Nanotechnology

Is Small Scary?

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- **“Military applications of molecular manufacturing have even greater potential than nuclear weapons to radically change the balance of power.”**

- Admiral (Ret) David E. Jeremiah, former vice chairman of Joint Chiefs of Staff *

* “Nanotechnology and Global Security,” (Palo Alto, CA; Fourth Foresight Conference on Molecular Nanotechnology), November 1995.

Security Puzzles

- Does nanotechnology have unique strategic value?
  - Security, economic, political, &/or scientific
- Disambiguate potential for unique capabilities from enabling previous capabilities
- Perception or ideation vs technical reality
  - "Hope" & "Horror" hype
  - Rhetoric
  - (Pseudo)-technical assessments
    E.g., *"New technologies (at risk for terrorist appropriation) include biotechnology,* ***nanotechnology, single nucleotide polymorphisms*** *(SNPs), and* ***Bose-Einstein condensates.*****"***
  - Influencing factors: institutional
- International regimes for emerging technologies
  - Adequacy of traditional arms control treaties
  - Value of norms
  - Role of NGOs, transnational actors, industry

*** "WMD Terrorism Research: Where to From Here?" International Studies Review, March 2005, vol. 7, p. 140**

Changing Strategic Environment

- Post-Cold War international security environment
- Technology no longer guarantees security
- Globalization and information revolution as drivers
  - Enable spread and accessibility
- Dual-use conundrum
- Changing nature of warfare
  - Asymmetric warfare
  - Interest in unconventional weapons
- Relationship between science and security
- Disruptive technologies

Evolutionary Approach: 1918 vs 2010

Impregnated suit and various masks

Placing pigeon in cage at trench entrance

Handheld decon unit & decon tank truck

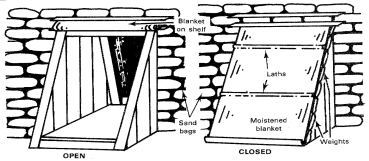


Figure 4. Entrance, gas-proof dugout.

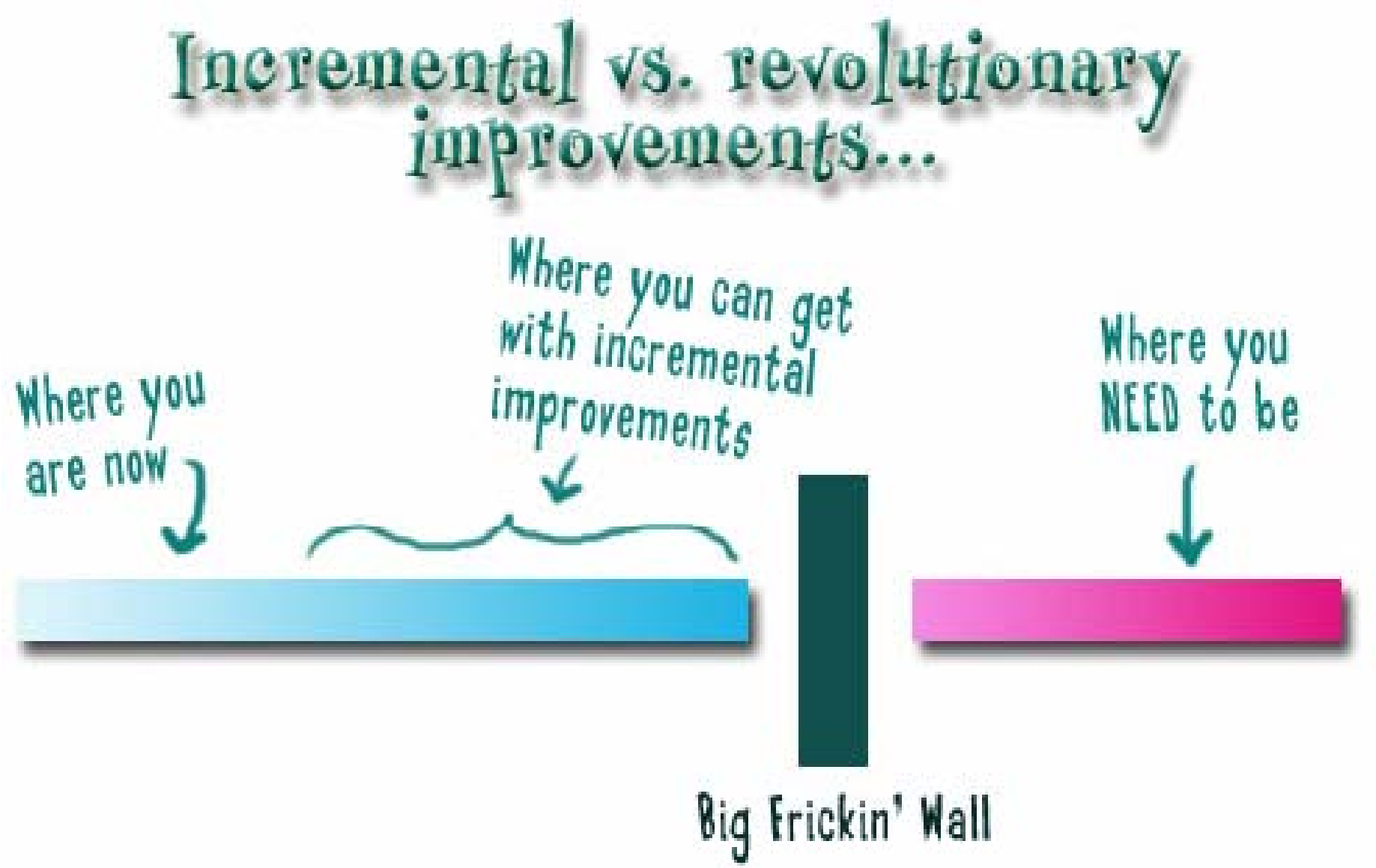
Trench fan and entrance way

Point & “standoff” detection

Suit, gloves, boots & various masks

Handheld decon unit and various applicators including tank trucks

Shelters & filters



Cartoon Courtesy Kathy Sierra,
Creating Passionate Users

What is Nanotechnology?

- Nanotechnology is a bundle of diverse capabilities
  - Expectations of synergies between them
- Danger of treating nanotechnology as a *thing*: determinate homogenous entity
- Term creates boundaries around the field and hierarchies within it
- Precision of terms:
  - Nanoscience, Nano-engineering, Nano-engineered materials, Bionanotechnology, & Nanotechnology
- *(Emerging?)* interdisciplinary area of science, engineering, and technology
- Concerned with materials and process at very small dimensions
- 1 nanometer = 10^{-9} m = 1/billionth of a meter

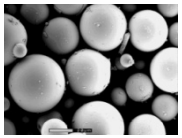
Examples of Nanoscale Objects

Things Natural


Dust mite
200 μm

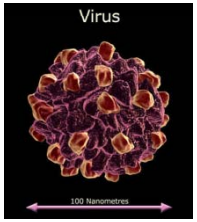

Ant
~ 5 mm


Human hair
~ 60-120 μm wide

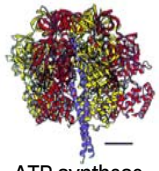

Fly ash
~ 10-20 μm

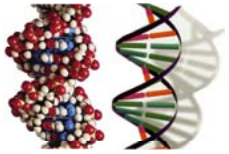
Red blood cells
(~7-8 μm)

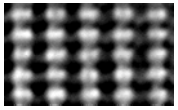

~10 nm diameter

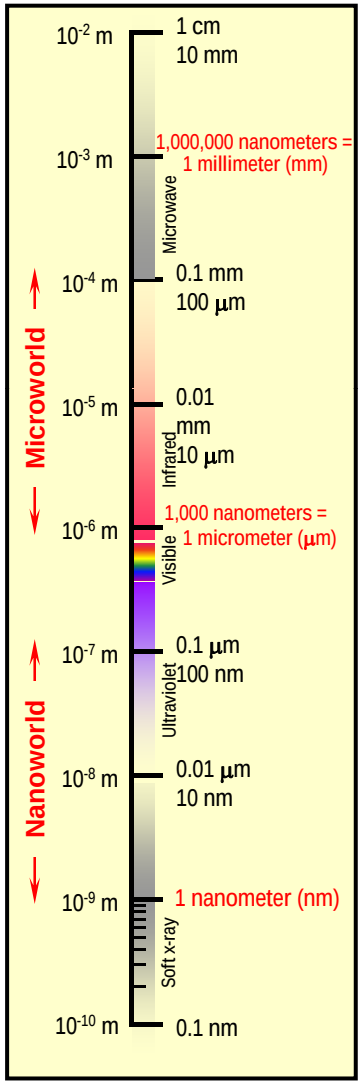


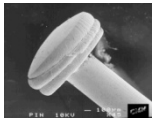
~100 nm


ATP synthase

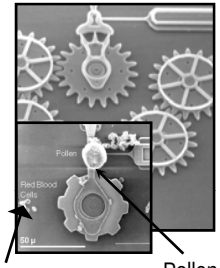

DNA
~2-1/2 nm diameter


Atoms of silicon
spacing 0.078 nm



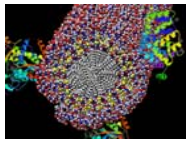

Head of a pin
1-2 mm

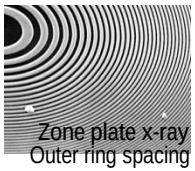
MicroElectroMechanical
(MEMS) devices
10 -100 μm wide



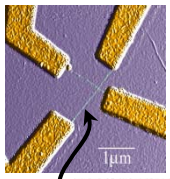
Red blood cells

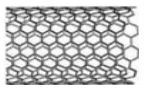
Pollen grain

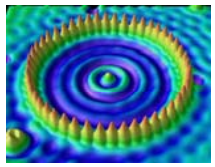

Self-assembled,
Nature-inspired structure
Many 10s of nm


Zone plate x-ray "lens"
Outer ring spacing ~35 nm

Nanotube electrode



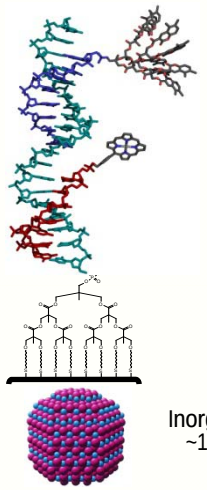

Carbon nanotube
~1.3 nm diameter

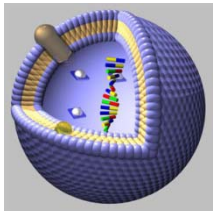

Quantum "corral"
48 iron atoms
(14 nm diameter)

Things Manmade

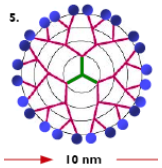
The Challenge:

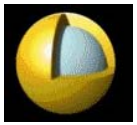
Fabricate and combine nanoscale building blocks (natural and manmade) to make useful devices that exploit novel properties and functions because of their small size.

