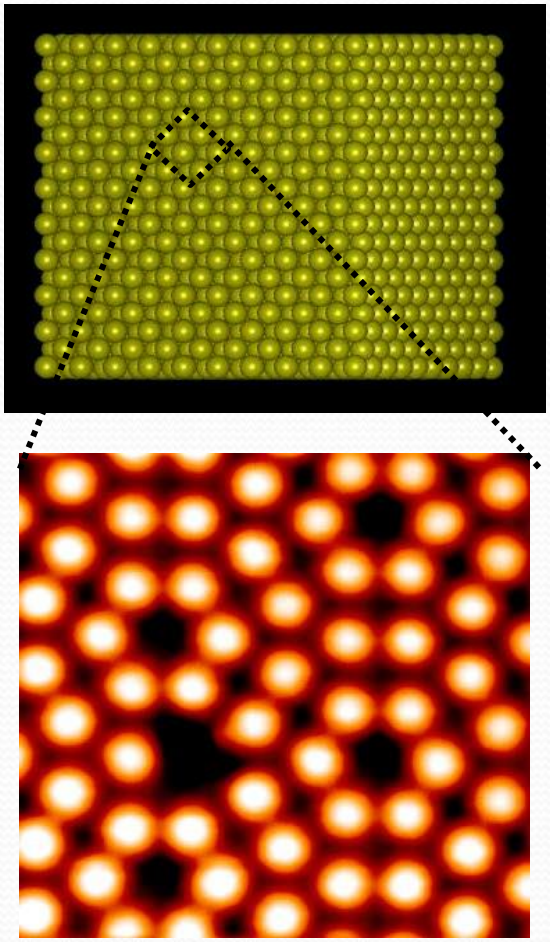
STM observing surfaces

Nickel



3 Angstroms = 0.3 nm

Silicon

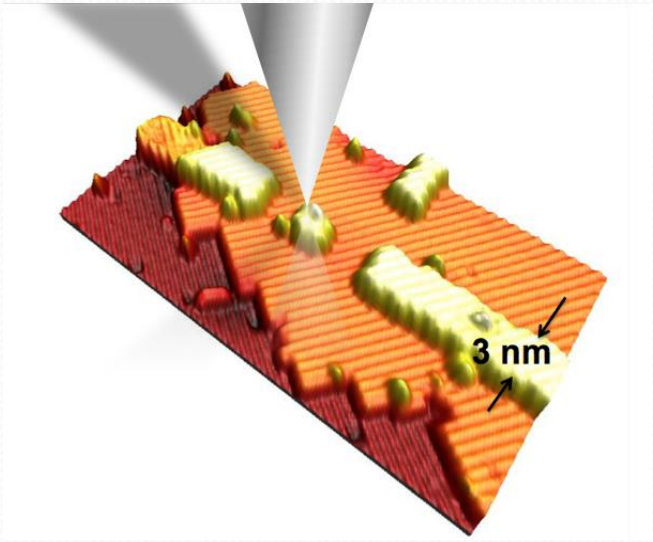


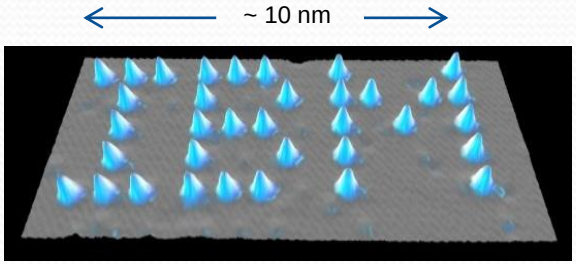
STM of Si(111) 7 x7 reconstruction

Nanofabrication: Writing Devices

Pick and Place

STM assisted nanofabrication

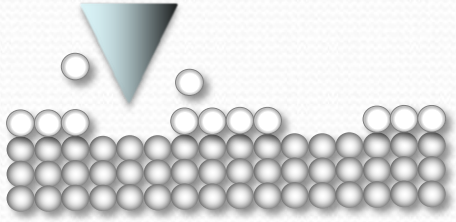


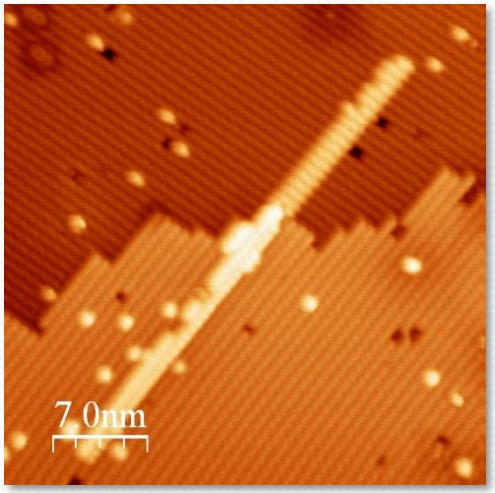


Eigler,D., Nature 344, 524 (1990)

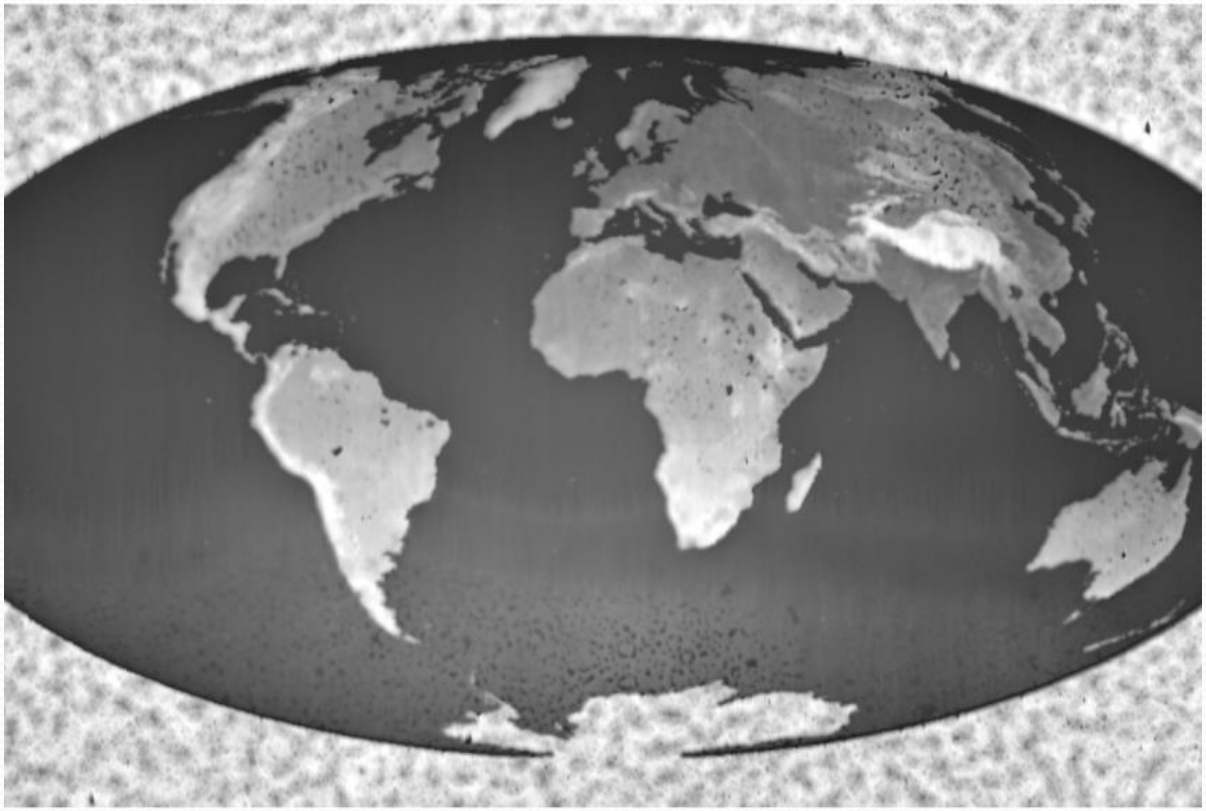
Atomic manipulation

Write …





The World's Smallest Map

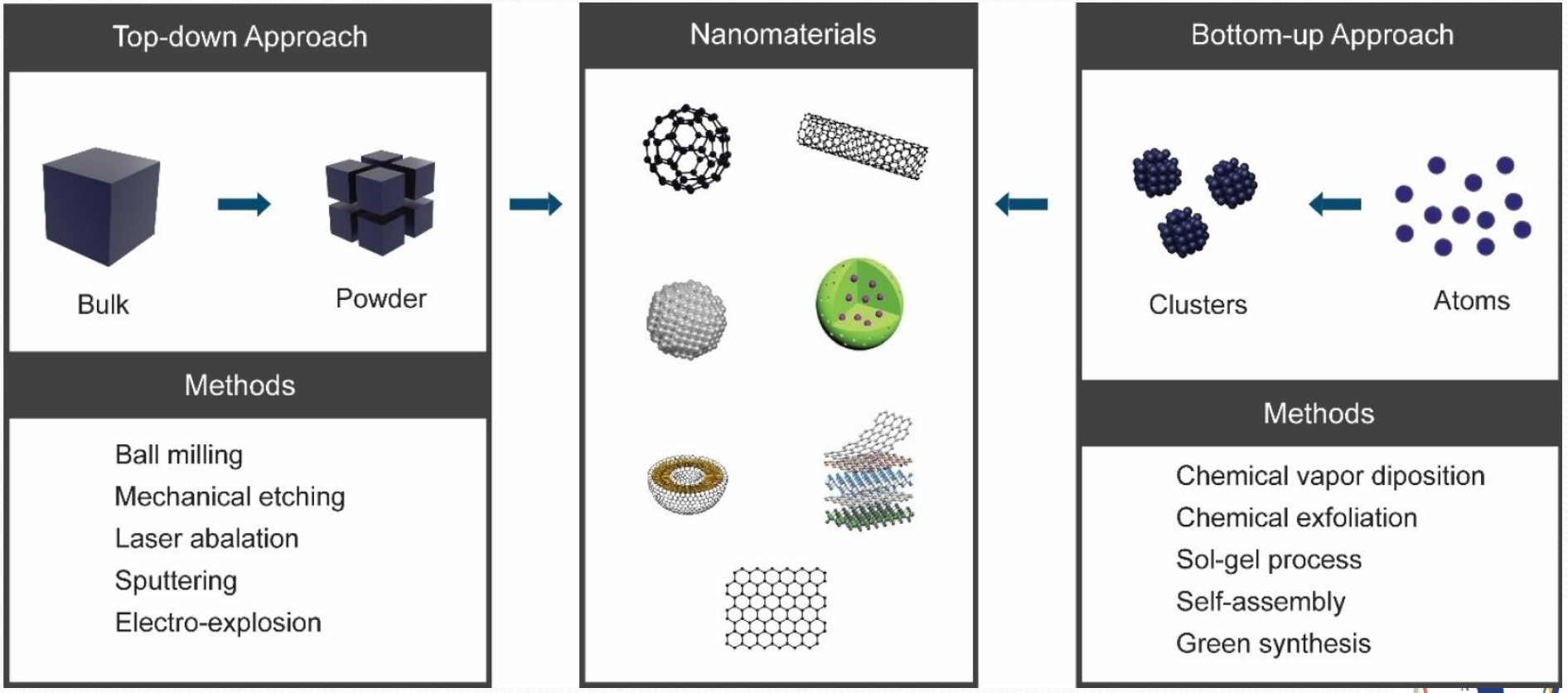


22 µm × 11 µm 3D map written on a polymer

IBM, 2012

Approaches

- **Top-Down**: Starting from larger structures and breaking them down into smaller components
- **Bottom-Up**: Building from individual atoms and molecules to create functional systems



Syduzzaman, M. et al., ChemNanoMat 2023, *9*, e202300205

Nanotechnology – Tools & Technology

- There are several important modern developments
  - Atomic Force Microscopy (AFM)
  - Scanning Tunneling Microscopy (STM)
- Advances in nanolithography
  - X-ray lithography
  - Dip-pen nanolithography
  - Electron beam lithography (inkjet printer)
- Advances in deposition techniques
  - PVD, ALD, ALE, ASD, CVD, PLD

Nano ➔ New Shapes and New Properties = Good

- Optical properties
- Magnetic properties
- Mechanical properties
- Surface reactivity
- Melting point
- Specific heat
- Conductivity
- Biocompatibility

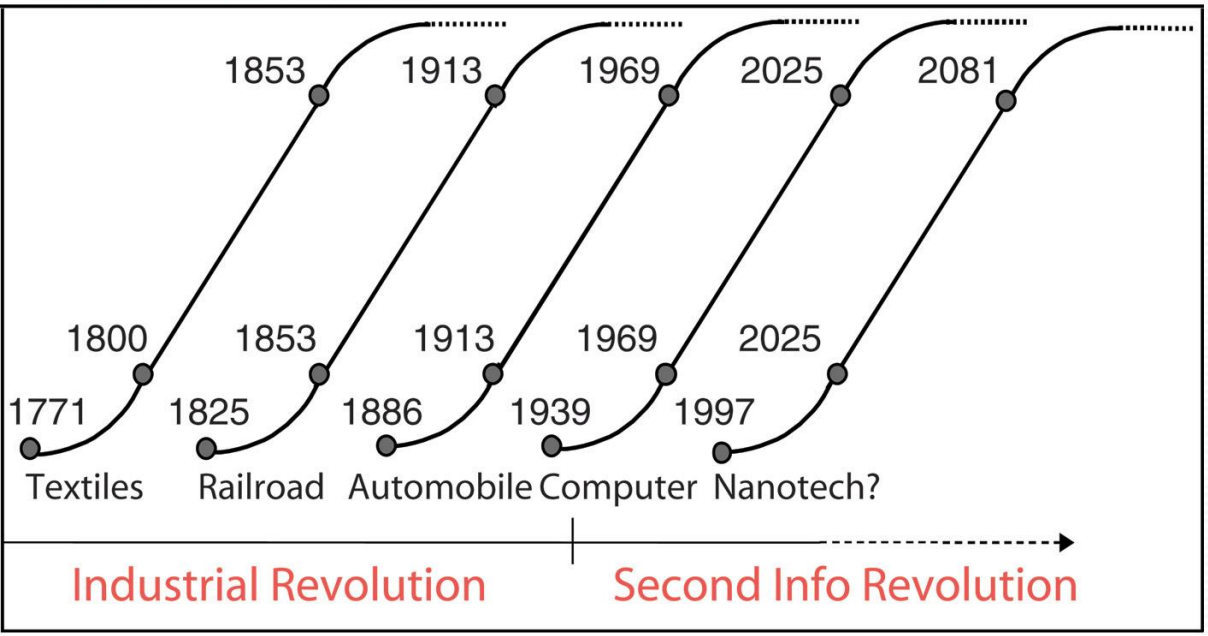
Stained glass window in a church

Evident Technologies

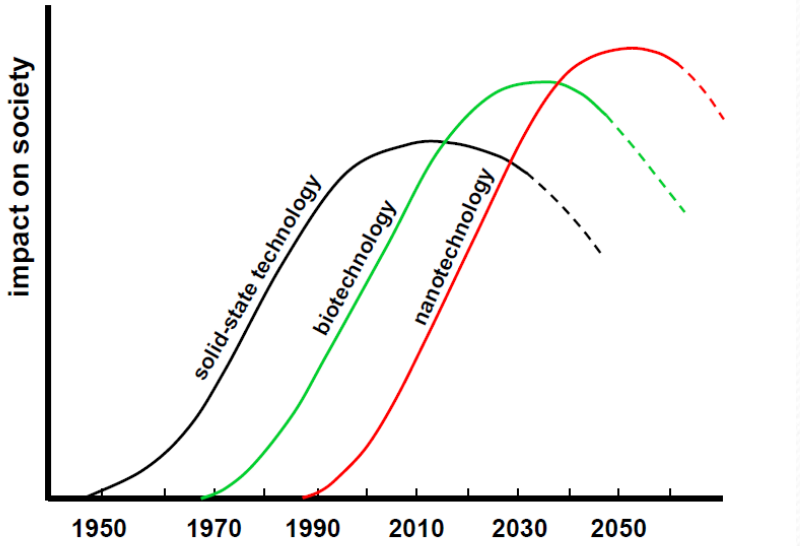
Maya warrior, The Cleveland Museum of Art, 250 – 900 AD