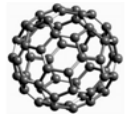

Inorganic nanoparticles
~1-100 nm diameters


Liposomes
~15 nm - microns diameter

5th generation dendrimer
~10 nm diameter

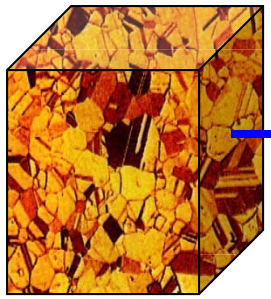


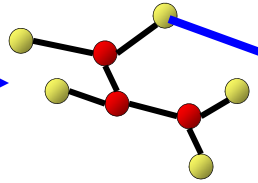

Nanoparticles and nanoshells
~1-100 nm diameter

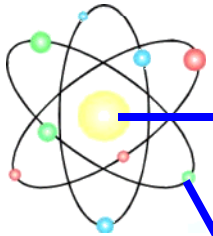

Fullerene
~1 nm diameter

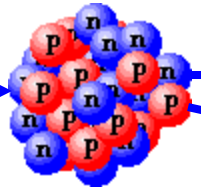
Courtesy DOE Office Basic Energy Sciences (http://www.er.doe.gov/bes/scale_of_things.html)

Structure of Matter









Matter

Molecule

Atom

Nucleus

Baryon
(Hadron)

Quark

10^{-2}m

10^{-9}m

10^{-10}m

10^{-14}m

10^{-15}m

$<10^{-19}$m

protons, neutrons, mesons, etc.
p,W,L...

top, bottom, charm, strange, up, down

Condensed matter/Nano-Science/Chemistry

Atomic Physics

Biology

Nuclear Physics

Electron
(Lepton)

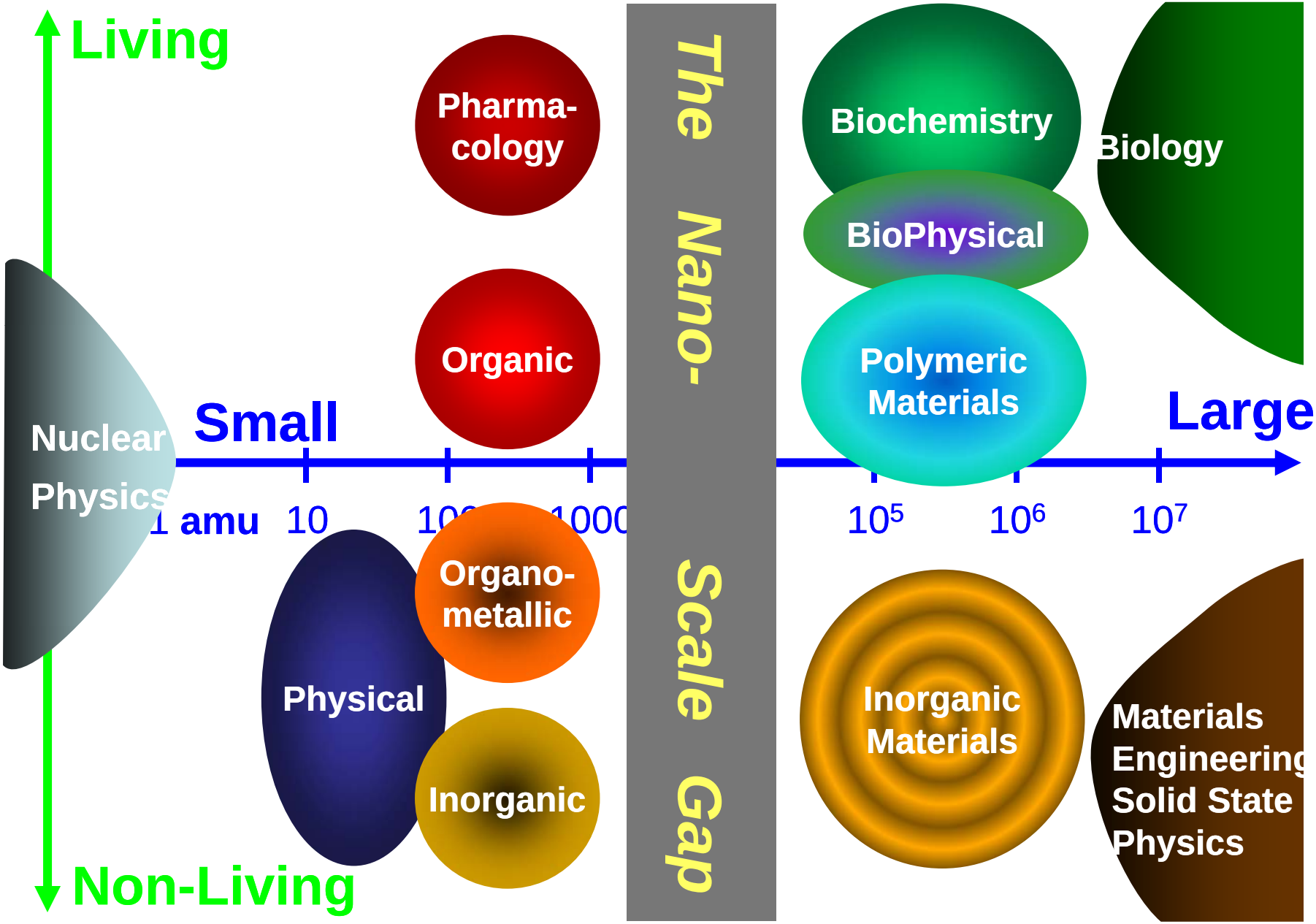
$<10^{-18}$m

High Energy Physics

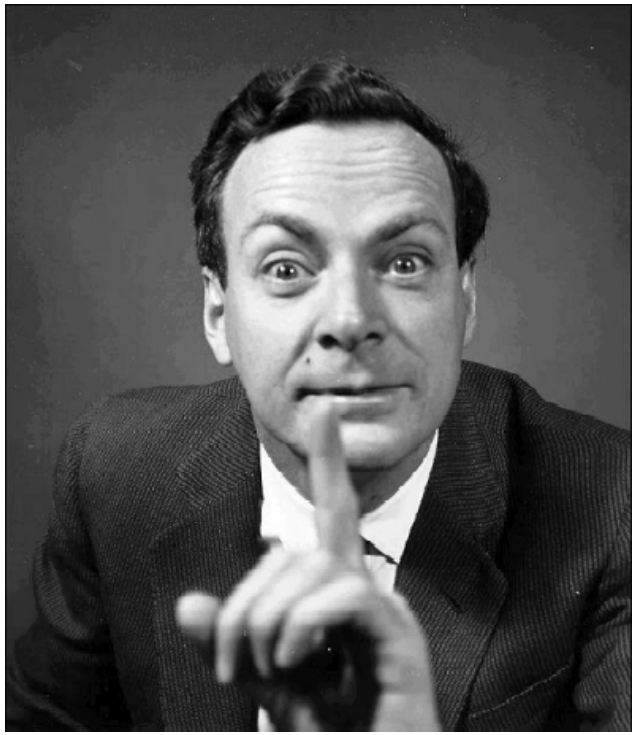
Social Sciences

Engineering

What Nanoscience Is



Feynman: the father of Nanotechnology



Prof. Richard Feynman
courtesy of Caltech

'There's Plenty of Room at the Bottom - An Invitation to Enter a New Field of Physics'
December 1959

"…furthermore, a point that is most important is that it would have an enormous number of technical applications."