Nanotechnology Growth

Growth Innovations

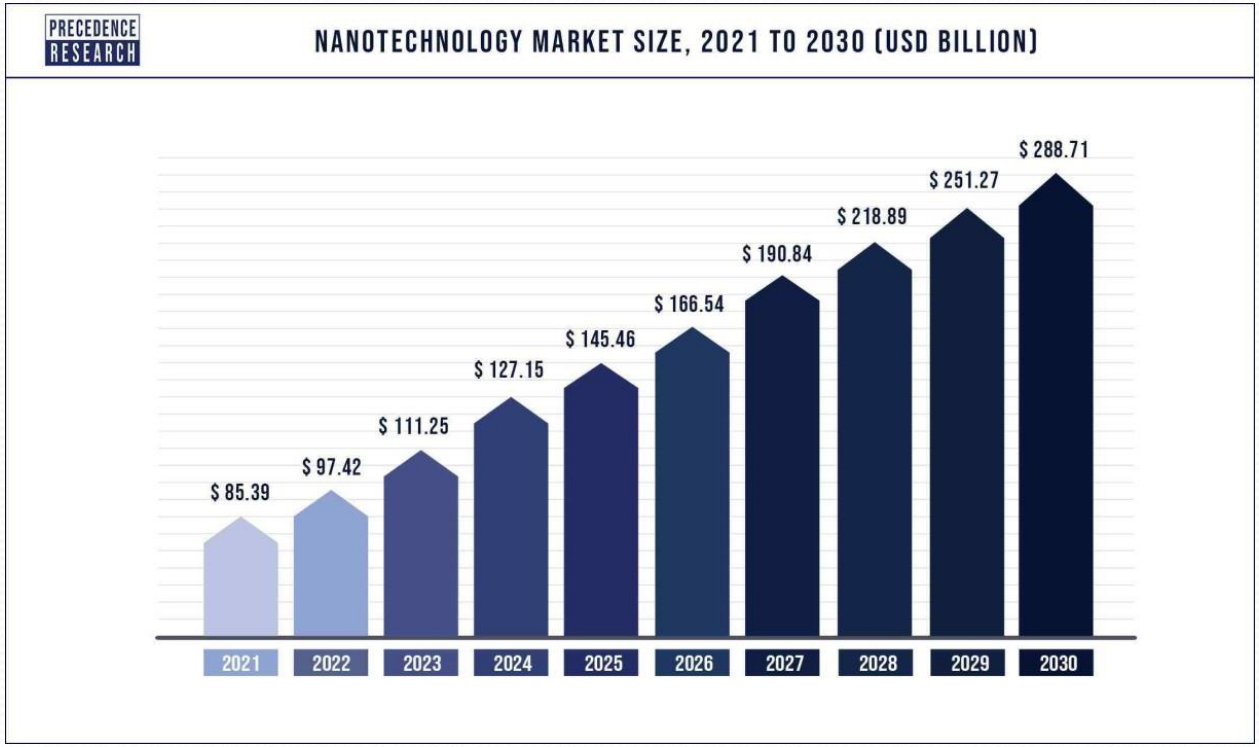


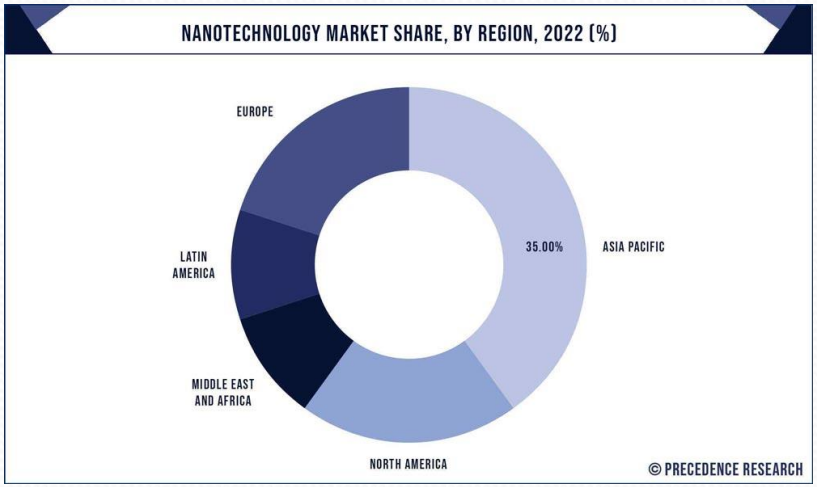
Sources: Norman Poire, Merrill Lynch



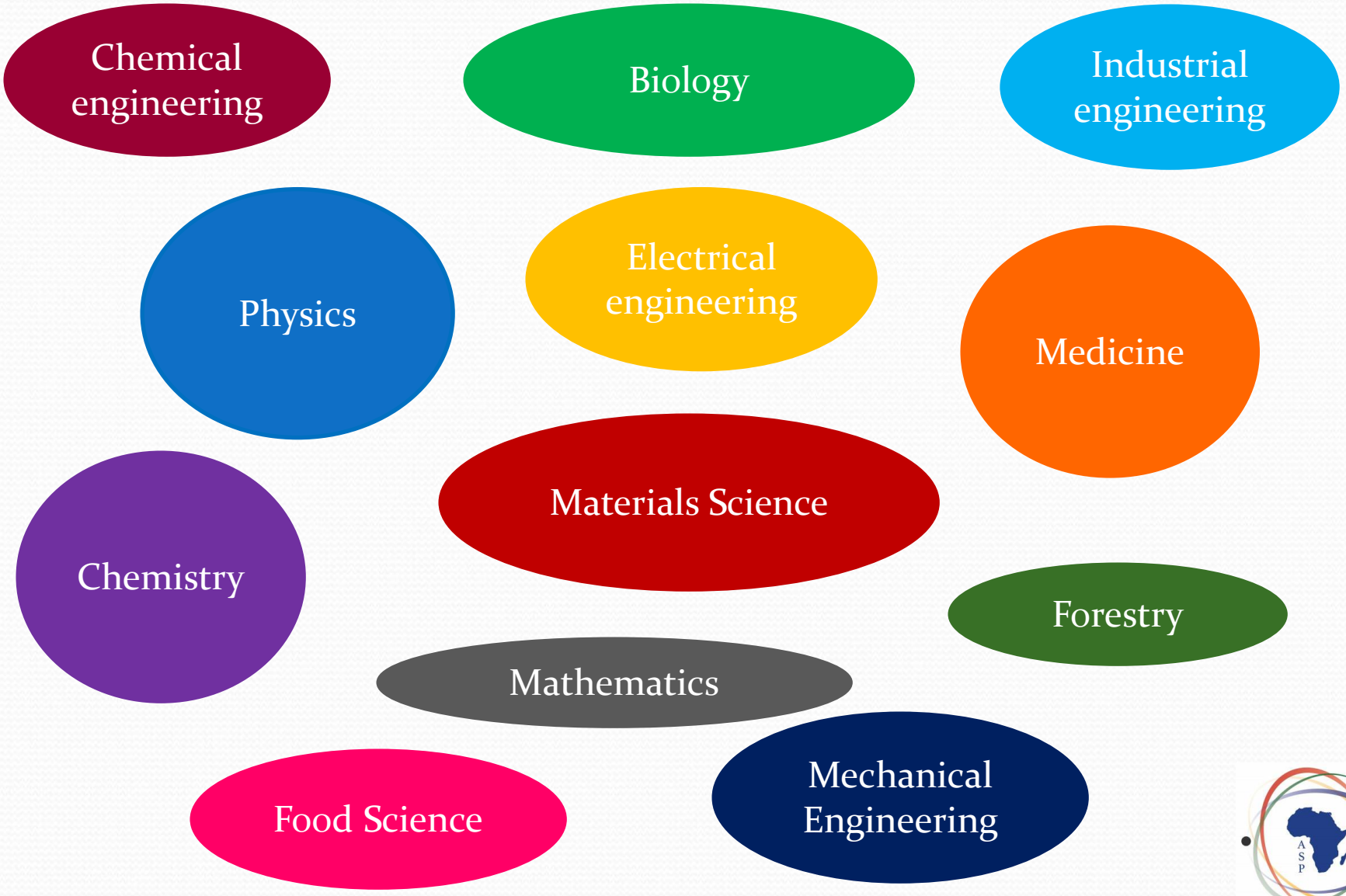
A. ten Wolde: "Nanotechnology; towards a molecular construction kit", Netherlands Study Centre for Technology Trends (STT), 1988

Predicted Global Market Growth

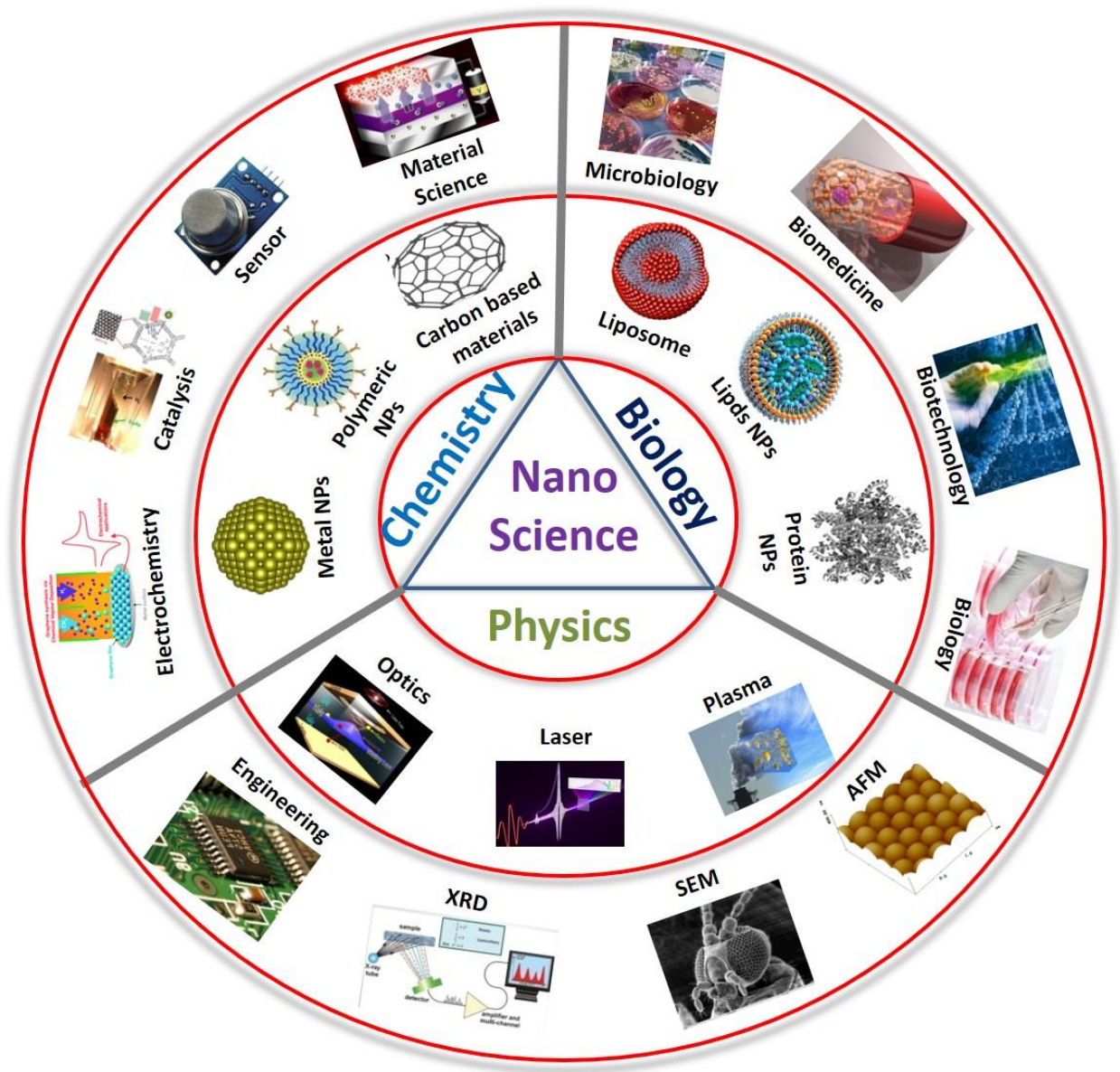




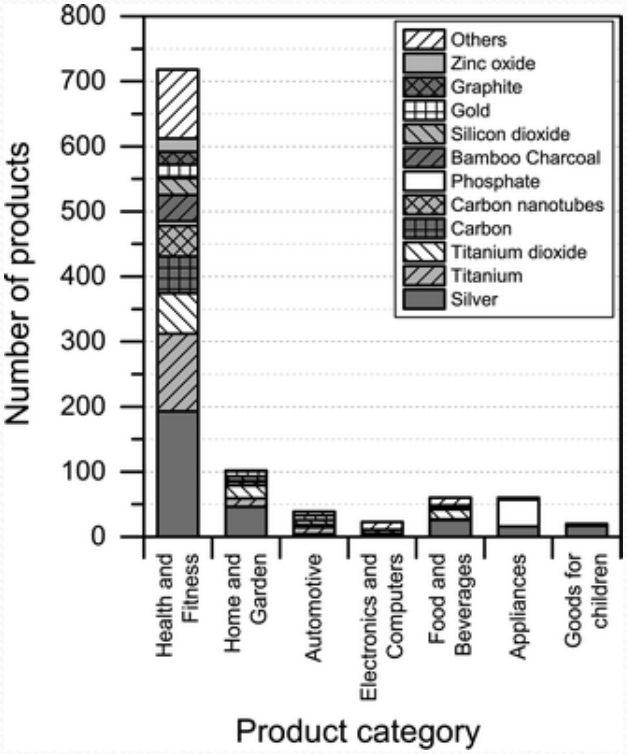
Nanotechnology → Multidisciplinary



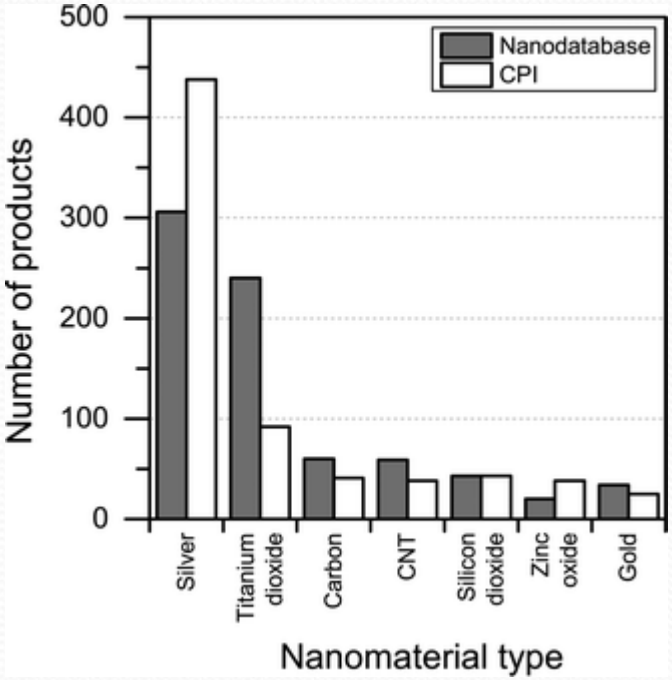
Nanotechnology ➔ Multidisciplinary



Materials in Use



Identity of nanomaterials claimed to be used in different product categories



Silver is a powerful anti-microbial agent and more than 300 products use nanoscale silver to make anti-bacterial surfaces, cosmetics, and clothing.