Historical Nanotechnology

The First Nanotechnologists

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:

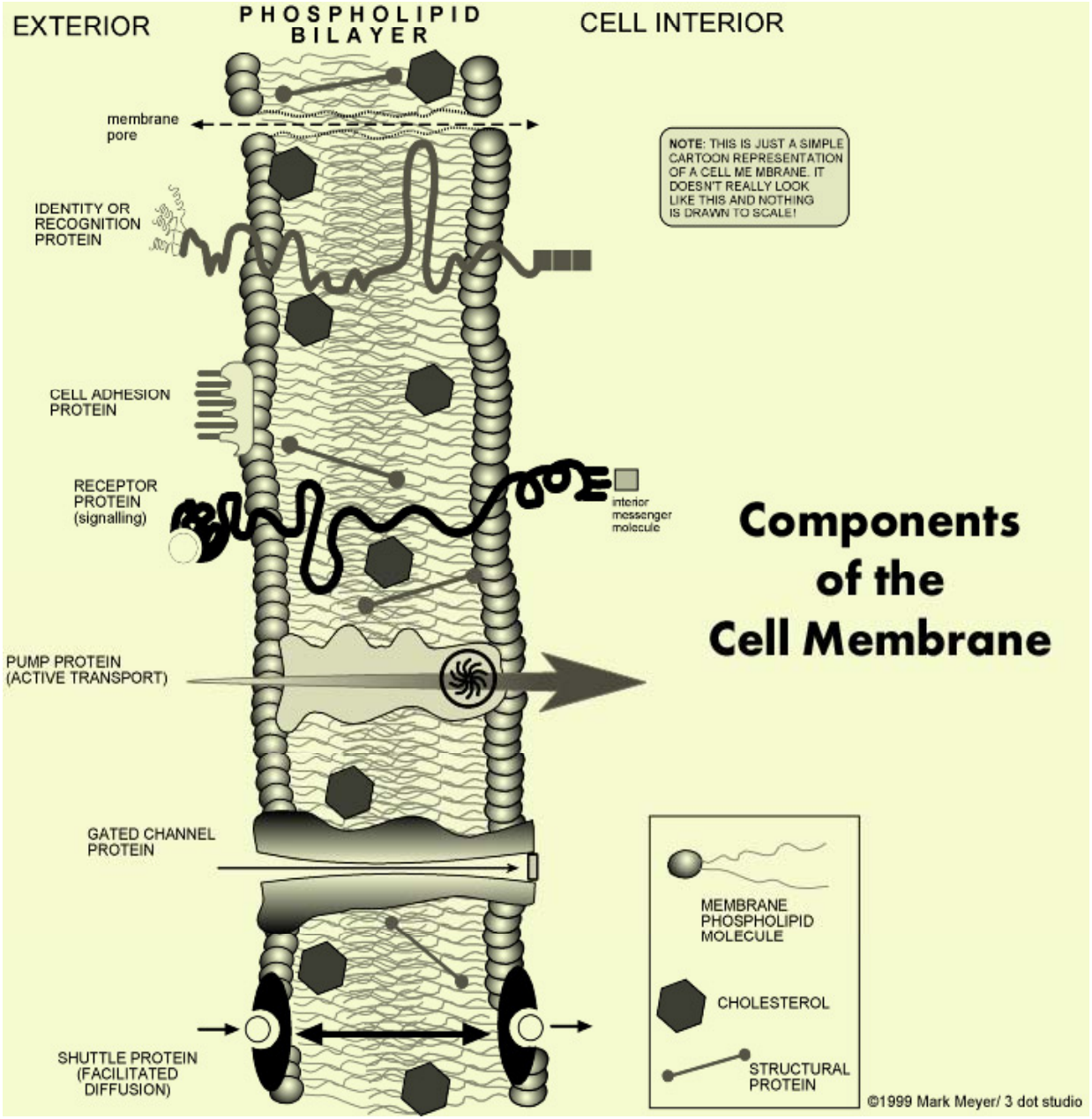
Size*: 100 nm
Shape: prism
Color reflected:

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

*Approximate

Courtesy Chad Mirkin, Northwestern University, in *NYTimes* article by K. Chang - 2005

Nature: the original Nanoscientist

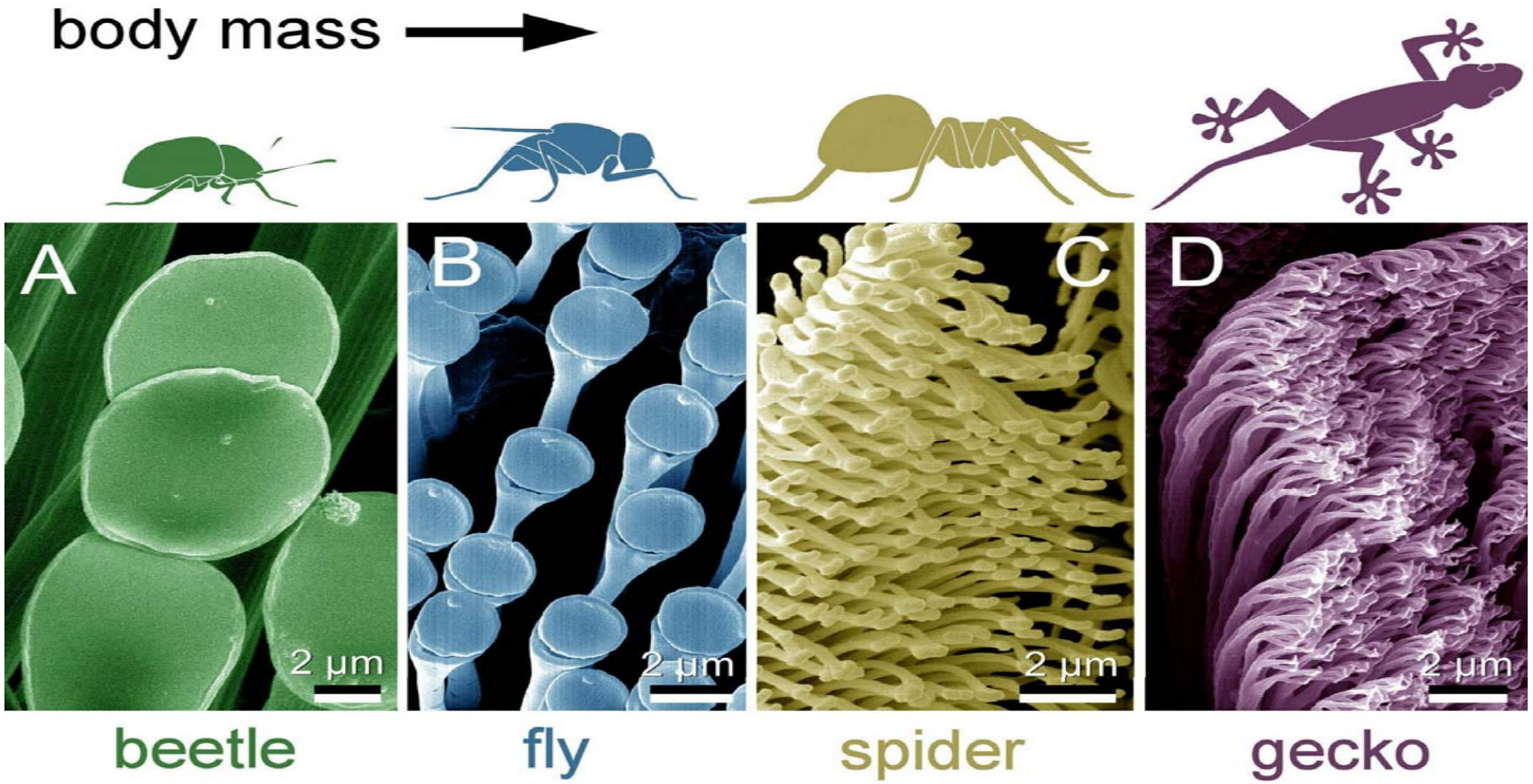


thickness
~ 10 nm

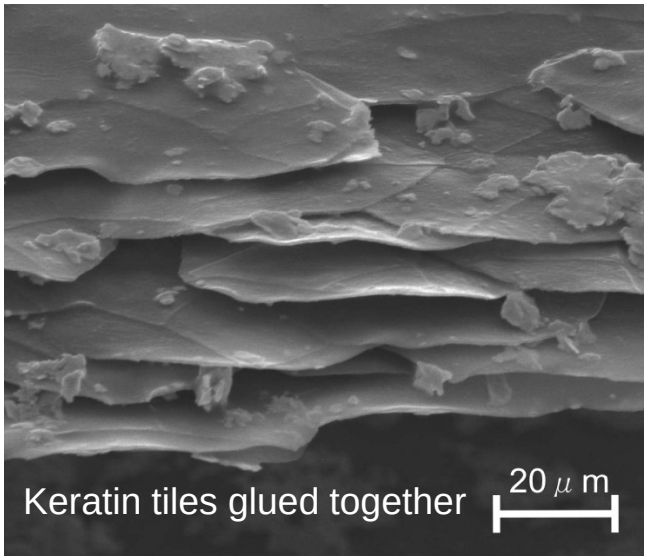
from
http://3dotstudio.com/membrane.html

“Nano-toes”

Beetles, flies, spiders, & geckos have nanostructures that help them stick to walls, ceilings, and what appear to be smooth surfaces.



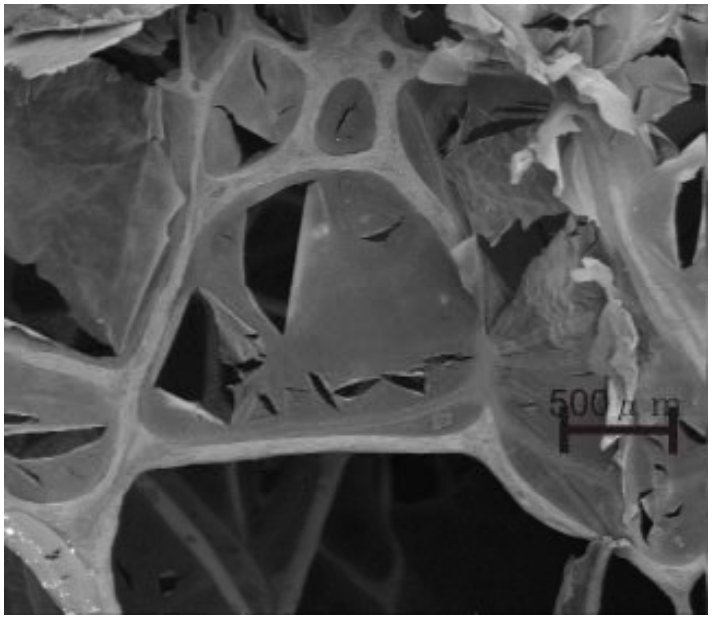
Toucan Beaks - Strong & Light Nanomaterials



Beak exterior:

overlapping nanosized tiles of keratin (same protein that makes up hair, fingernails, and horn)

http://www.nuthatch.birdnature.com/jan1897/toucan.html

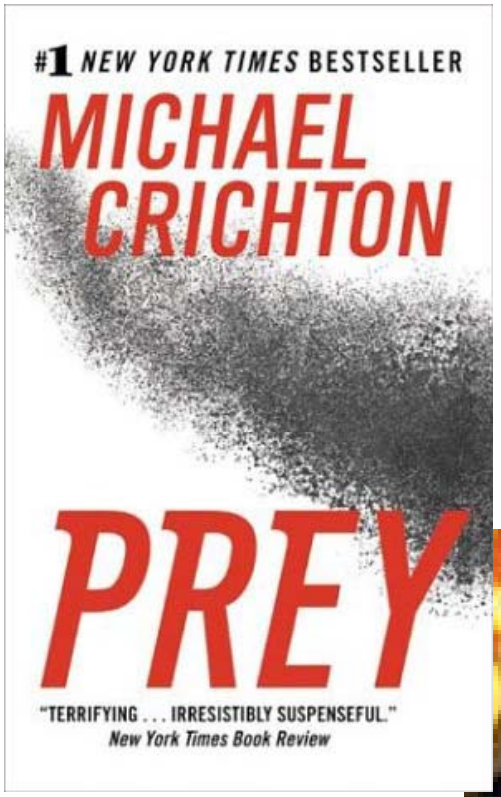


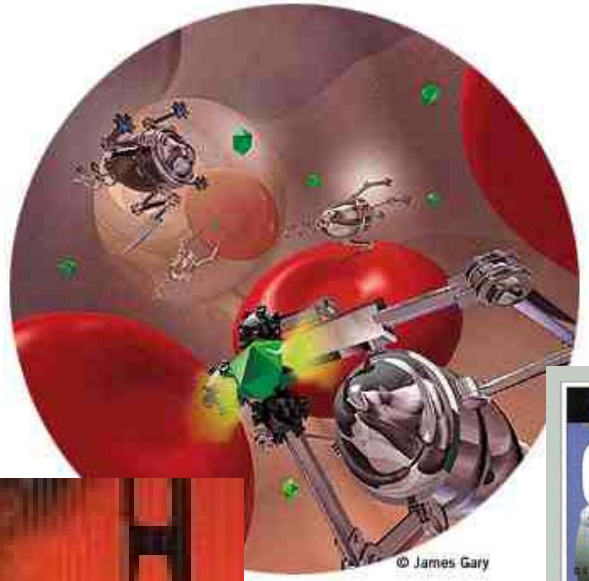
Beak interior:

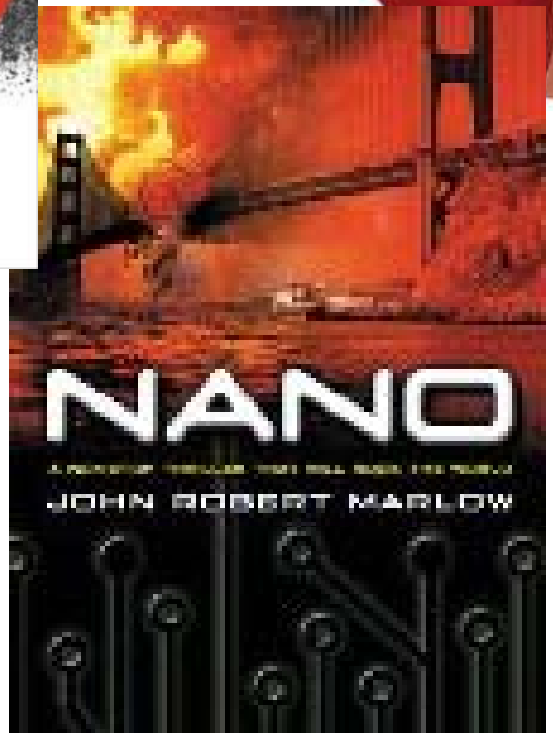
- rigid foam made of a network of nanosized bony fibers connected by drum-like membranes
- allows the beak to absorb high-energy impacts.

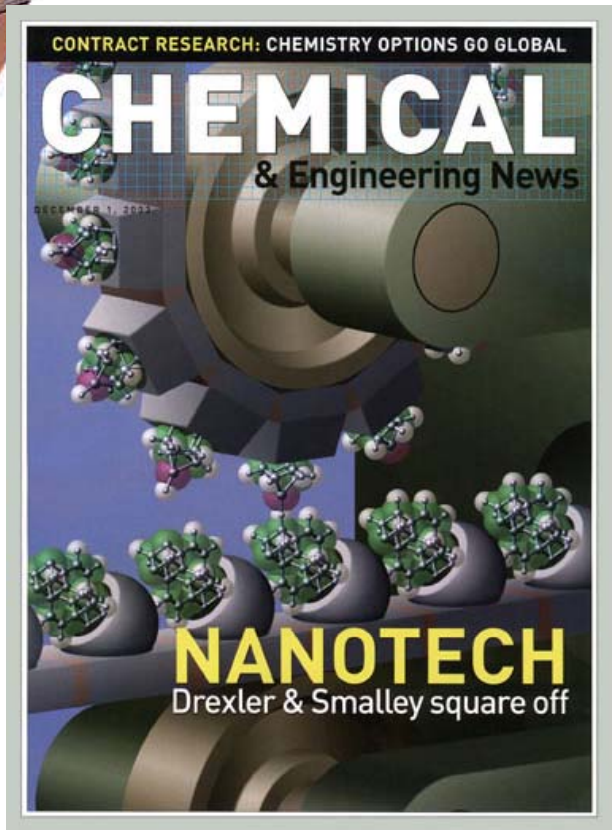
Courtesy C&E News, http://pubs.acs.org/cen/news/83/i50/8350toucan.html

What Nanoscience Is Not …









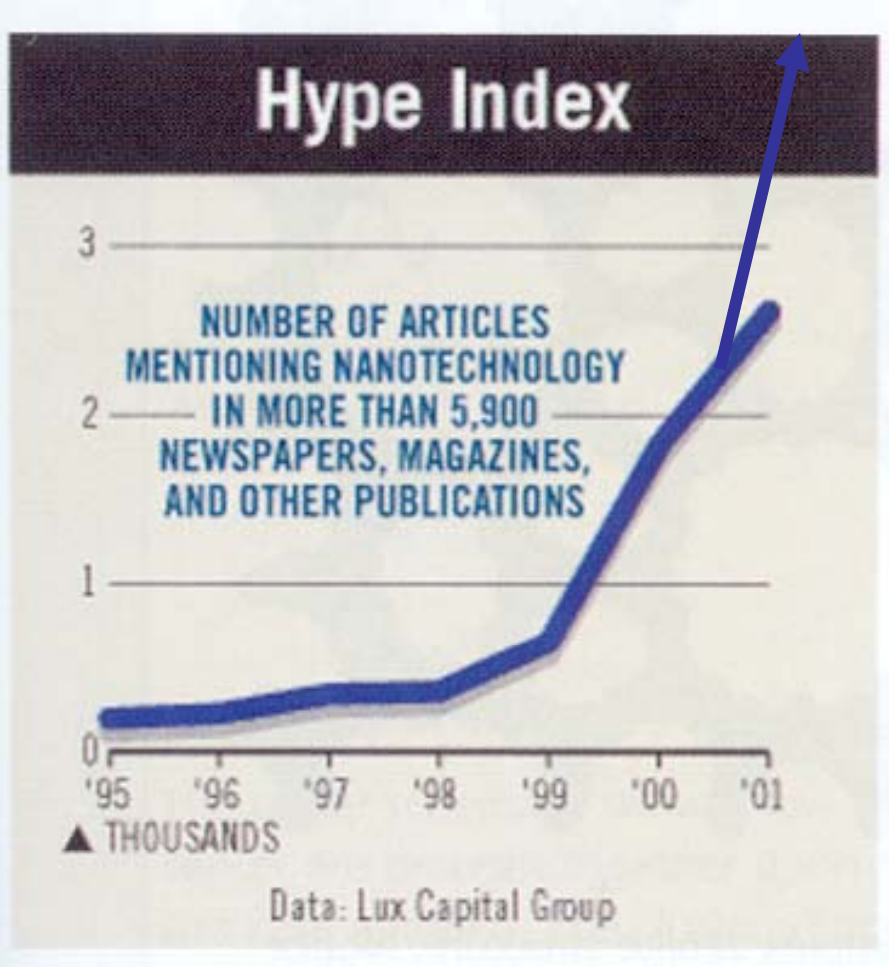
Today's Nano-Enabled Products

- Step assists on vans and bumpers on cars
- Paints, waxes and coatings to protect against corrosion, scratches and radiation
- Protective and glare-reducing coatings for eyeglasses and cars
- Metal-cutting tools
- Sunscreens and cosmetics
- Longer-lasting tennis balls and longer-distance golf balls
- Light-weight, stronger tennis racquets, skis, and bicycle frames
- Stain-free clothing and mattresses
- Dental-bonding agent
- Burn and wound dressings
- Ink
- Automobile catalytic converters
- Batteries and fuel cells

State of the Field (or Art)

- Structural nanotechnology (SNT)
  - Current technology
  - Exploiting properties of nanoscale structures
- Molecular nanotechnology (MNT)
  - Future *(far or maybe never?)* technology
  - Designing and manipulating individual molecules
  - Building shapes…machines…products
  - Also known as molecular manufacturing

Nano-Hype?



Dilemma or opportunity or both?

What Other People Are Saying

"Nanoscale science will give us not dozens, not scores, not hundreds, but thousands of new capabilities in biology, physics, chemistry and computing. Nanotechnology is our country's future."

-- Former Speaker of the House Newt Gingrich

http://www.forbes.com/2002/10/10/1010soapbox.html

What Other People Are Saying

“Military applications of molecular manufacturing have even greater potential than nuclear weapons to radically change the balance of power.”

Admiral (Ret) David E. Jeremiah,
former vice chairman of Joint Chiefs of Staff *

* "Nanotechnology and Global Security," (Palo Alto, CA; Fourth Foresight Conference on Molecular Nanotechnology), 9 November 1995.