Hansen, S., et al., Environ. Sci. Nano, 2016, **3**, 169-180

Examples of the Use of NanoSilver: Almost Everywhere …


Nano silver beauty soap


Nano silver hair shampoo

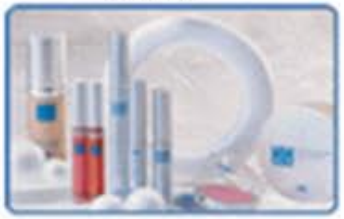

Nano silver body cleanser


Nano silver toothpaste


Nano silver hand sanitizer


Nano silver facial mask sheet


Nano silver skin care line


Nano silver makeup line


Nano silver wet wipes


Nano silver disinfectant spray


Nano silver toothbrush


Nanosilver hair conditioner


Nano silver wash dish & laundry detergent


Nano silver colloid


Nano silver antimicrobial masterbatch

Rai, M., et al., Nano. Rev. 3 (2014) 3

Some Uses of Nanotechnology

1. Organic light emitting diodes (OLEDs) for displays;
2. Photovoltaic film that converts light into electricity;
3. Scratch proof coated windows that clean themselves with UV;
4. Fabrics coated to resist stains and control temperature;
5. Intelligent clothing measures pulse and respiration;
6. Bucky-tubeframe is light, but very strong;
7. Hipjoint made from biocompatible materials;
8. Nano-particle paint to prevent corrosion;
9. Thermo-chromic glass to regulate light;
10. Magnetic layers for compact data memory;
11. Carbon nanotube fuel cells to power electronics and vehicles;
12. Nano-engineered cochlear implant.

http://news.bbc.co.uk/2/hi/science/nature/3920685.stm

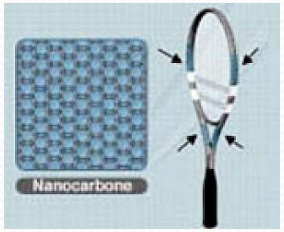
Consumer Products

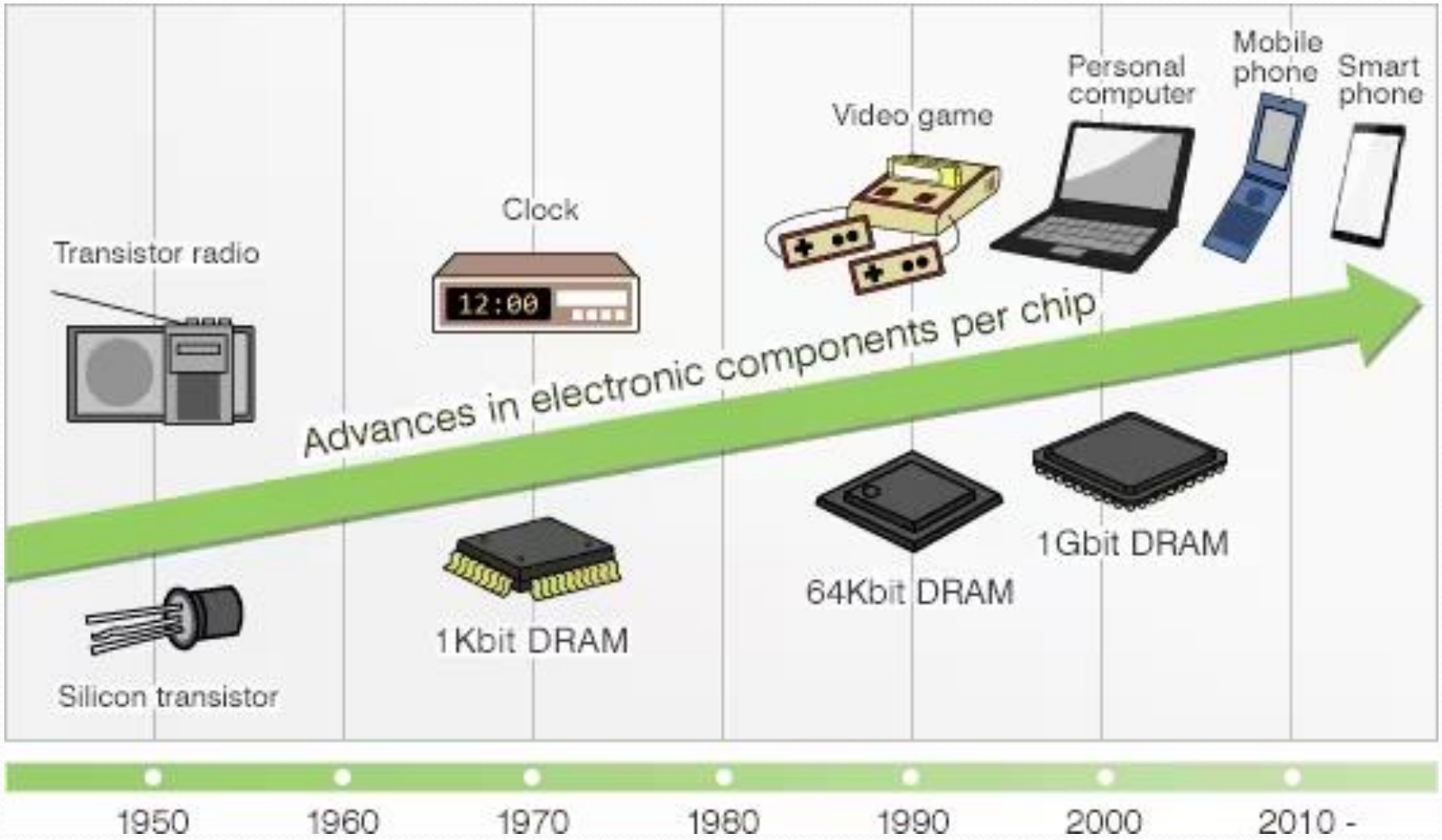
- **Nanoelectronics** ➔ **XBOX One** by Microsoft; Intel hard drives.
- **Nano air filters** ➔ **NanoBreeze Car Air Purifier by NanoTwin Technologies Inc.**

- **Cosmetics** ➔ TiO_2 or ZnO nanoparticles are used in sunscreens.
- **Clothing** ➔ Swimsuits, rain jackets, body armor, stain-repellant fabric.

- **Nanochocolate** ➔ **Nanoceuticals Slim Shake Chocolate by RBC Life Sciences, Inc.**

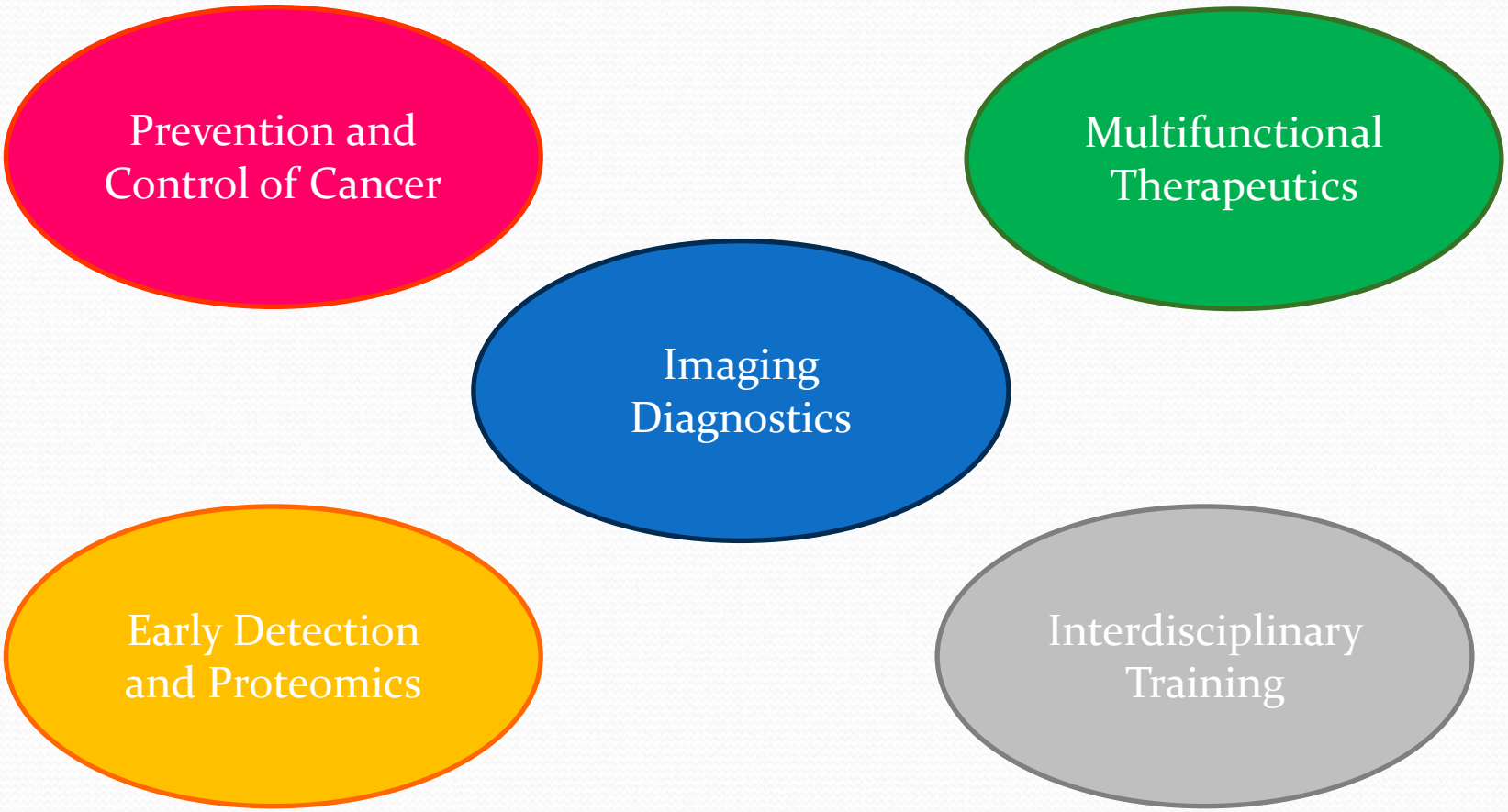
- **Nanocomposites** ➔ **BMC Racing Fourstroke FS01** (BMC Cycling); light tennis rackets; artificial muscles.
- **Targeted imaging probes** ➔ **CellTracks** [Immunicon Corporation].





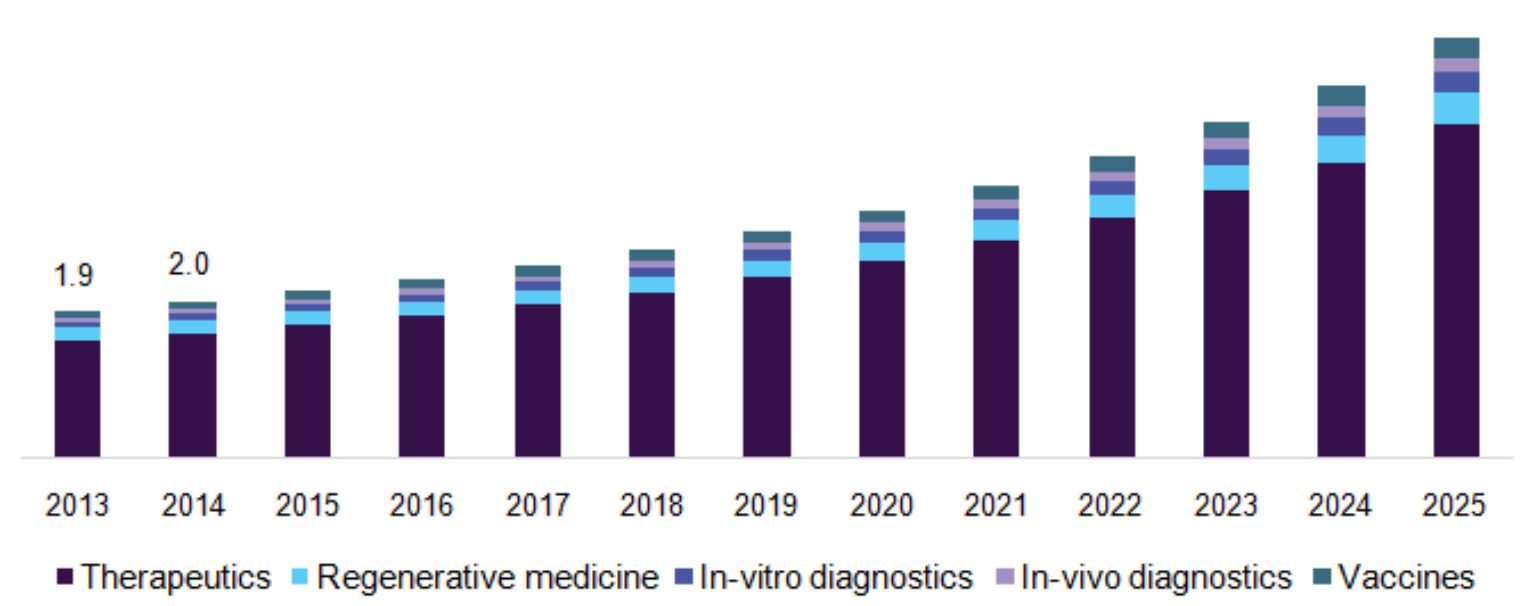
History of semiconductors : Hitachi High-Tech Corporation (hitachi-hightech.com)

Applications of Nanotechnology in Medicine



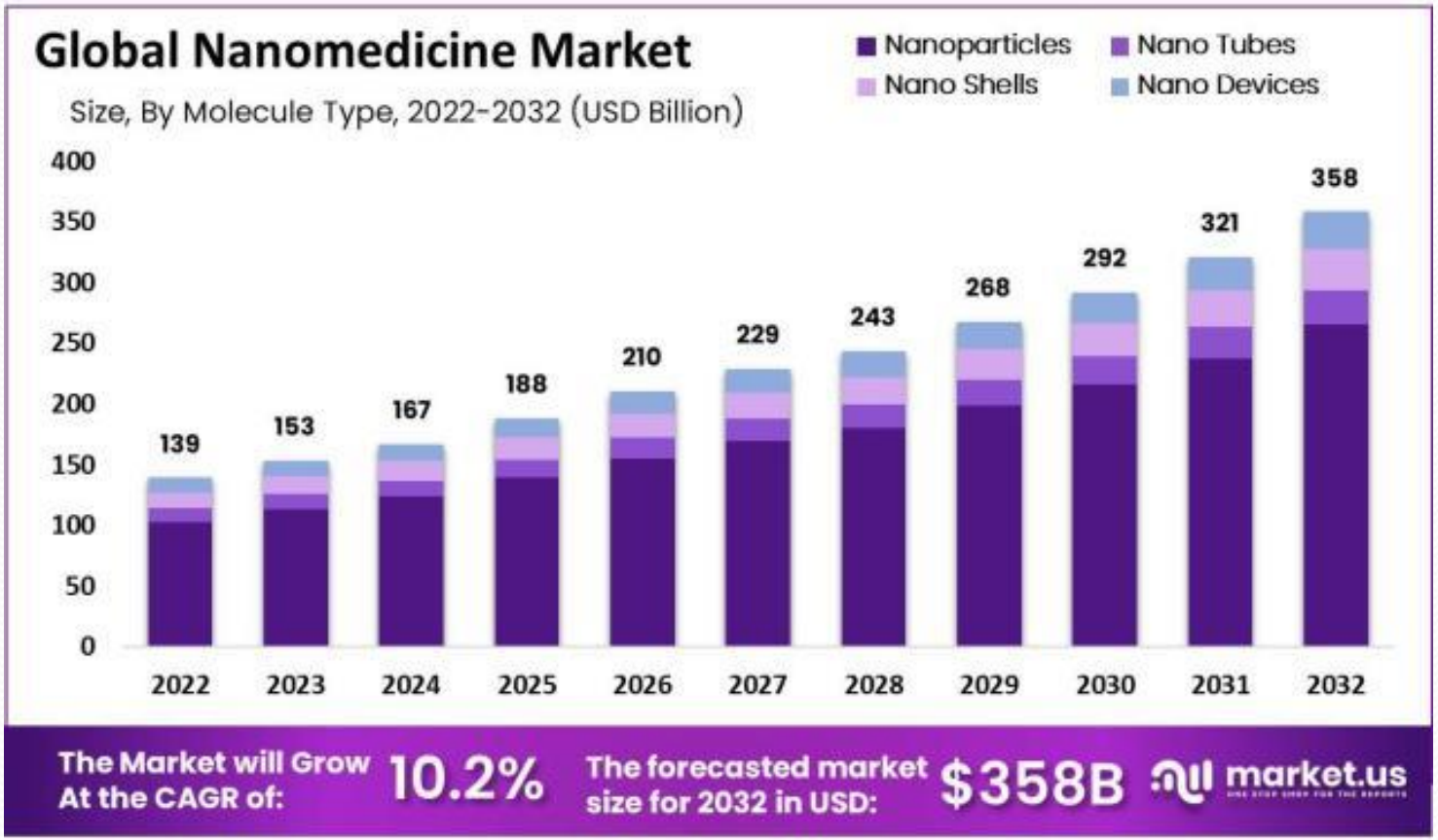
Growth of Nanomedicine

U.S. Nanomedicine market by products 2013 – 2025 ($Billions)