Public Policy Discourse

- Ethics, Legal & Social Issues (ELSI)
  - Health and environmental impacts
    - NSF, EPA, NIOSH, NIH-NIEHS, DOD R&D (~$38M/year)
    - NNI EHS Research Needs
    - Woodrow Wilson Institute Project on Emerging Nanotechnologies
    - OECD Working Group on Safety of Nanomanufactured Materials
  - Privacy and legal implications
  - Pro-actively avoiding an anti-GMO food backlash
  - Uncontrolled replication ("nano-assemblers") and artificial intelligence
- **Security is rarely in the dialogue**

  Could there be an "AQ Khan" of nanotechnology?
  - Literature: limited & emphasizes "nano-assemblers"
  - How to build a framework to assess analytically?
  - Reconcile with (political science) theories?
    - Balance of Power
    - Offense-Defense
  - Pragmatically, what can be done now to prevent such scenarios?

A Warfighter's Perspective on Possible Nanotechnology Applications for CBRNE/WMD Operations

COL Barry Lowe
Chief of Staff
20th Support Command (CBRNE)

- "Individual Protection"
- Applications to make uniform material capable of providing protection against chemical and biological agents, as well as other toxic materials
- Applications to make uniform material "react instantly" to become armor in the event of a bullet or fragment impact
- Applications for prophylaxis against inhalation or ingestion of chemical or biological agents, and toxic materials
- Applications for use as antidotes

CBIRF Perspective

TECHNOLOGY

An Operators Perspective

CDR Mike Penny
Senior Medical Officer

What Do They Think of Technology?

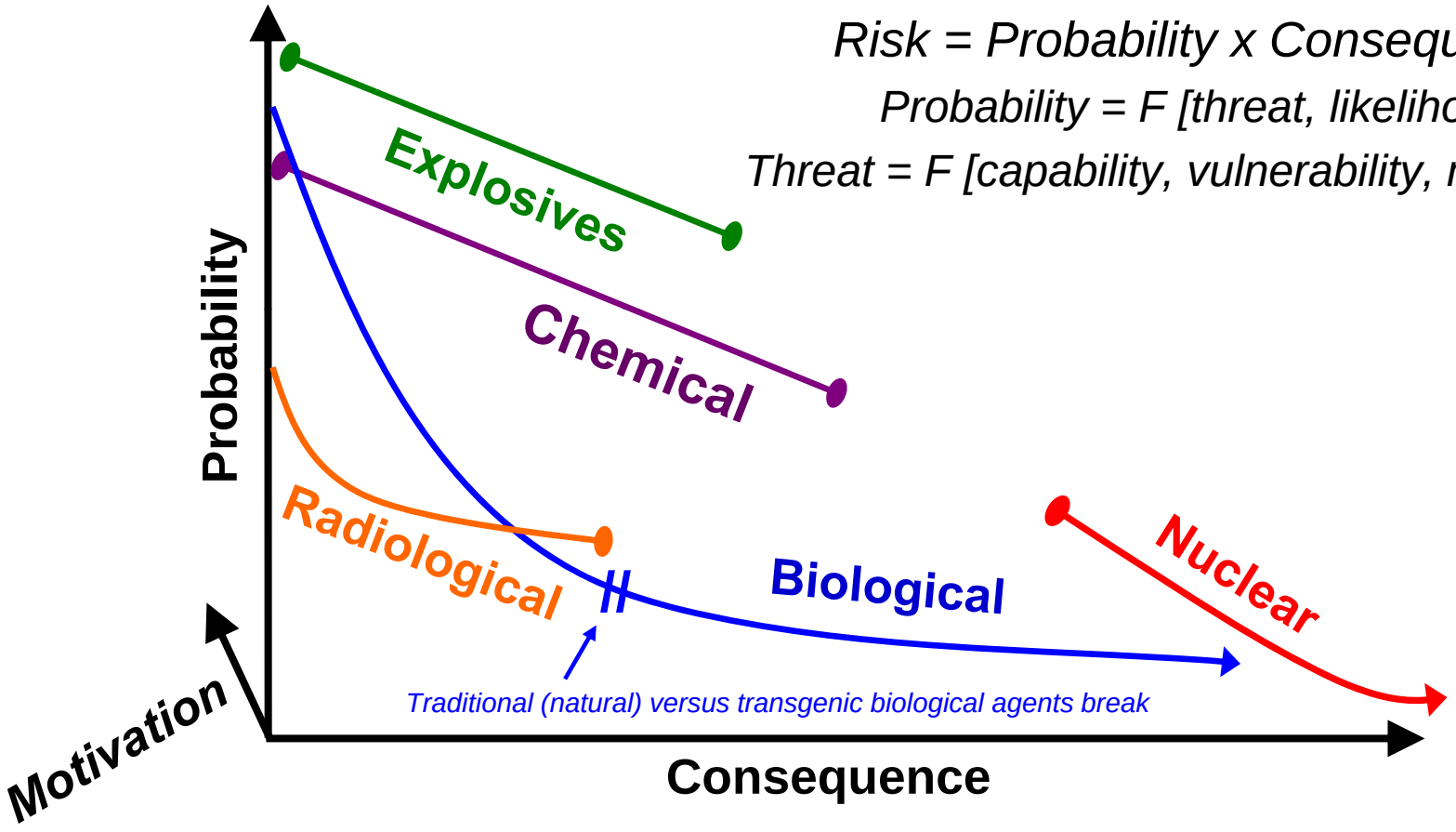
Requires too much training
Requires too much maintenance
Too delicate
Too expensive
Then… it lets you down when you need it the most

WMD Terrorism Risk Assessment

Risk = Probability x Consequence

Probability = F [threat, likelihood]

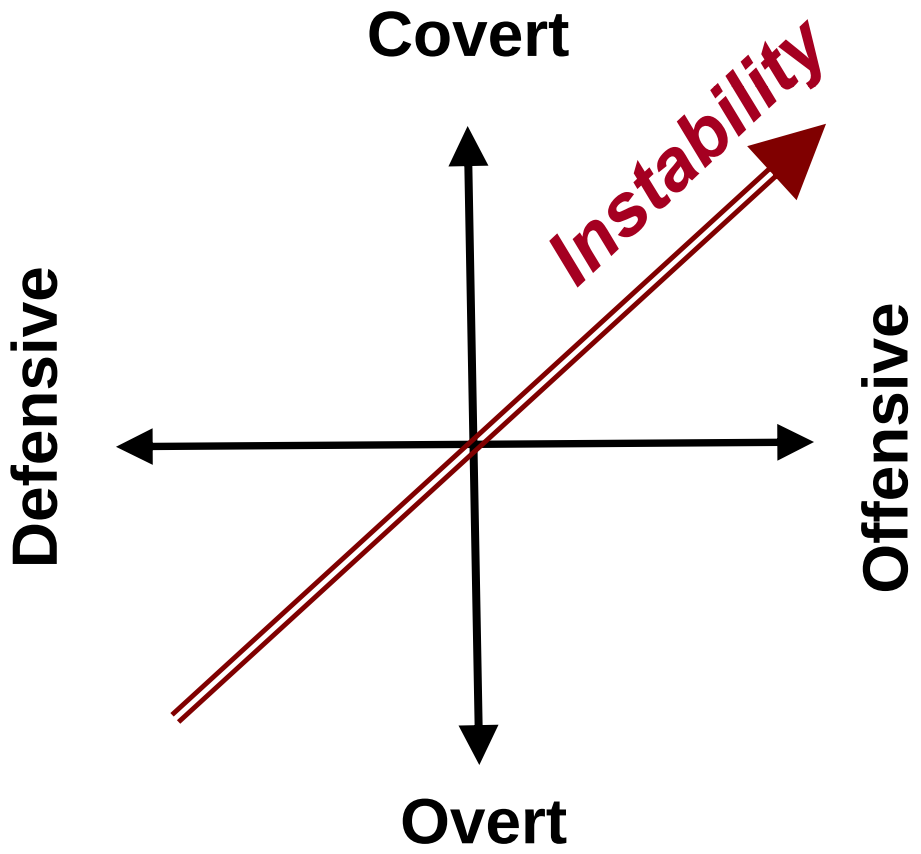
Threat = F [capability, vulnerability, motivation]



Where to place nanotech weapons?
Probability is very low.
Consequence is potentially very large but also hard to gauge meaningfully.

Analytical Frameworks for Assessing Strategic Significance of Technology

- Offense-Defense Theory
- 4GW



These are all

Notional

Scenarios

that means not real, intellectual thought experiments, etc

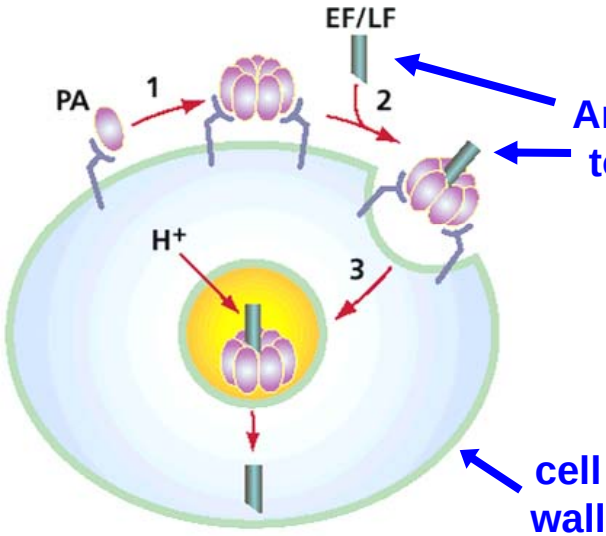
Circumventing Vaccines

- Biothrax (AVA) & BioShield-funded recombinant vaccines based on protective antigen (PA)
- PA necessary to endocytose toxic proteins *(the lethal and edema factors (EF & LF))* to cytosol
- Functionalized single-walled carbon nanotubes (*f*-SWNTs)