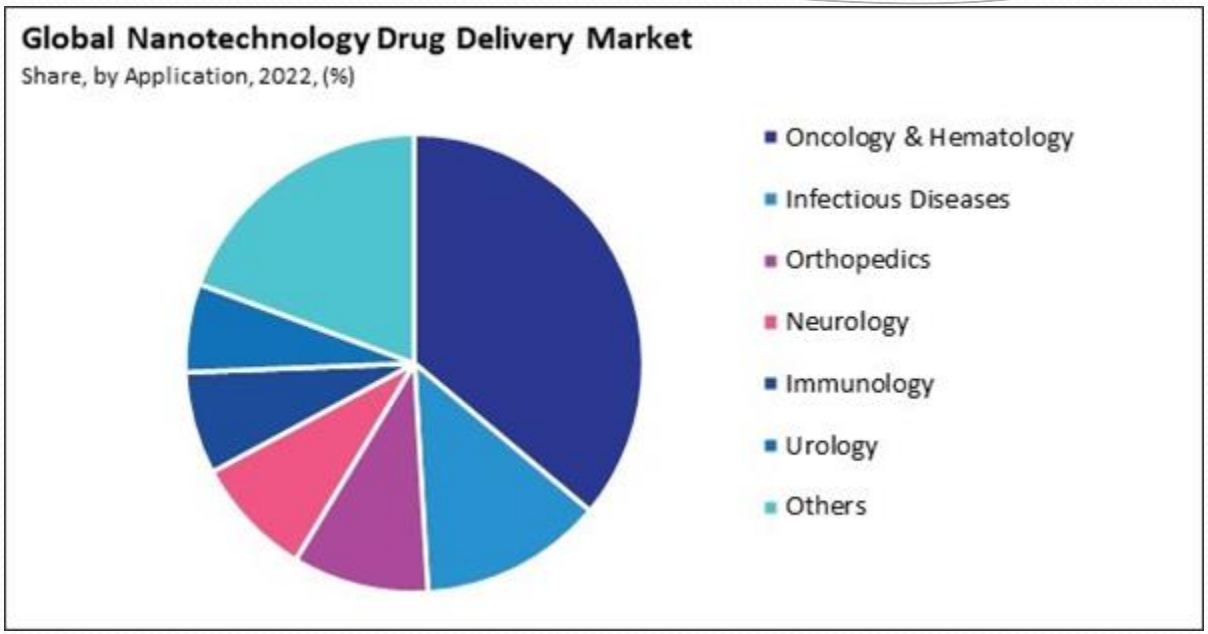
Grand View Research, Market Research Report (2017)

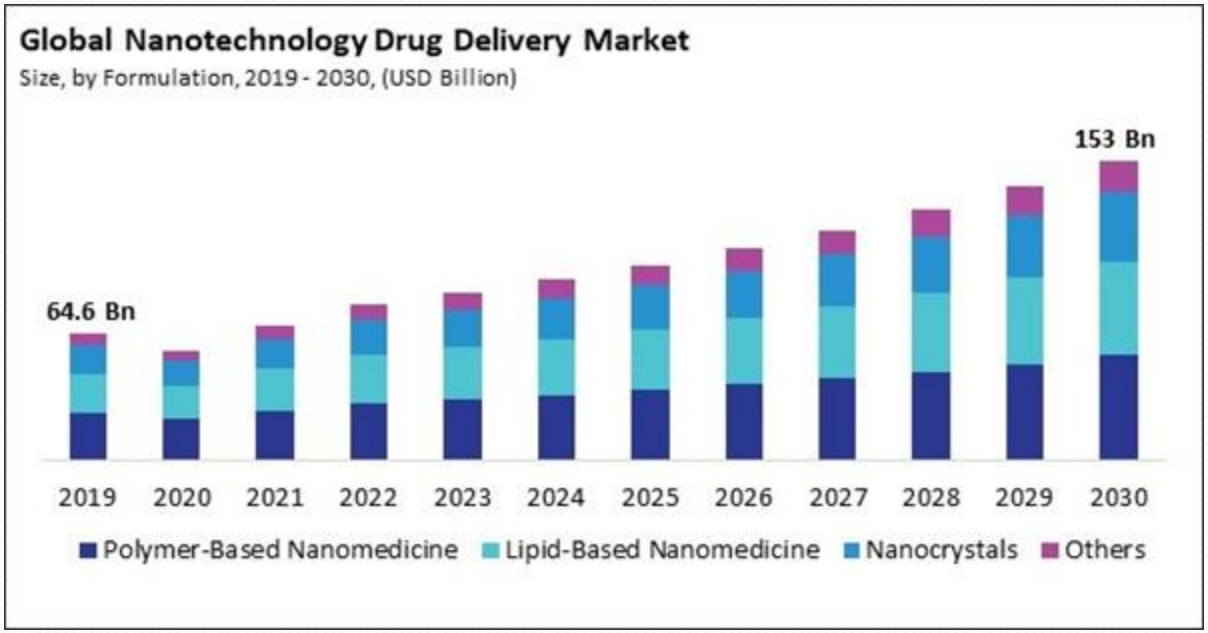
Global Nanomedicine Market



Yahoo Finance (2022)

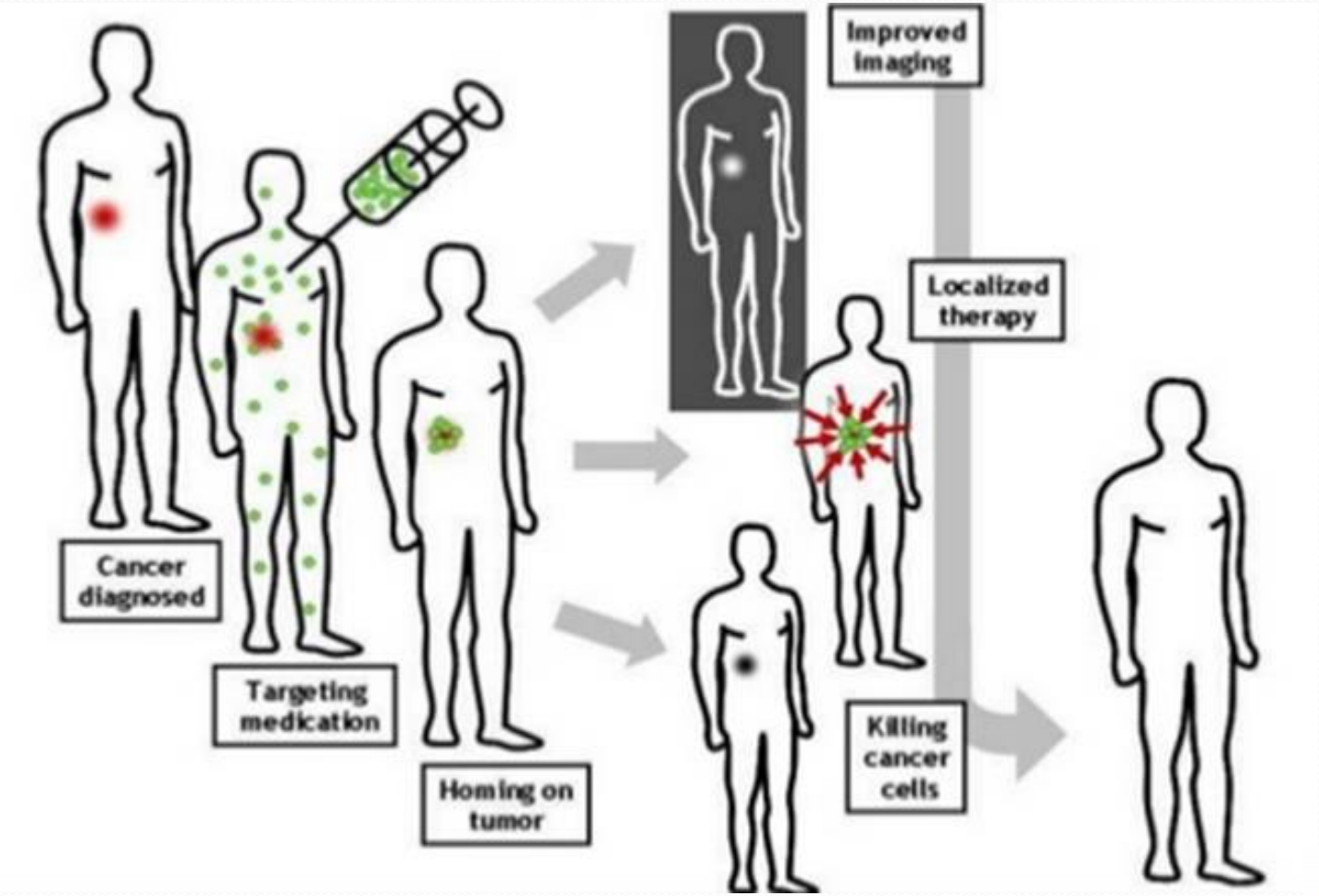
Global Nanotechnology Drug Delivery Market





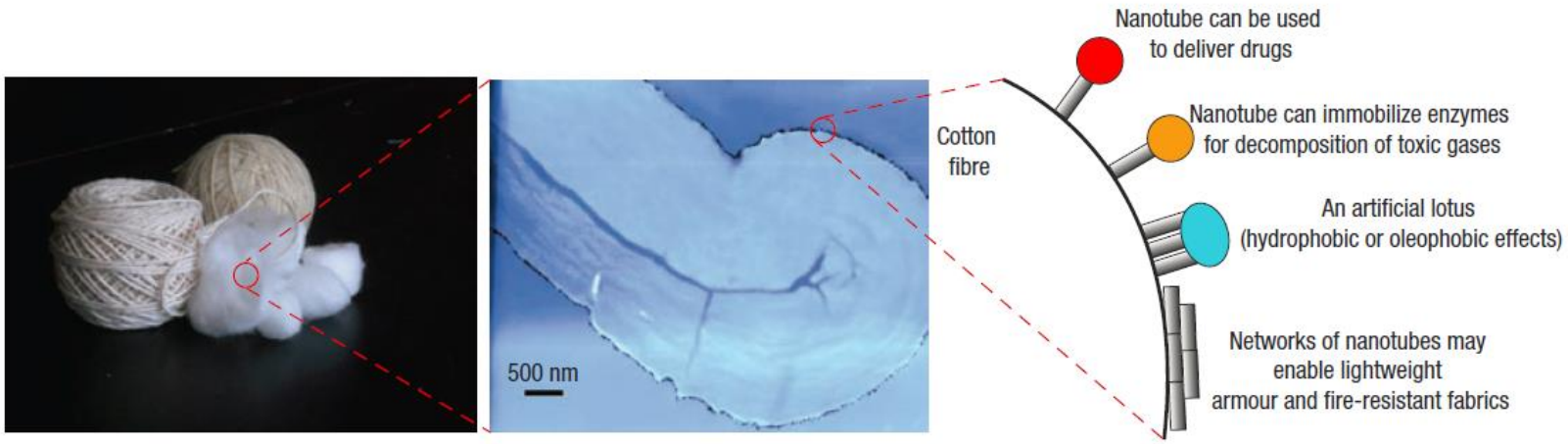
Globenewswire.com

Example of Medical Application: Molecular Imaging and Therapy



Wikipedia

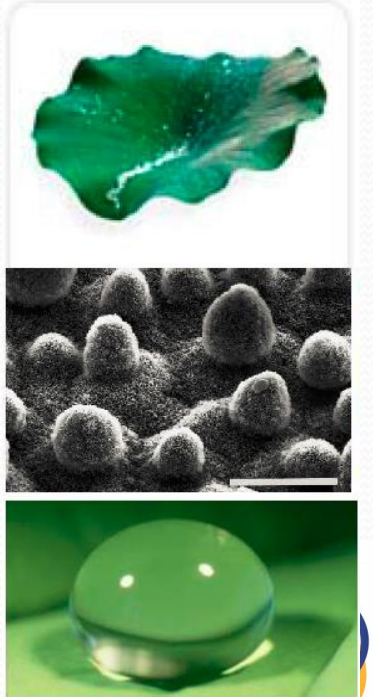
Nanotechnology in Textiles



A. Avila et al., Nature Nanotechnology 3, 458 (2008)

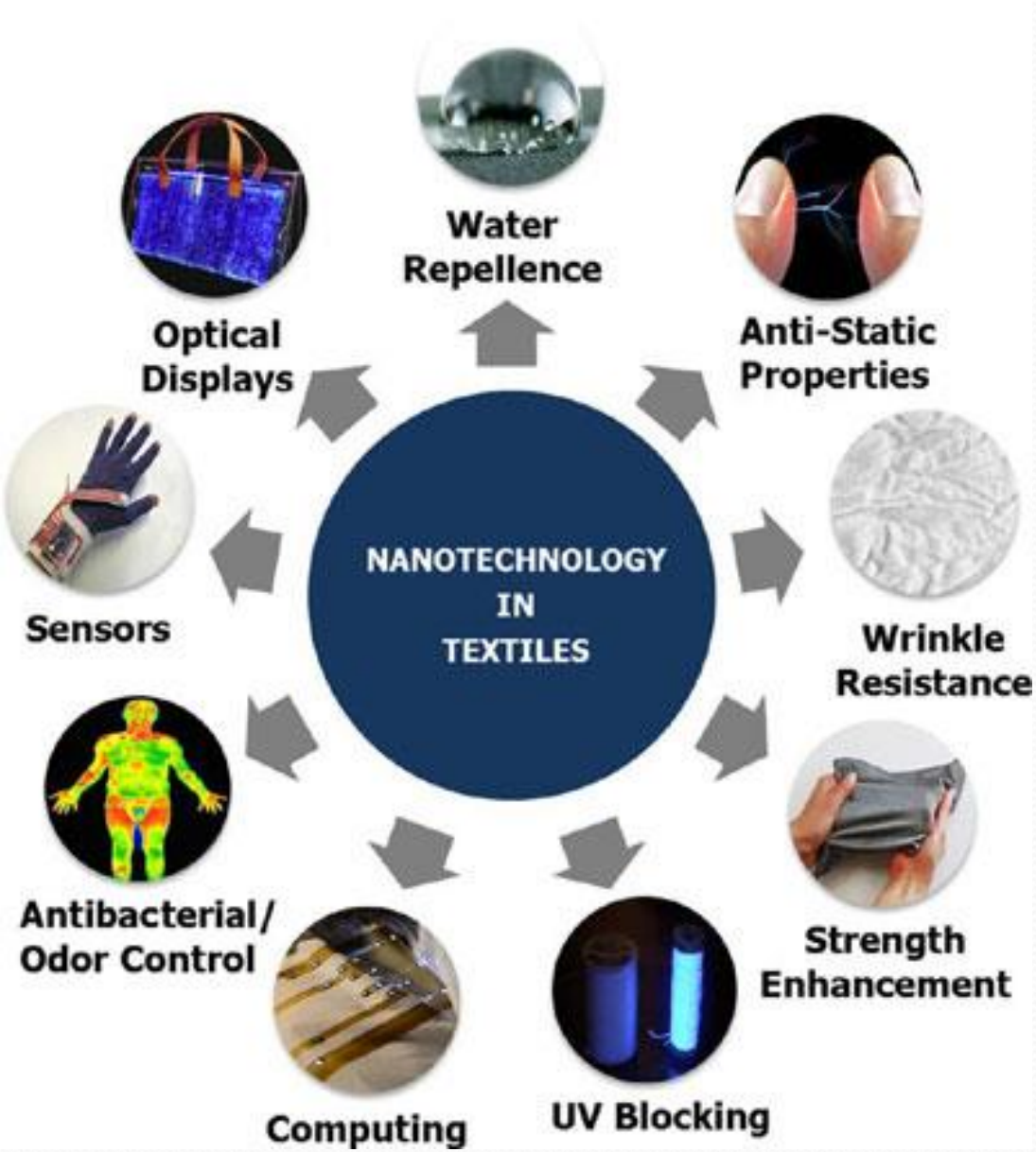
Yetisen, A.K., ACS Nano (2016) 10, 3, 3042

Lotus Effect



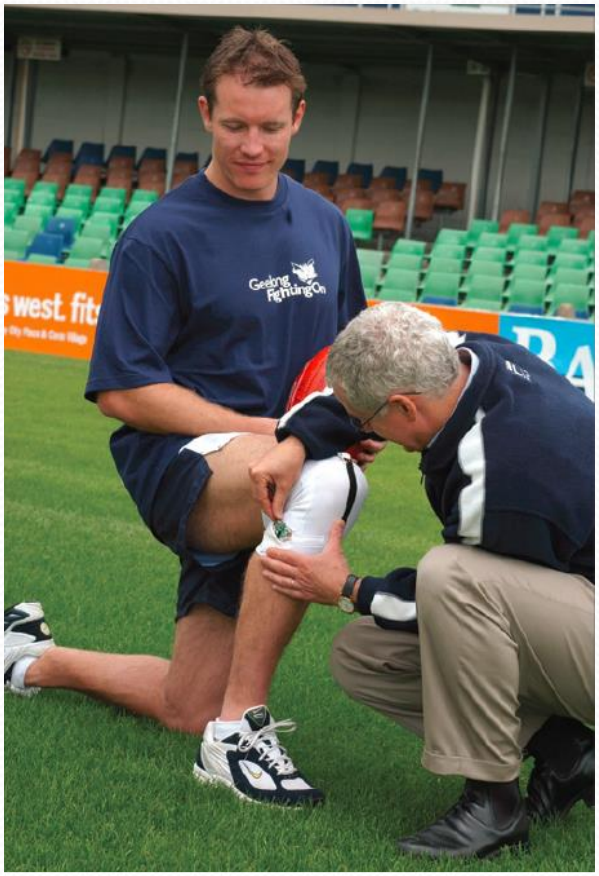
http://www.nanoprotect.co.nz/

In Essence, Nanotechnology in Textiles …



Toyota Center, home of the NBA Houston Rockets, nanotechnology-treated upholstery for stain-resistance and easy cleaning

M. Gurian, Upholstery Journal Feb/Mar(2009)



The intelligent knee sleeve is a bio-feedback device monitoring the knee joint

S. Coyle et al. MRS Bulletin 32, 434 (2007)

Lumalive textile from Philips features flexible arrays of colored LED fully integrated to the clothes

Nanotechnology in Sports

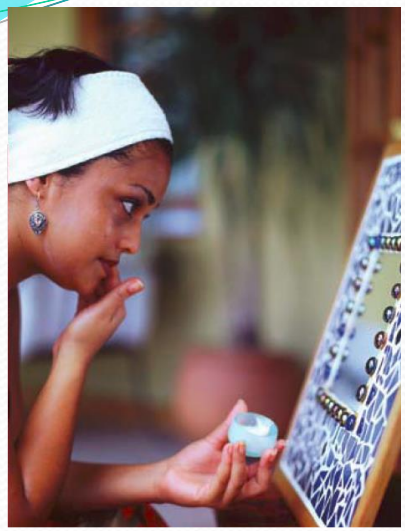
AP photo 1 July 2024

- Tennis / Badminton
- Golf
- Kayaking
- Archery
- Skiing
- Cycling
- Fly-fishing

- Carbon nanotubes
- Silica nanoparticles
- Fullerenes
- Carbon nanofibers
- Nano clay

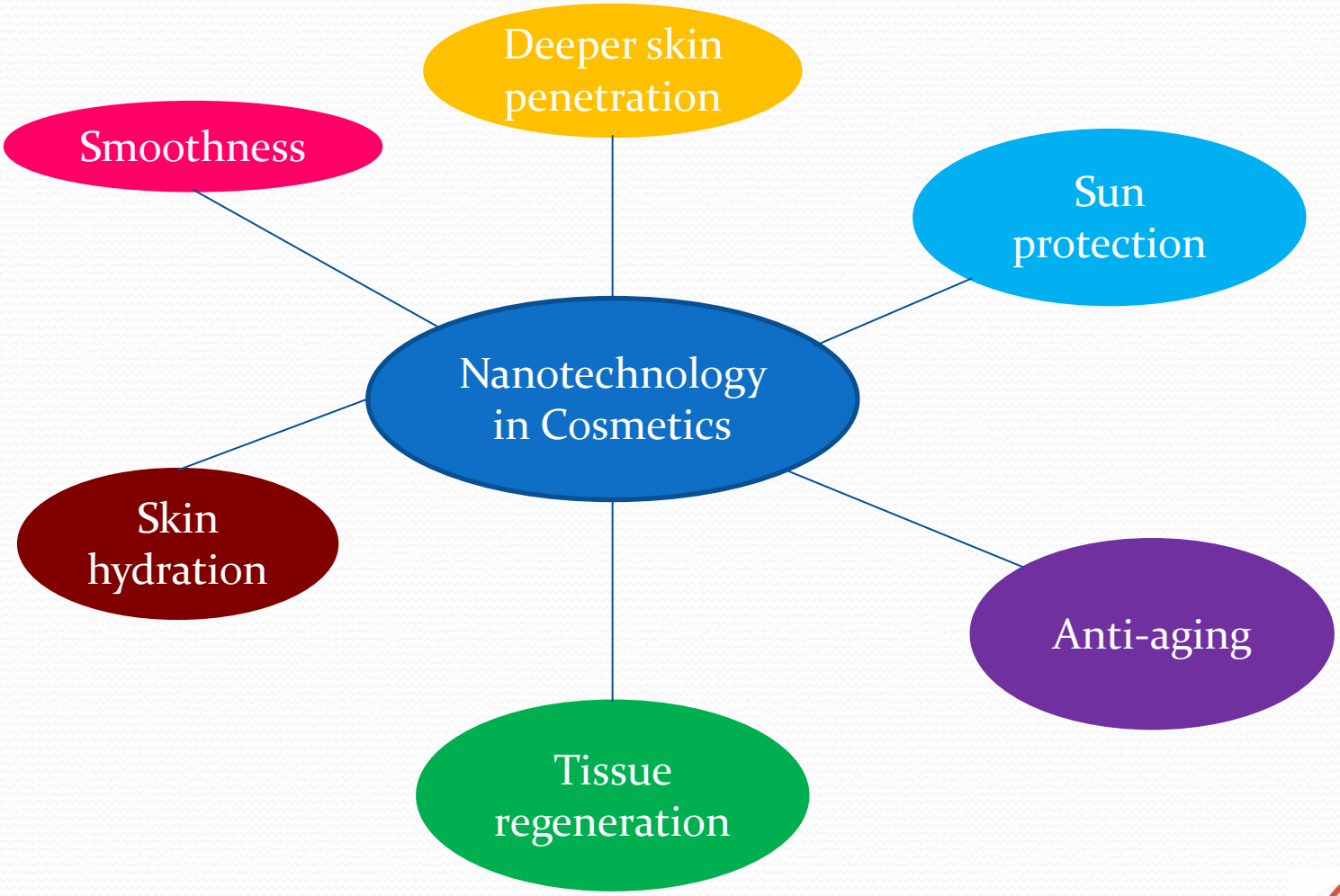
- Enhance stiffness and durability
- Reduce the vibration impact
- Reduce weight
- Improve crack resistance
- Better vibration control in arrows
- Enhance hoop & strength
- Improve flexibility
- Increase bouncing of balls

Nanotechnology in Cosmetics

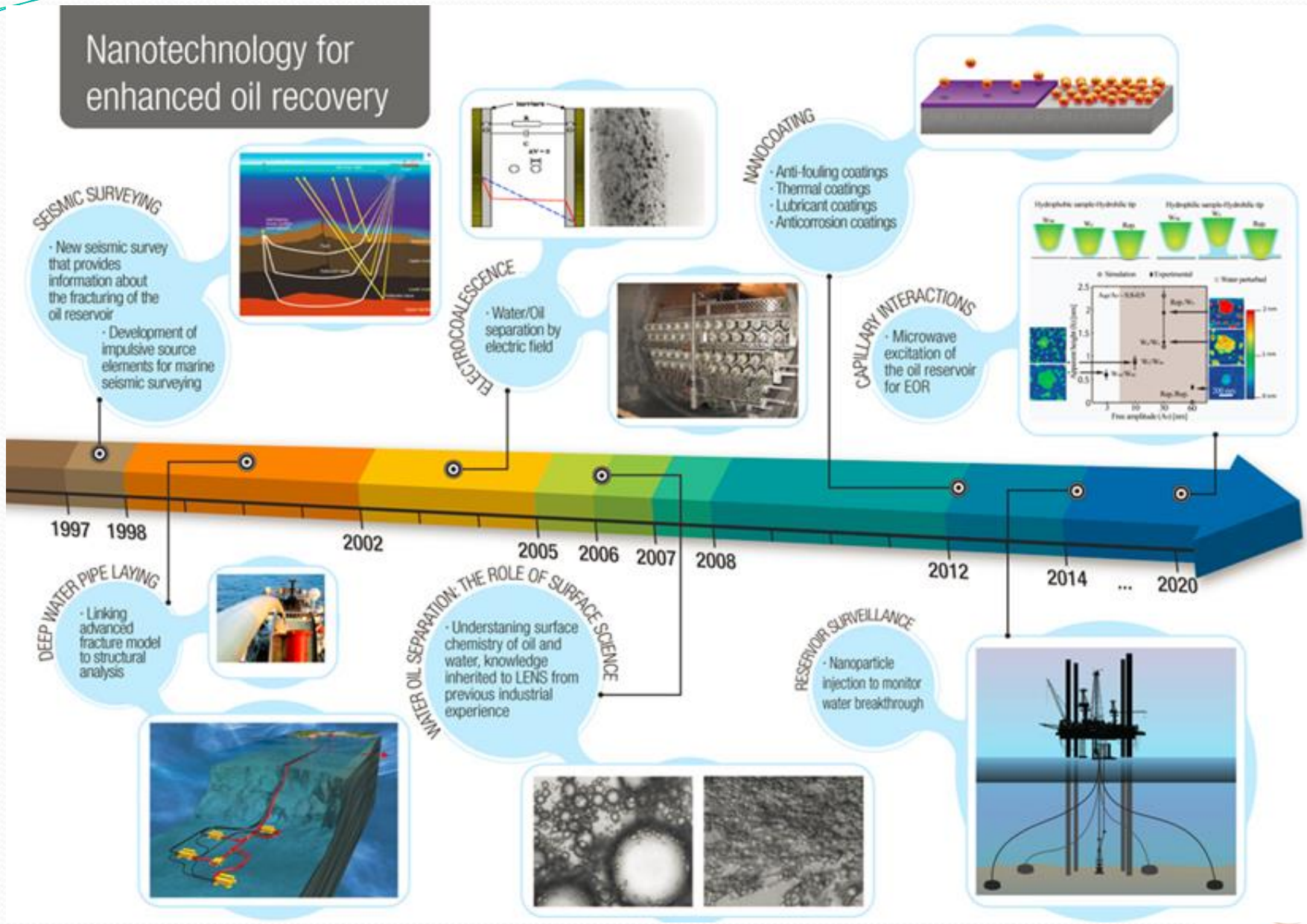


Beneath the skin, The Rose Foundation

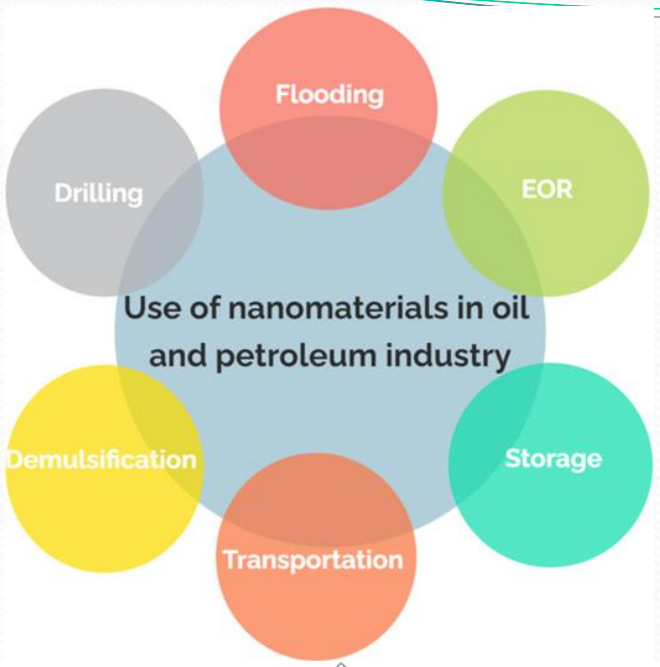
Nanotechnology in Cosmetics



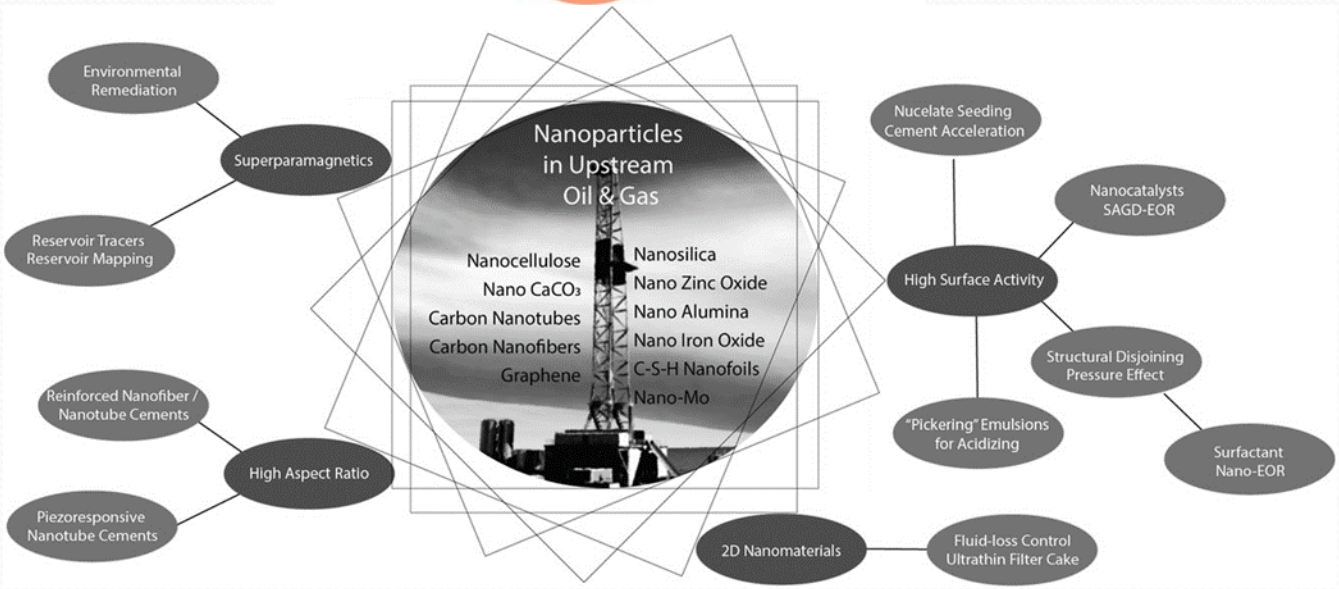
Nanotechnology in the Oil Industry



Use of Nanomaterials in the Oil & Petroleum Industry

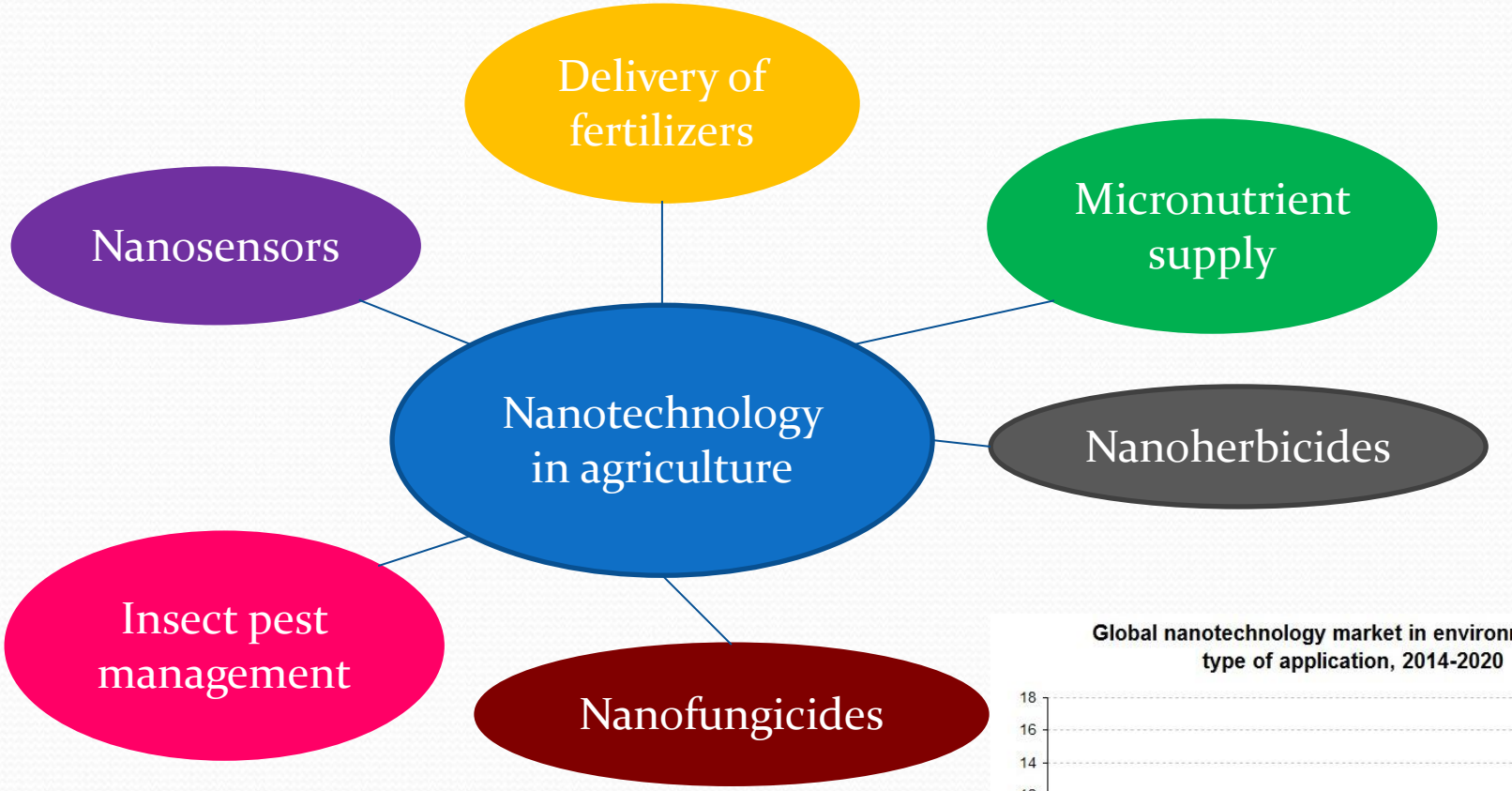


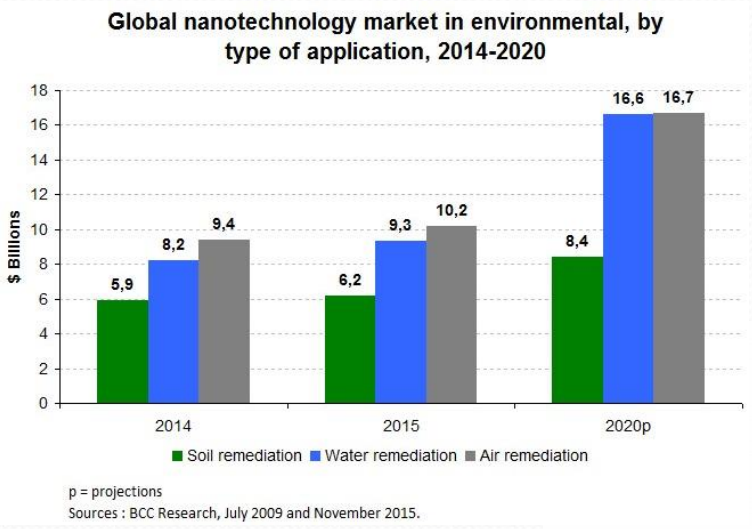
Roy, A., et al Nano Ex. 4, 022002 (2023)