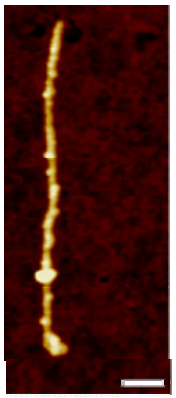
  cross mammalian cell walls &

  release *biologically active "cargos"* - proteins, peptides, DNA, RNA, small molecules
- Motivated by medical applications

  drug delivery & gene therapy



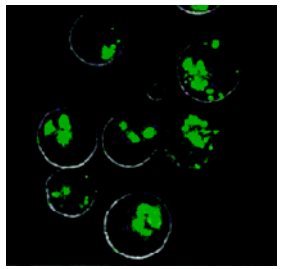
Courtesy National Academy of Sciences



100 nm

AFM image of SWNT + Staphylococcal Protein A (SpA)

***f*-SWNTs inside human cells**



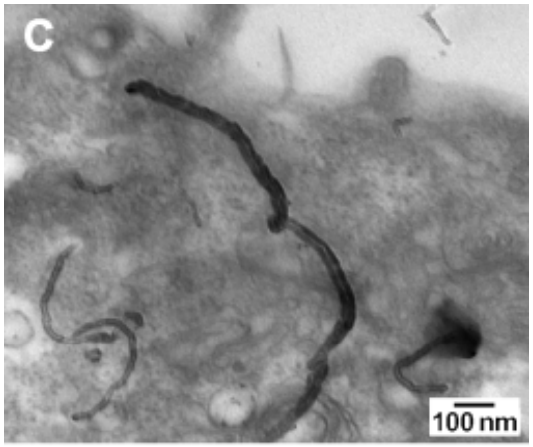
Courtesy Hongjie Dai, Stanford

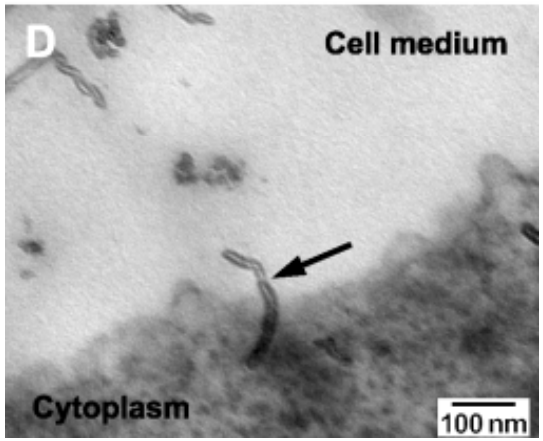
Toxin Delivery

Applicable to other BW agents, e.g., Botulinum toxin

- Difficult to produce in large quantities via traditional microbiological methods *(Commercial Botox requires 30-275 vials to achieve one LD_{50}, strain-dependent)*
- Current transgenic methods can only produce light chain (LC) of toxin from *E. coli* or yeast
- Heavy chain (HC) necessary for toxin to cross cell wall
- *LC + carbons nanotubes could circumvent technical difficulties*

Courtesy Alberto Bianco, CNRS



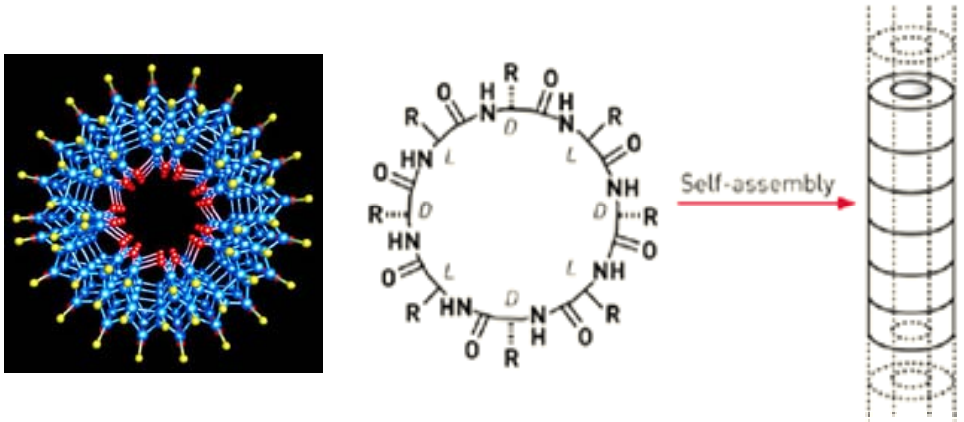


C) Human HeLa cells treated with functionalized multi-walled carbon nanotubes (f-MWNTs) to deliver DNA into cells.

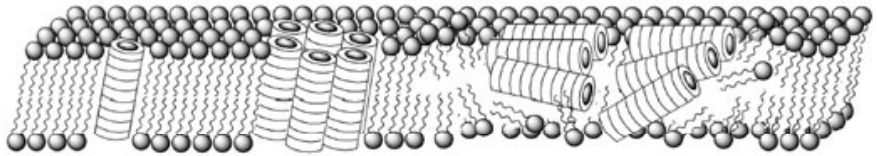
D) A multi-walled carbon nanotube crossing the cell membrane.

New or Bio-Vesicants

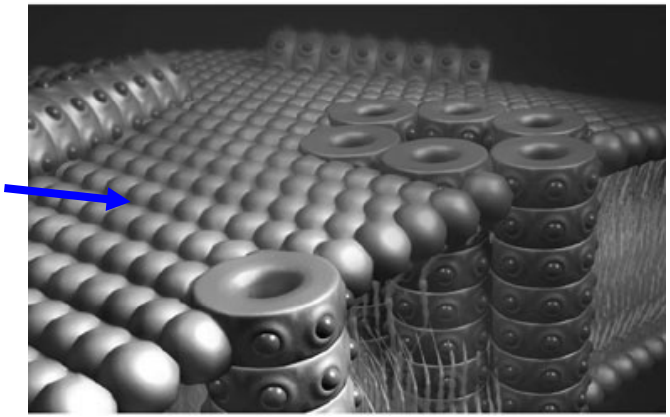
- Supramolecular Peptide Nanotubes (SPN)
  - lyse cell walls
  - rupture phospholipid layer
- Easier, cheaper and uses technology more widespread than Wimmer's illustrious 'synthetic polio' experiment
- Potentially more environmentally robust than mustard agents
- Motivated by emergence of antibiotic resistant bacteria goal to disrupt bacterial cell walls



Courtesy Nature Magazine



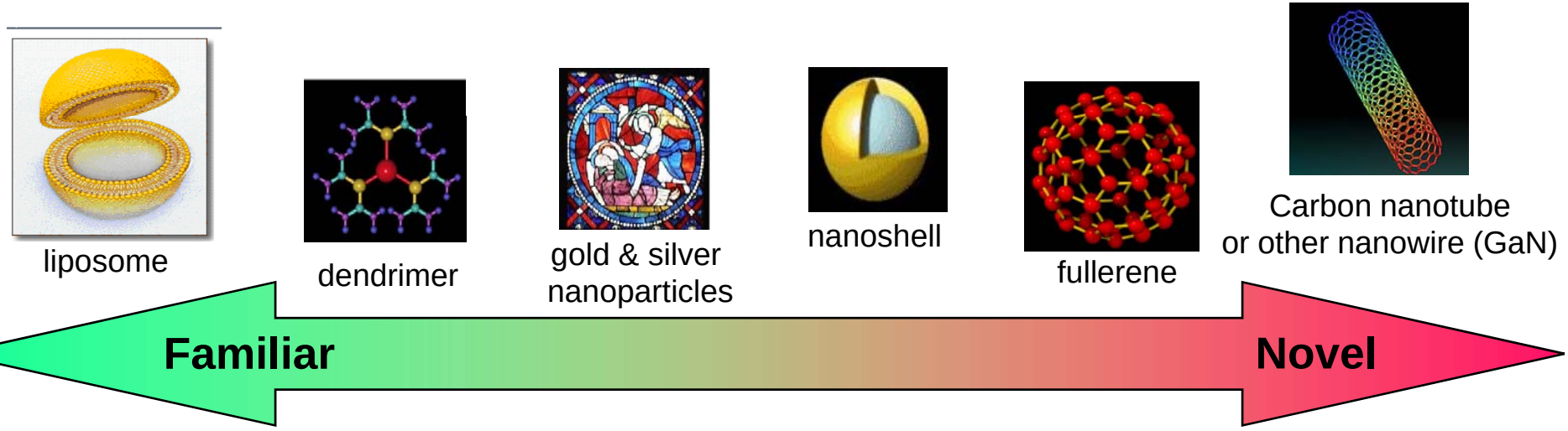
Cell wall or skin (lipid bilayer)