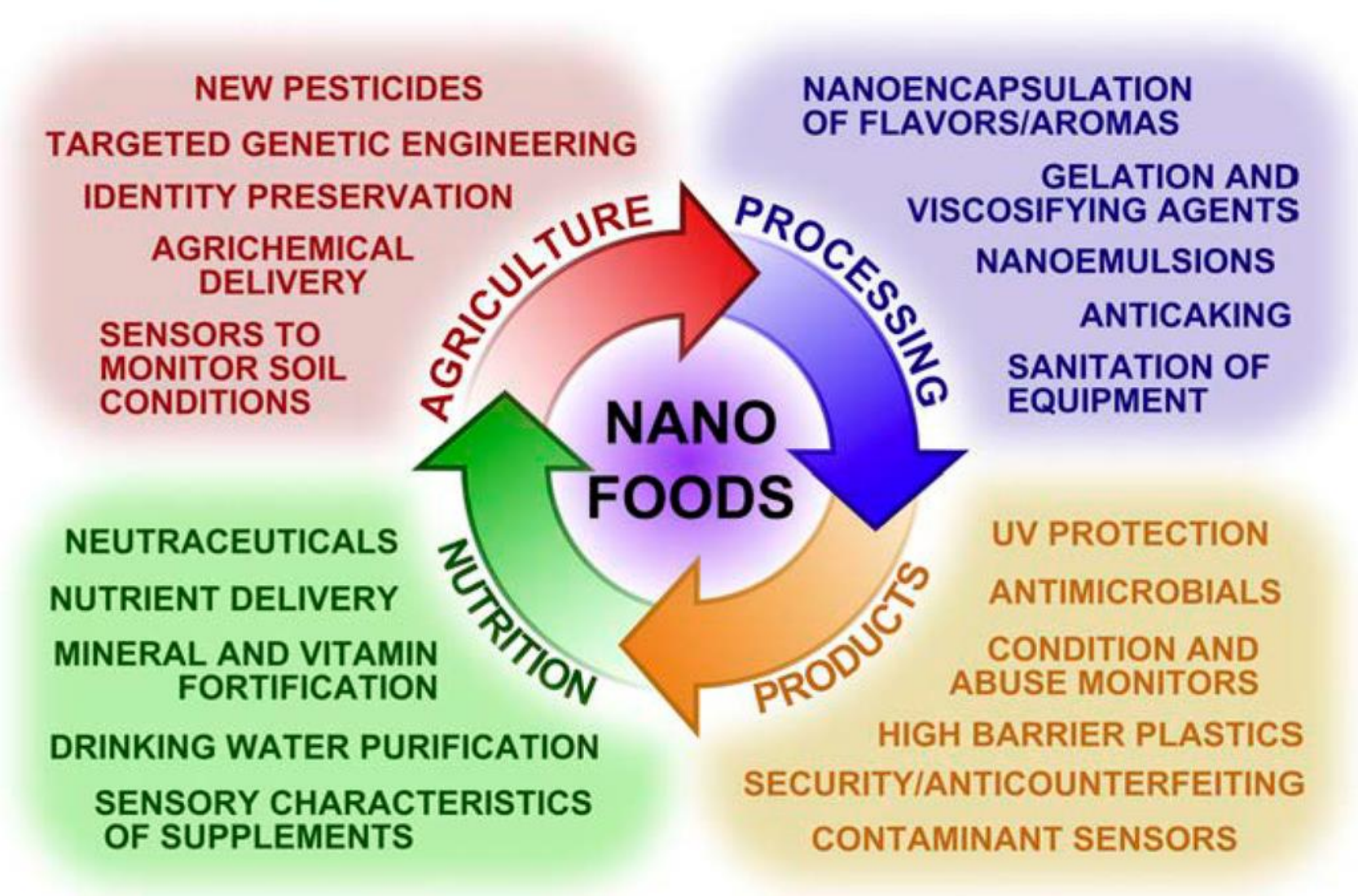
Boul, P.J., et al., Energy Tech, 8, 1, (2019)

Nanotechnology in Agriculture





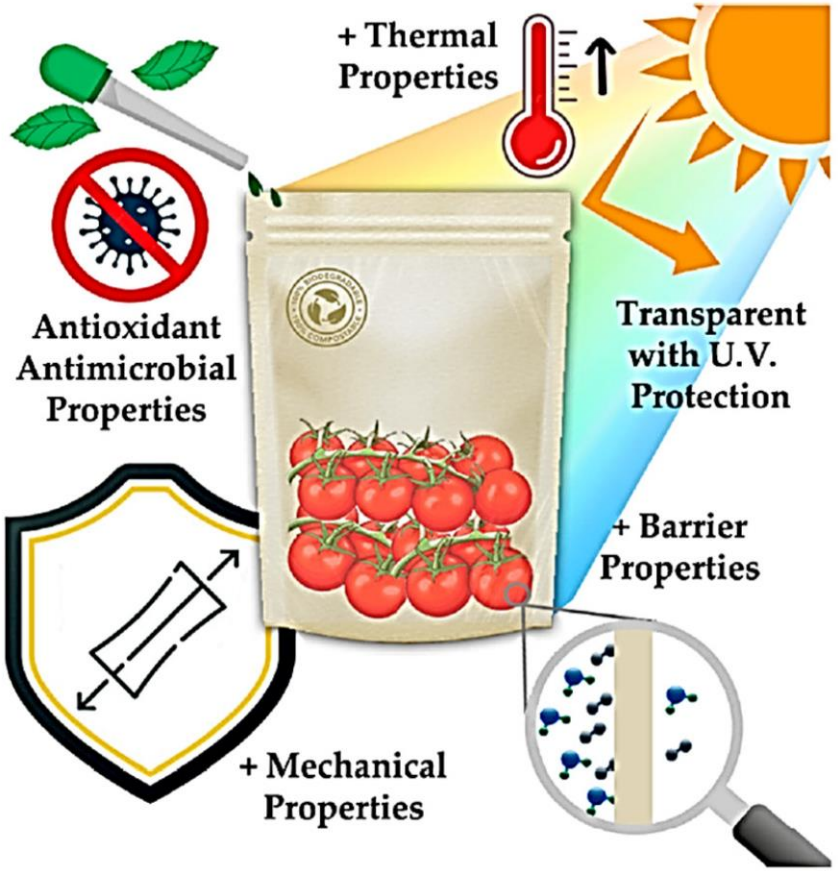
Nano-Foods


NEW PESTICIDES
TARGETED GENETIC ENGINEERING
IDENTITY PRESERVATION
AGRICHEMICAL DELIVERY
SENSORS TO MONITOR SOIL CONDITIONS
AGRICULTURE
NANOENCAPSULATION OF FLAVORS/AROMAS
GELATION AND VISCOSIFYING AGENTS
NANOEMULSIONS
ANTICAKING
SANITATION OF EQUIPMENT
PROCESSING
NANO FOODS
NEUTRACEUTICALS
NUTRIENT DELIVERY
MINERAL AND VITAMIN FORTIFICATION
DRINKING WATER PURIFICATION
SENSORY CHARACTERISTICS OF SUPPLEMENTS
NUTRITION
UV PROTECTION
ANTIMICROBIALS
CONDITION AND ABUSE MONITORS
HIGH BARRIER PLASTICS
SECURITY/ANTICOUNTERFEITING
CONTAMINANT SENSORS
PRODUCTS

Nanotechnology – Enhancing Food Packaging Solutions

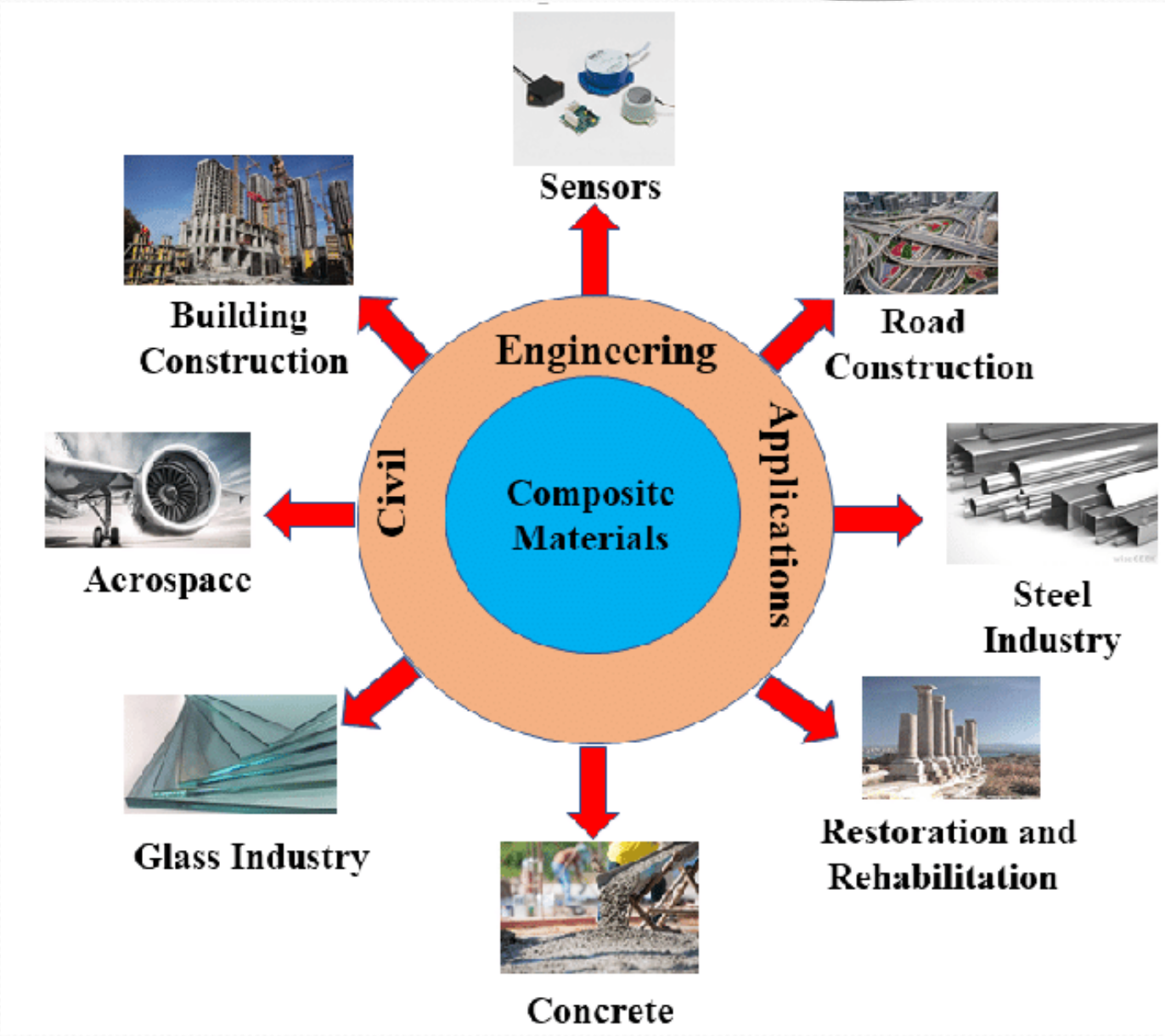
Traditional
Plastic Packaging

Bionanocomposite
Packaging



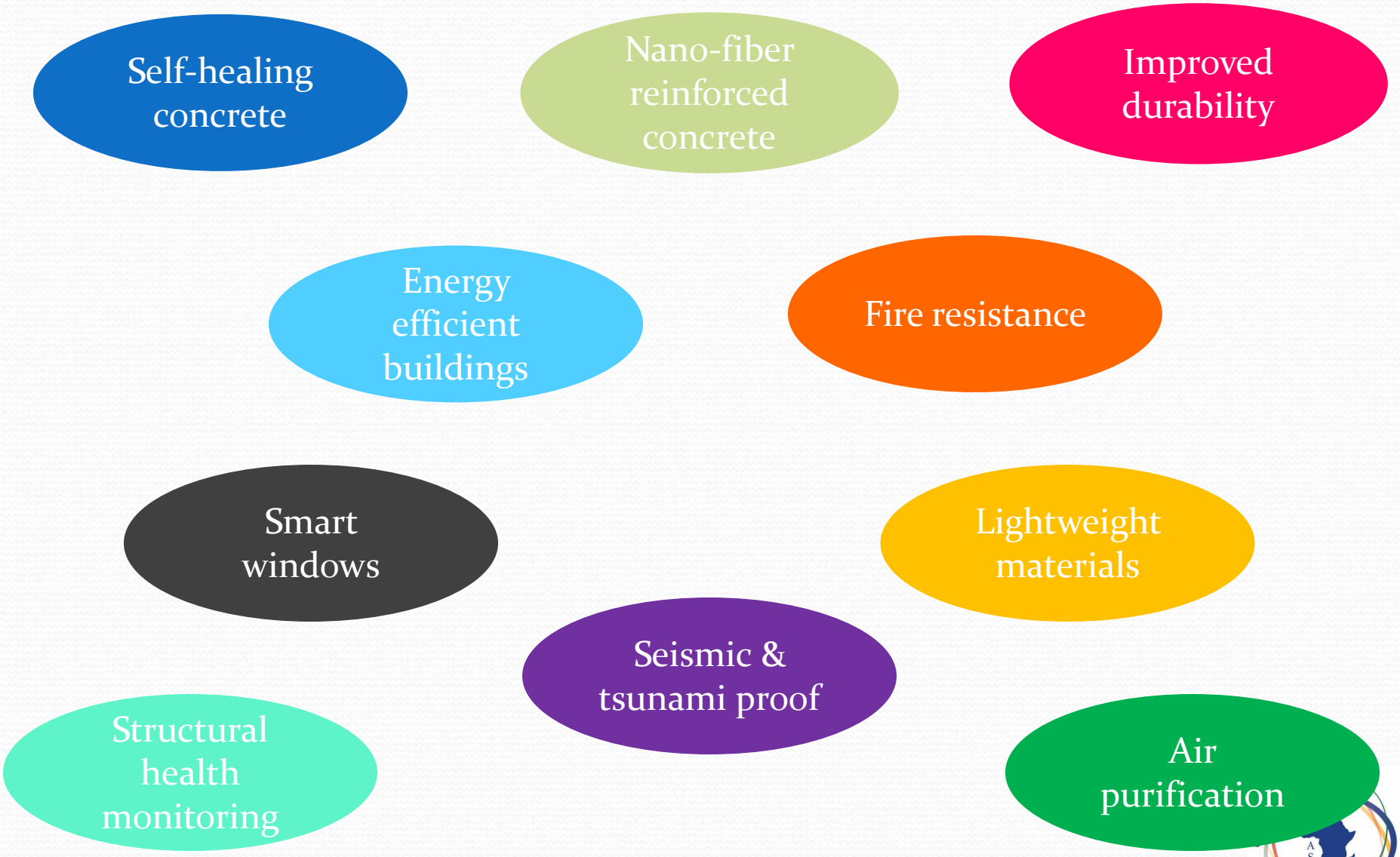
de Sousa,M. Coatings ***2023****, 13(8), 1411*