Courtesy Reza Ghadiri, Scripps Institute

Nanotoxicity: Range of Novelty

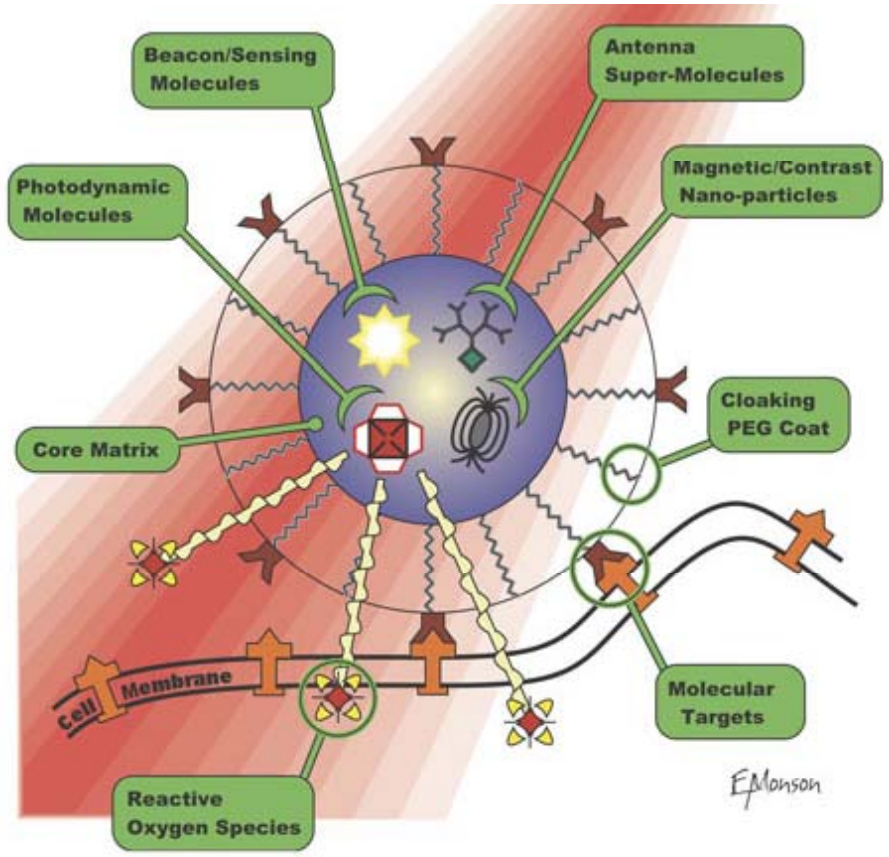
- Some classes of nanoparticles not actually new
  - Liposomes
  - Ultrafine (<100 nm) particles
- Toxicology of more familiar materials is better understood
  - Ultrafine “associated with exacerbations of airway disease” and implicated in enhanced inflammation
- Carbon nanotubes (CNTs) – highly unusual aspect ratio and material properties
  - Focus of many early nanotoxicity studies
  - Not top candidate for medical applications



Controlled Agent Distribution

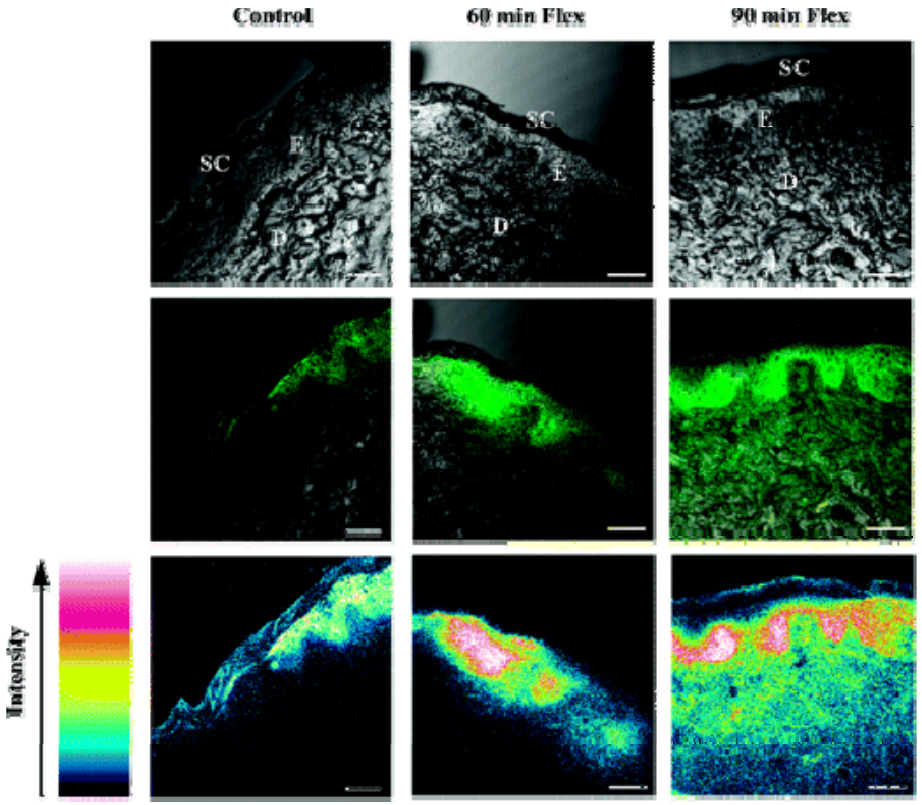
Advectus's Nanocure™

- Nanoparticle-based formulation for the delivery of approved chemotherapeutic (doxorubicin) that does not cross the blood-brain barrier
- Polymer nanoparticle coated with chemotherapeutic and emulsifying saccharide layer (polysorbate-80)
- Outer layer attracts lipoproteins that camouflage particles
- Blood-brain barrier treats the particles as if they were low-density lipoproteins (LDL) - cholesterol
- LDL receptors in the brain transport the Nanocure particles through the blood-brain barrier
- Nanoparticles break down, allowing the diffusion of doxorubicin into the brain tissue



Penetration of Bio-Nano Conjugates

Courtesy Nancy Monteiro-Riviere, NCSU

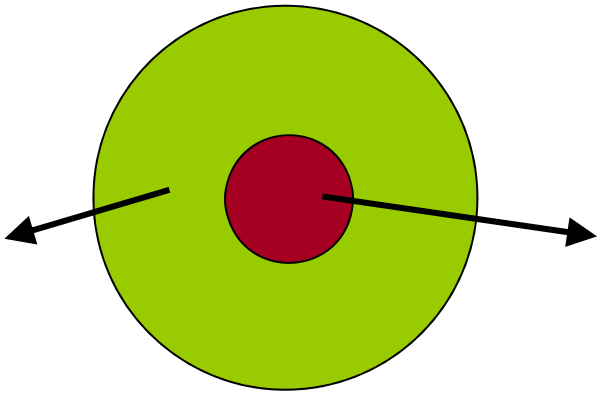


Uptake of fullerene-lysine-FITC complex through intact stratum corneum (SC) and underlying epidermal (E) and dermal layers (D). Scale bar = 50µm

- Fullerenes conjugated to cationic peptide show substantial uptake through skin
- Mechanical stressed increased penetration
- Skin observed to be surprisingly permeable to nanomaterials (fullerenes & quantum dots) with diverse physicochemical properties
- Motivated by transdermal drug delivery applications & nanoparticle safety assessments

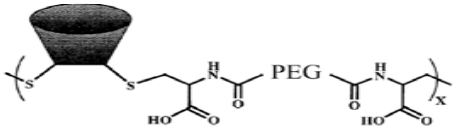
“Brain Fry”

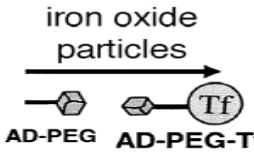
Stealth coat – defeats detection and optimizes aerosolization

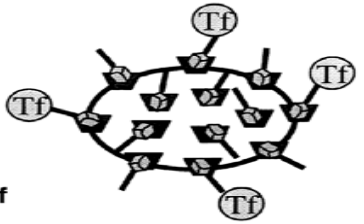


NP that heats up A LOT upon absorption of EM – maybe from a cell phone

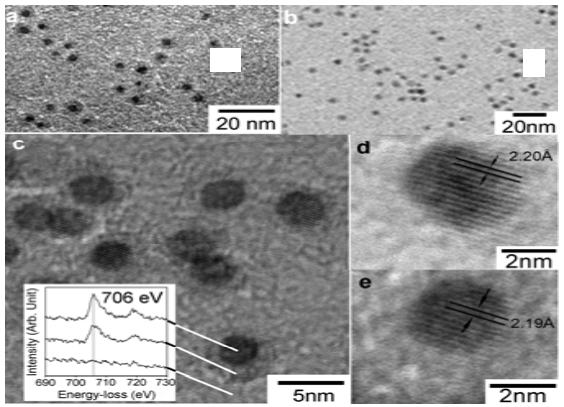
- Coated Fe_2O_3 nanoparticles
- Pass the blood brain barrier
- EM-activatable
- Unique combination of people, materials, & facilities:
  - Expertise in nanoparticle production (especially biological apps),
  - Directed energy experts who may have worked on ablation therapies,
  - Engineers who have experience in battlefield delivery of EM radiation,
  - Vets to oversee animal testing,
  - Aerosol expert- someone who specializes in aerosol drug delivery.
- Current research motivated by need for targeted chemotherapeutics and diagnostic imaging







Transferrin-modified, iron oxide particle



Courtesy Hong Yang, University of Rochester

Platinum-iron oxide core-shell nanoparticles

Molecular Assemblers, aka “nanobots”

- Self-replicating machines and products built from molecular, “the bottom up”
  - ***Currently more Sci-Fi than Science Fact,*** *e.g., Star Trek & Crichton’s Prey*
    - “Blue/Grey sky” outlook: autonomous behavior & grey goo phenomenon
    - *Caveats: The Laws of Thermodynamics & limitations of behavior at low Reynolds Number will still apply*
  - Supramolecular chemistry is “version 0.2” of molecular assemblers.
- Molecular Manufacturing Proponents point to commercially available 3-D printers
  - rapid model prototyping of models from computer-aided design (CAD) programs
- Tissue engineering applications:
  - Organ/bio-printing
  - Combined with synthetic biology???

Research Underlying Scenarios

CNTs Crossing Cell Walls: Nadine Wong et. al., “Carbon Nanotubes as Intracellular Protein Transporters: Generality and Biological Functionality,” *J. Am. Chem. Soc.,* 2005, vol. 127, p. 6021; Alberto Bianco, et. al., “Cationic Carbon Nanotubes Bind to CpG Oligodeoxynucleotides and Enhance Immunostimulatory Properties,” *J. Am. Chem. Soc.* 2005, vol. 127, p. 58; Qi Lu, et. al., “RNA Polymer Translocation with Single-Walled Carbon Nanotubes," *Nano Lett.,* 2004, vol. 4, p. 2473; and Davide Pantarotto, et. al., "Immunization with Peptide-functionalized Carbon Nanotubes Enhances Virus-specific Neutralizing Antibody Responses" *Chem. Biol.*, 2003, vol. 10, pp. 961. D. Pantarotto; et. al., “Functionalized Carbon Nanotubes for Plasmid DNA Gene Delivery,” *Angew. Chem., Int. Ed*,. 2004, vol. 43, p. 5242.