Nanotechnology in Construction

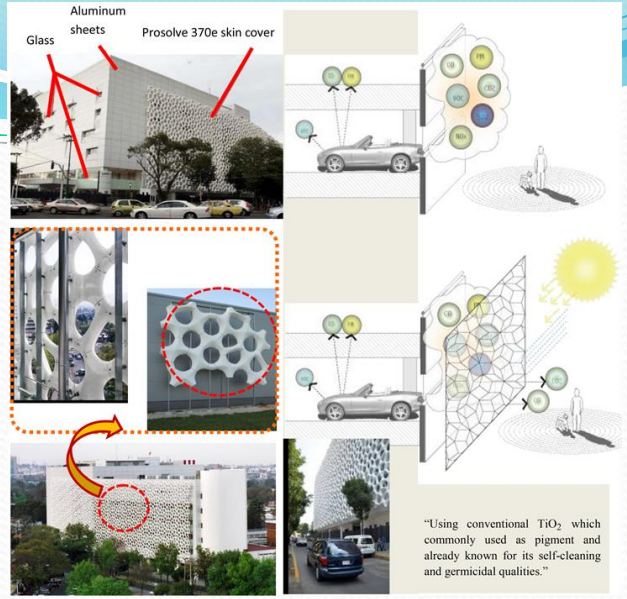


Medlej, A., ITU J. on Future and Evolving Technologies Vol. 2, Issue 7 - Terahertz communications (2021)

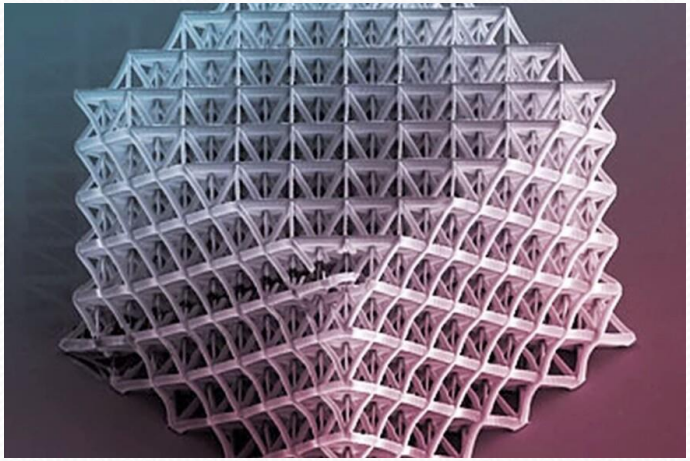
Nanotechnology in Construction



The Jubilee Church in Rome, quartiermagazin.com/quartier08/ der-weise-riese



Manuel Gea Gonzalez Hospital using conventional TiO_2—CNN



A nanotruss structure fabricated by Caltech Prof. Julia Greer

[MIT Scientists Create Smart Window that Can Shut Out Light (futurism.com)]

Inside Ethiopian airlines flight – Boeing

NanoProducts

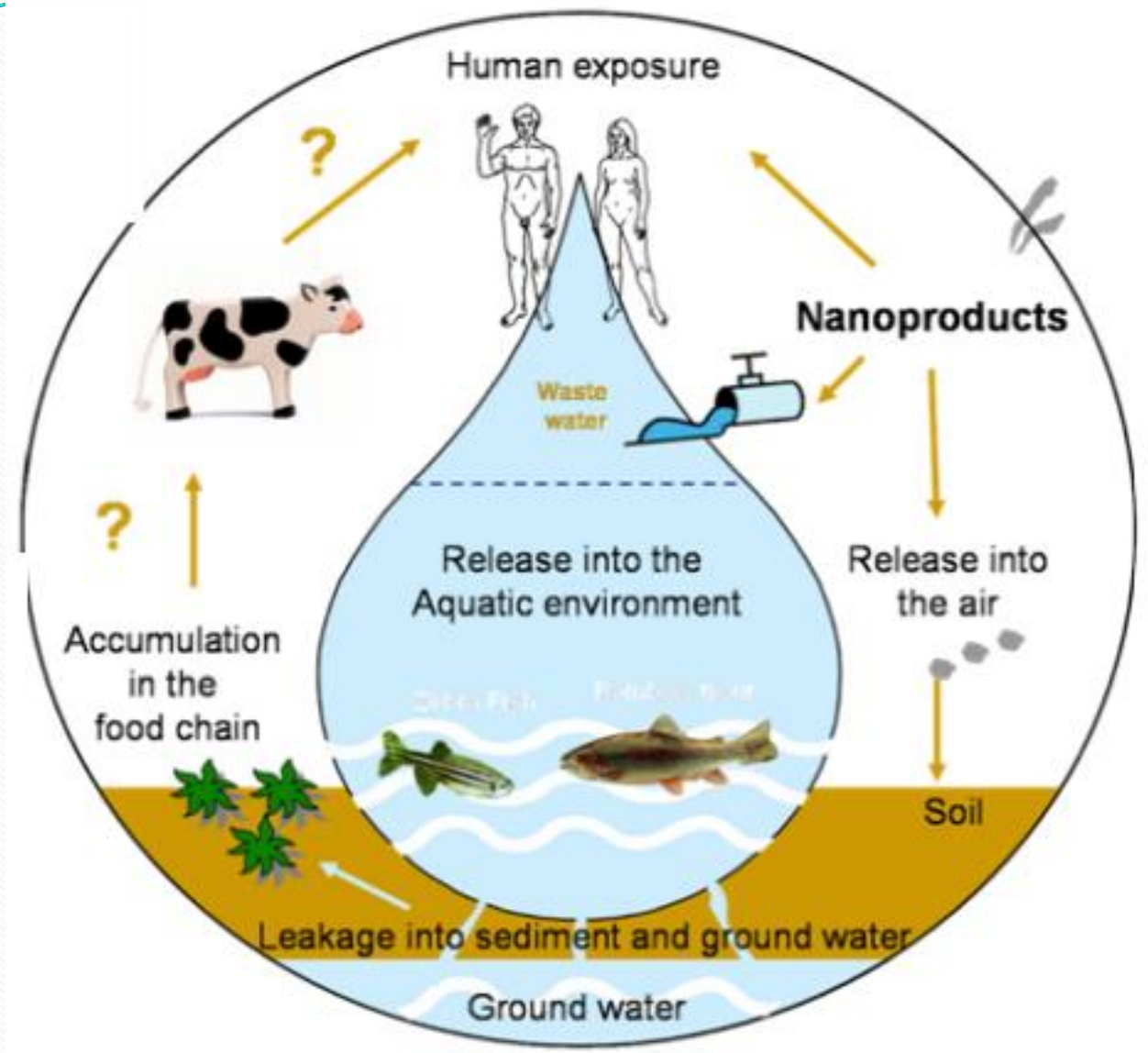
Where is it used?

Future use?

How do you dispose of it?

A user's guide to Nanotechnology
http://www.theguardian.com/nanotechnology-world/a-user-s-guide-to-nanotechnology

Risks: Toxicity, Assessment, Exposure



Exposure routes in humans?

Reaction with the environment ?

Primary issues

Detection techniques

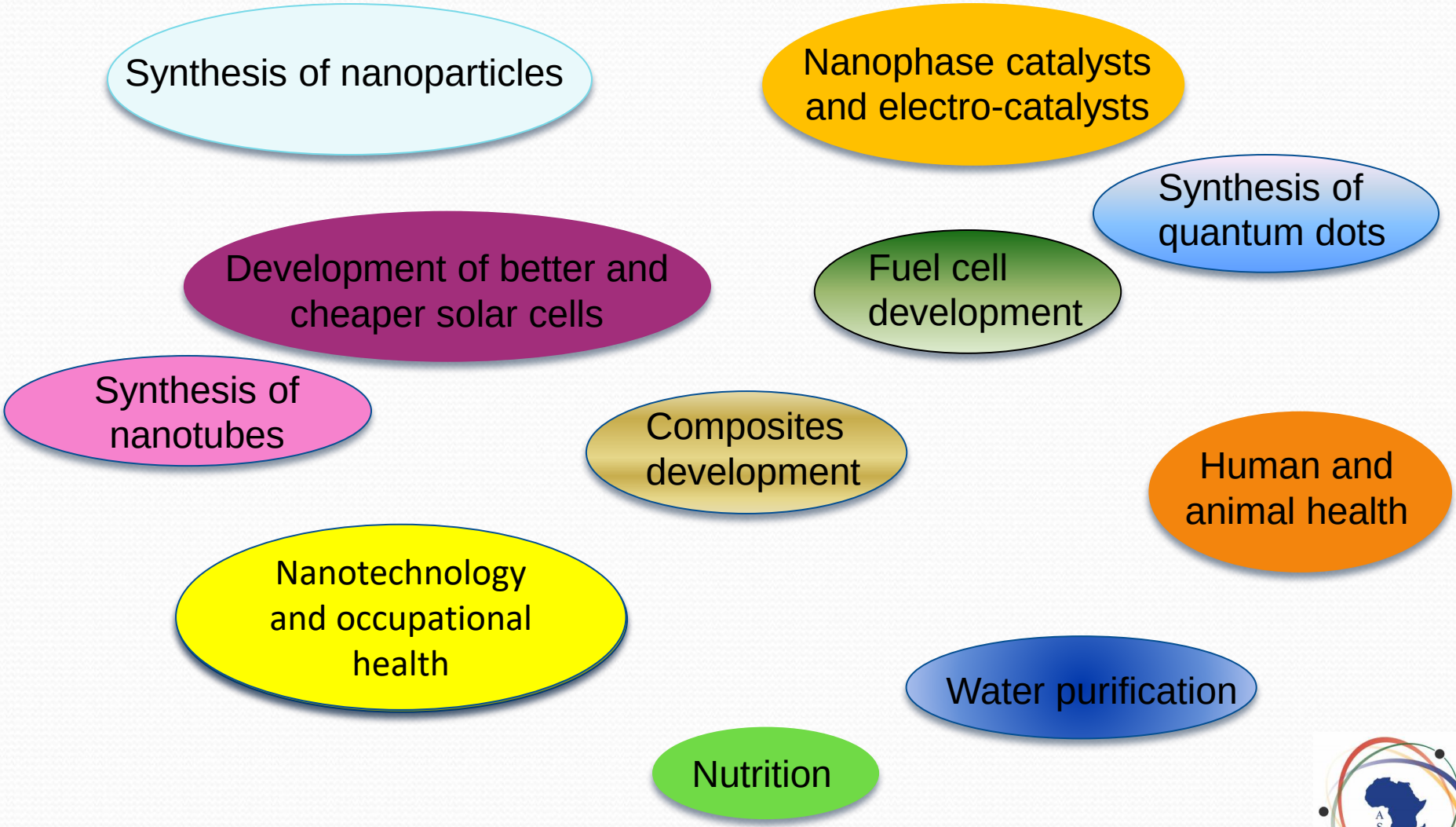
Solutions

Nanotechnology in Africa

The African Union recognizes nanotechnology as a compelling imperative and identifies nanotechnology as one of six priority areas in its Science, Technology and Innovation Strategy for Africa 2024.

Towards an African nanotechnology future, United Nations, Economic Commission for Africa (2020)

Nanotechnology in Africa



Nanotechnology in Africa

Egypt
Top nanotechnology research country in Africa – Big collaboration with IBM (health, oil, photovoltaics,...)

South Africa
African country with the most patents, nanotech emerging companies & institutions, SANi

Nigeria
Nanotechnology in medicine, nutrition, electronics, catalysis

Kenya
Efforts focus in medicine, agricultural productivity, water treatment, purification

Ethiopia
Water purification, nanomaterials, solar energy and single-walled carbon nanotubes

Senegal
Synthesis, characterization, & application of nanomaterials

Tanzania
Nanotechnology for human and animal health and in biotechnology

Sudan
Synthesis & characterization of nanomaterials, and drug delivery

Cameroon
Synthesis & characterization of nanomaterials, water purification and treatment

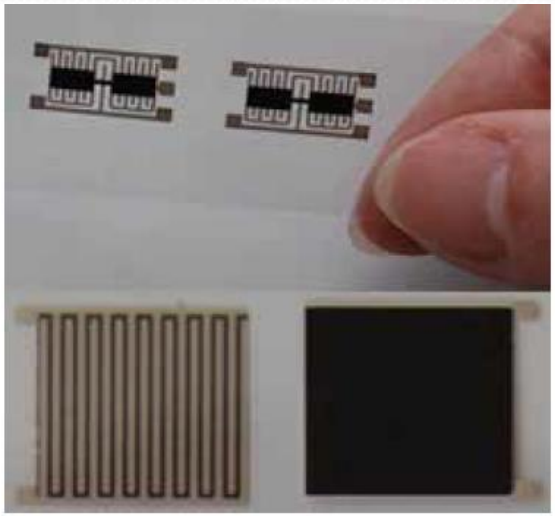
African Newsletter on Occupational Health and Safety, 22, 3 (2012)

All African Nanoscience-Nanotechnology Initiative (2014)

Towards an African nanotechnology future, United Nations, Economic Commission for Africa (2020)

Nanotechnology in Africa: Some Examples

Water purification plant in Tanzania

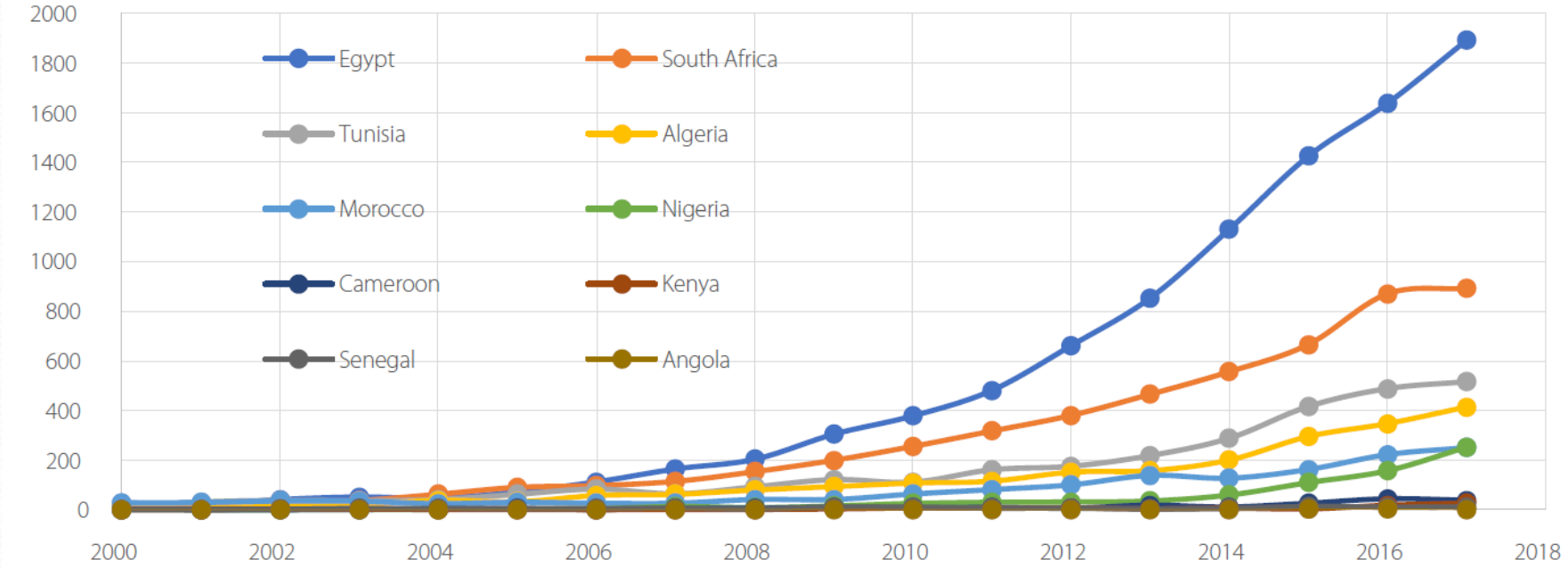


Heat sensors using innovative technology in South Africa

NanoTech in Egypt manufacture custom-tailored nanomaterials

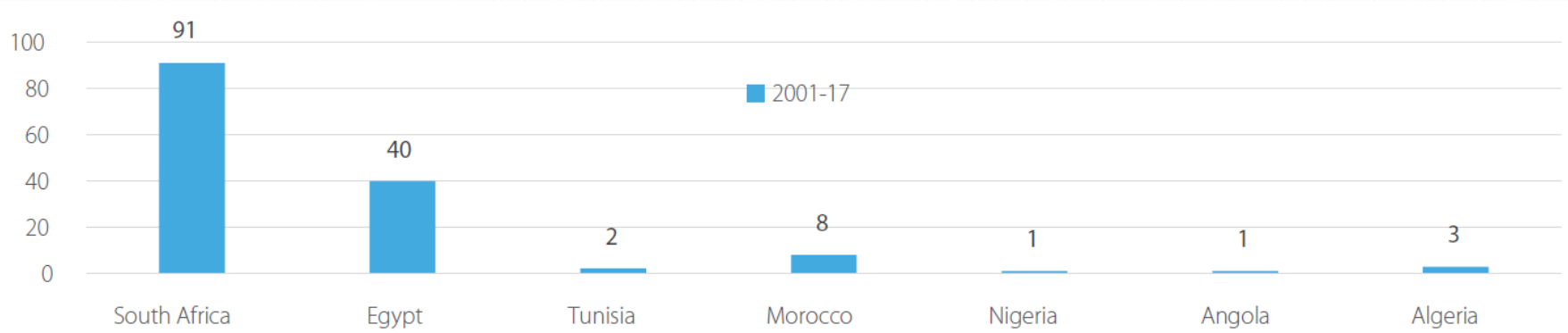
Towards an African nanotechnology future, United Nations, Economic Commission for Africa (2020)

Nanotechnology Publications in Top 10 African Countries



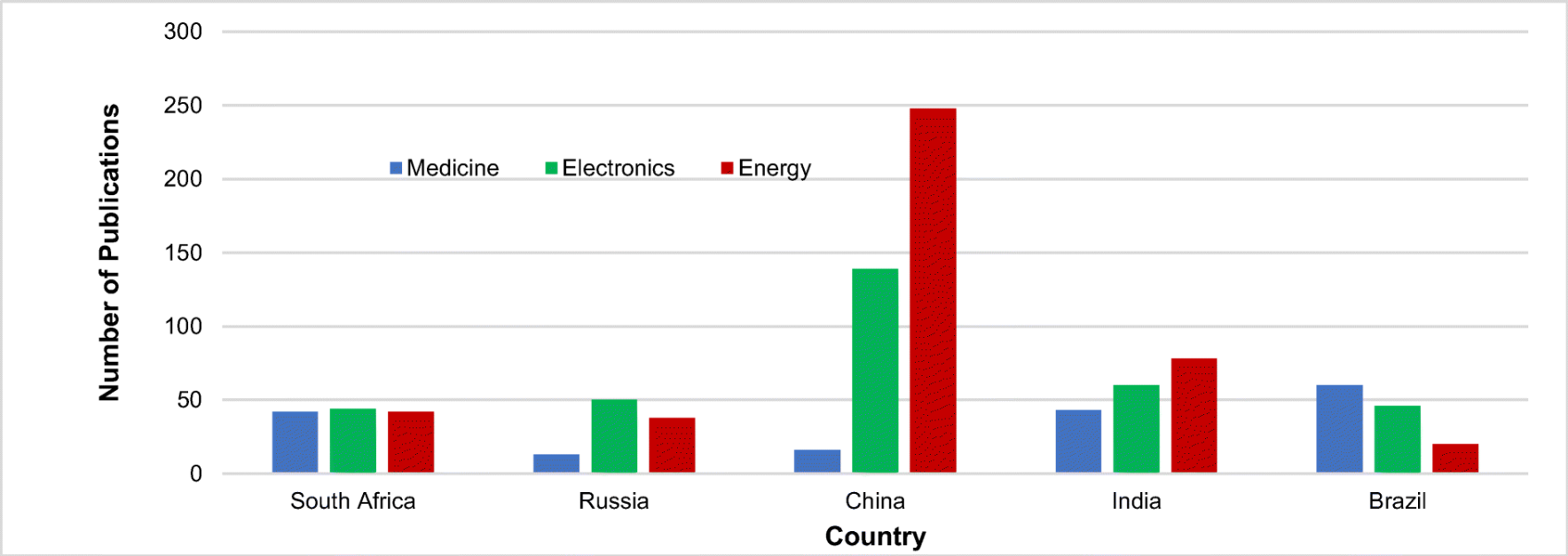
Source: *NanoStat database.*

Patent Applications per Selected African Countries (2001 – 2017)



Source: *NanoStat database.*

Number of Publications Nano-related in the BRICS (2021)

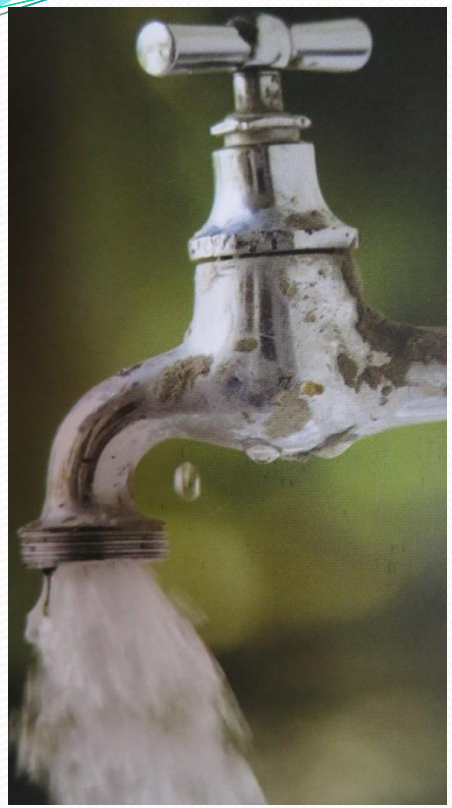


South Africa publications reporting on nano-enabled products relative to BRICS countries, Masara, B., J. of Nanoparticle Res., Vol. 23, 92 (2021)

Strategy for Nanotechnology Innovation in Africa

Jhurry, D., Univ. World News, Africa Edition (2022)

Water Purification



Mining

wikipedia.

Effects on population

Nanofiltration membranes

Nanocatalysts and magnetic nanoparticles

Nanosensors

How Nanotechnology saved a Contaminated Lake in Peru

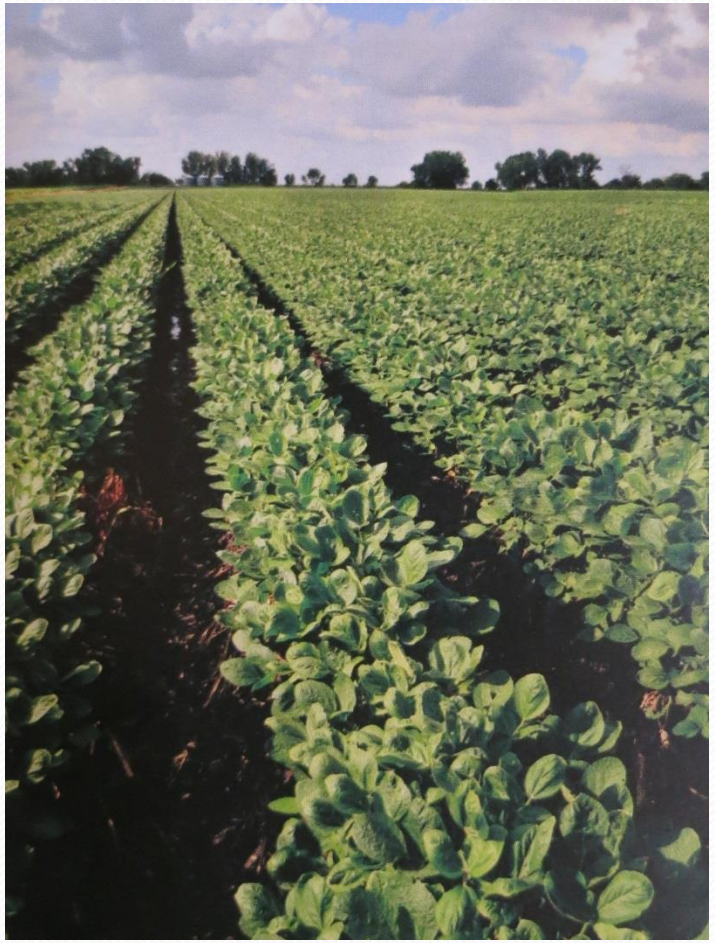
El Cascajo Wetlands in Peru were cleaned using micro nano bubbling system and a biofilter

Marino Morikawa

http://www.tea-after-twelve.com/all-issues/issue-02/issue-02-overview/chapter3/the-nanotechnology-miracle/#

National Nanotechnology Initiative
http://www.nano.gov/

Agriculture & Forestry



Plant treatment

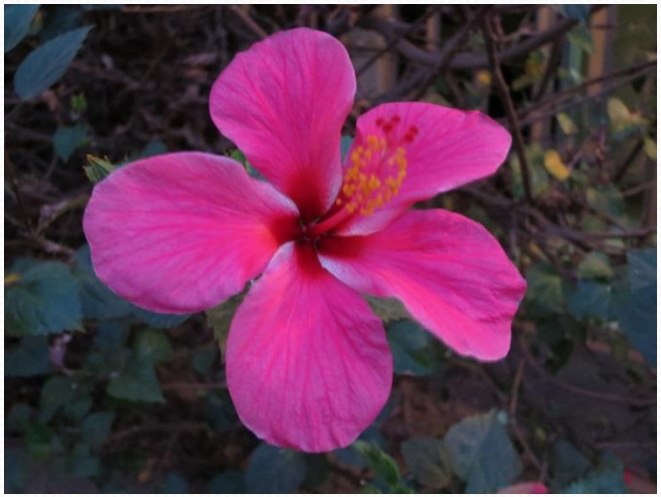
Tracking & Conservation

Preservation & Prevention

Natural Extracts

Using green chemistry only ➔ no harsh acids / no harsh bases

Pr. Malik Maaza, South Africa



Hibiscus flowers

Callistemom viminalis

Agathosmal betulinia

Alfalfa

Tamarind

Other Plants?

Eucalyptus

Lantana

Calendula

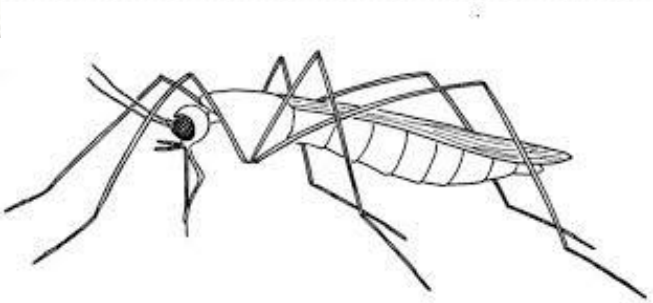
Moringa oleifera

What if I am a Theorist?

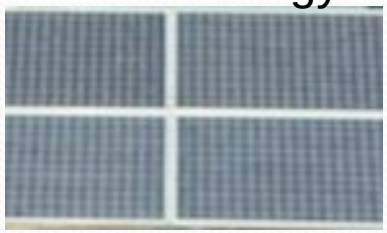
Paper battery

Air quality

TB or malaria detection?

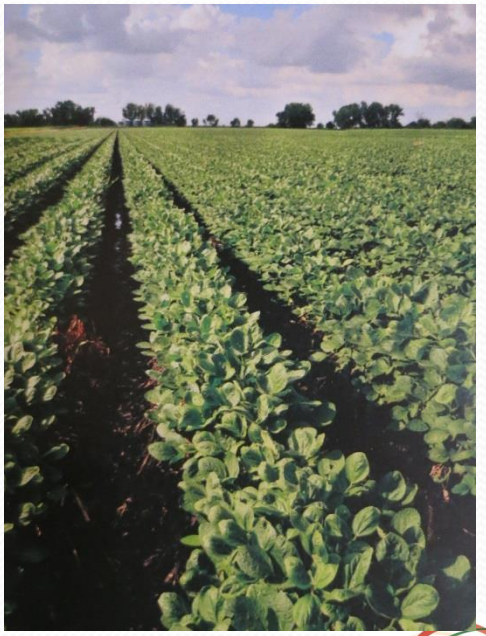


Solar energy



AI

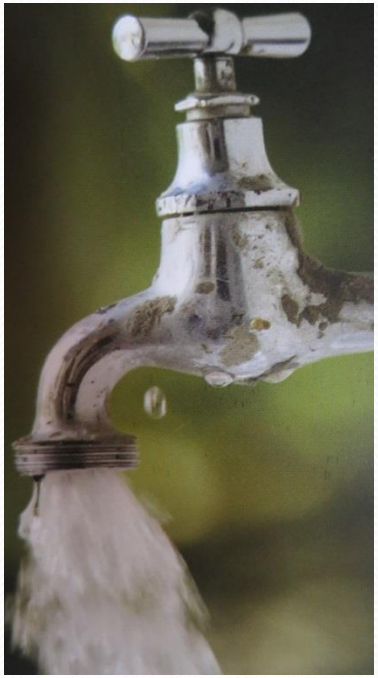
Lengau - Africa's fastest computer



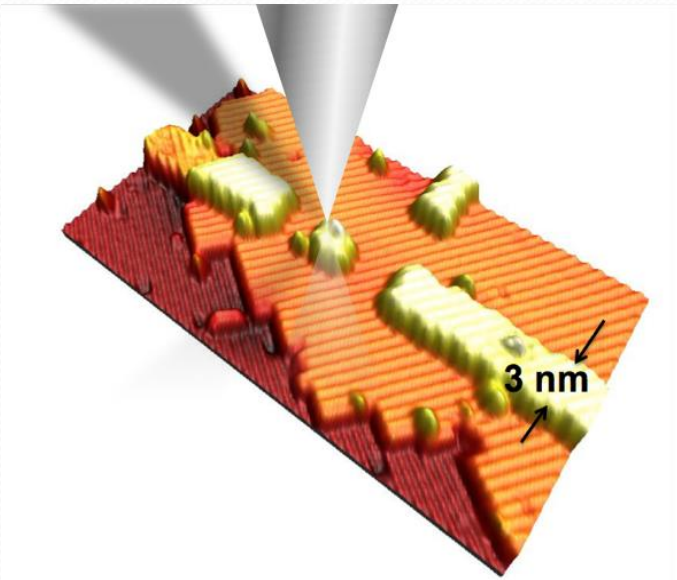
Precision farming

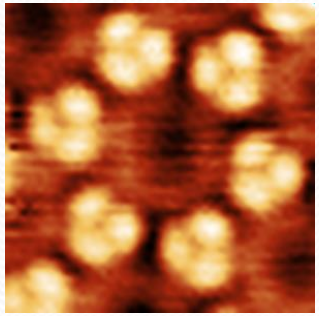
Thank you for your attention

شكراً



ⵜⴰⵏⵎⵉⵔⵜ !





References

- National Nanotechnology Initiative : http://www.nano.gov/
- AT&T Archives
- NobelPrize.org
- "There's Plenty of Room at the Bottom" Richard Feynman at an American Physical Society (APS) meeting at Caltech on December 29, 1959
- N. Taniguchi, Proc. Intl. Conf. Prod. Eng. Tokyo Part II, Japan Society of Precision Engineering, 1974, pp 18-23.
- Poh, T.Y., Particle and Fibre Toxicology 15 (1), 2018
- *Rai, M., et al., Nano. Rev. 3 (2014) 3*
- Intel.com
- *Eigler,D., Nature 344, 524 (1990)*
- *Syduzzaman, M. et al., ChemNanoMat* 2023, *9*, e202300205
- Precedence Research
- *Hansen, S., et al., Environ. Sci. Nano*, 2016, **3**, 169-180
- *Yetisen, A.K., ACS Nano (2016) 10, 3, 3042*
- *A. Avila et al., Nature Nanotechnology 3, 458 (2008)*
- *Yahoo Finance*
- *Beneath the skin, The Rose Foundation*
- *Grand View Research, Market Research Report (2017)*
- Nanomaterials: An overview of synthesis, classification, characterization, and applications, Mekuye, Nano Select (2023), 4, 486
- Medlej, A., ITU J. on Future and Evolving Technologies Vol. 2, Issue 7 - Terahertz communications (2021)
- MIT Scientists Create Smart Window that Can Shut Out Light (futurism.com)
- de Sousa, M. Coatings 2023, 13(8), 1411
- *M. Gurian, Upholstery Journal Feb/Mar(2009)*
- The Jubilee Church in Rome : quartiermagazin.com/quartier08/ der-weise-riese
- http://www.tea-after-twelve.com/all-issues/issue-02/issue-02-overview/chapter3/the-nanotechnology-miracle/#
- Nanostat database
- Statnano database
- Can Africa risk missing the nanotechnology revolution? (universityworldnews.com), Jhurry, D., Univ. World News, Africa Edition (2022)
- *South Africa publications reporting on nano-enabled products relative to BRICS countries, Masara, B., J. of Nanoparticle Res., Vol. 23, 92 (2021)*
- African Newsletter on Occupational Health and Safety, 22, 3 (2012)
- All African Nanoscience-Nanotechnology Initiative (2014)