Vesicants: Sara Fernandez-Lopez, et. al., “Antibacterial Agents Based on the Cyclic d,l-alpha-peptide Architecture,” *Nature,* 2001, vol. 412, p. 452; W. Seth Horne, et. al., “Heterocyclic Peptide Backbone Modifications in an alpha-Helical Coiled Coil,” *J. Am. Chem. Soc.,* 2004; vol.126, p. 15366; and Jorge Sánchez-Quesada, et. al., “Modulating Ion Channel Properties of Transmembrane Peptide Nanotubes through Heteromeric Supramolecular Assemblies,” *J. Am. Chem. Soc.,* 2002, vol. 124, p. 10004.

Drug Delivery: D. Missirlis, N. Tirelli, J.A. Hubbell, “Amphiphilic hydrogel nanoparticles. Preparation, characterization, and preliminary assessment as new colloidal drug carriers,” *Langmuir*, 2005 vol. 21, p. 2605; H.S. Yoo, T.G. Park, “Folate-receptor-targeted delivery of doxorubicin nano-aggregates stabilized by doxorubicin-PEG-folate conjugate,” *J. Control. Release,* 2004, vol. 24, p. 247; C.Y. Huang, Y.D. Lee, “Core-shell type of nanoparticles composed of poly[(n-butyl cyanoacrylate)-co-(2-octyl cyanoacrylate)] copolymers for drug delivery application: Synthesis, characterization and in vitro degradation,” *Int. J. Pharm.,* 2006 vol. 9, p. 345; R. M. Mainardes, et al., “Liposomes and micro/nanoparticles as colloidal carriers for nasal drug delivery,” *Curr. Drug Deliv.,* 2006, vol. 3, p. 275; and Y. Zeng, W.G. Pitt, “A polymeric micelle system with a hydrolysable segment for drug delivery,” *J. Biomater. Sci. Polym. Ed.,* 2006, vol. 17, p. 591.

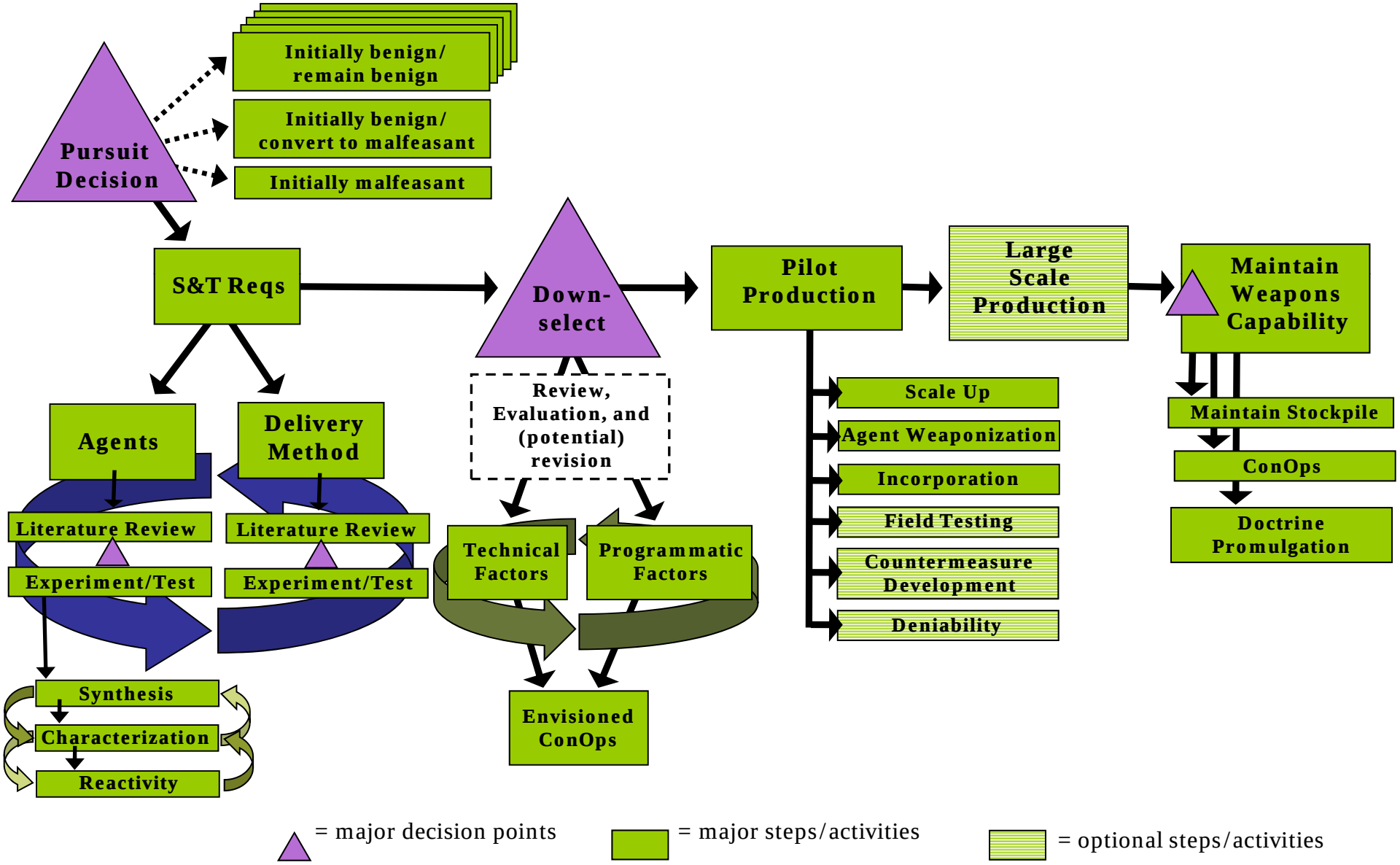
Anti-Material Agents: S.L. Scott, C.M. Crudden, C.W. Jones, eds., *Nanostructured Catalysts*, (Plenum Publishing Corporation; New York), 2003; K.S. Suslick, et. al., "Nanostructured Materials Generated by High-Intensity Ultrasound: Sonochemical Synthesis and Catalytic Studies," *Chemistry of Materials*, 1996, vol. 8, p. 2172; N. Arul Dhas, et. al., “Sonochemical Preparation of Hollow Nanospheres and Hollow Nanocrystals *J. Am. Chem. Soc.* 2005, vol. 127, p. 2368; and A.J. Zarur, J.Y. Ying, "Reverse Microemulsion Synthesis of Nanostructured Complex Oxides for Catalytic Combustion," *Nature*, 2000, vol. 403, p. 65.

Brain Fry: Peter Varallyay, et al., “Comparison of Two Superparamagnetic Viral-sized Iron Oxide Particles Ferumoxides and Ferumoxtran-10 with a Gadolinum Chelate in Imaging Intracranial Tumors” *American Society of Neuroradiology*, 2002, vol. 23; Jun Sung Kin, et al., “Toxicity and Tissue Distribution of Magnetic Nanoparticles in Mice” *Toxicological Sciences*, 2006, vol. 89, p. 338; and K Hynynen, et al., “Focal Disruption of the Blood-Brain Barrier Due to 260-kHz Ultrasound Bursts: a Method for Molecular Imaging and Targeted Drug Delivery” *Journal of Neuosurgery*, 2006, vol. 105, p. 455.

Self-Assembly: Jean-Marie Lehn, “Toward Complex Matter: Supramolecular Chemistry and Self-organization,” *Proc. Natl. Acad. of Science,* 2002, vol. 99, p. 763; George M. Whitesides and Mila Boncheva, Beyond Molecules: Self-Assembly of Mesoscopic and Macroscopic Components,” *Proc. Natl. Acad. of Science,* 2002, vol. 99, p. 769; C. P. Collier, et. al., “Electronically Configurable Molecular-Based Logic Gates,” *Science*, 1999, vol. 285, pp. 391; and Kelly S. Chichak, et. al. “Molecular Borromean Rings,” *Science,* 2004, vol. 304, p. 1308.

The Science is Real, *the Scenarios are Notional!*

Notional General Nanotech Decision Pathway



Characterizing Emerging Technologies

- Disambiguate potential for unique capabilities from enabling previous capabilities
- Perception or ideation *vs* technical reality
  - "Hype" & "Horror"
  - Danger of (Pseudo)-Technical Assessments
    - Not understanding the underlying science
    - Presuming that anything with a science-sounding name is inherently dangerous
    - E.g., *"New technologies (at risk for terrorist appropriation) include biotechnology,* ***nanotechnology, single nucleotide polymorphisms*** *(SNPs), and* ***Bose-Einstein condensates****."**
- Fundamental interdisciplinarity

*** "WMD Terrorism Research: Where to From Here?" International Studies Review, March 2005, vol. 7, p. 140**

Global Overview

European Union
- ~$2.5B/y since 2008

Japan
- ~$800M - $1B/y since 2004

ROK
- ~$200M/y since 2003

Southeast Asia
- Singapore Nanyang Technological University (NTU)
  - "NanoFrontier" >$200M/y
- Malaysia
- Taiwan ~$600M over 6 years

China
- Estimated ~$250M per year *(PPP)* 2000-2005
- Estimated $1.5-1.8B/y *(PPP)* 2007-2009

Russia
- ~$5B 2008-2012 for research and infrastructure modernization
- "nano-enabled thermobaric bomb"

Iran
- Majles Rep "America cannot tolerate Iran's success in scientific fields such as ***nanotechnology*** and ***nuclear technology***," Dec 2005

- US
  - 21st Century Nanotech Act (2003-2008) $3.7B/5years
  - NNI, US federal nanotech (2000) $710**M**
    (2011 PBR) $1.7**B**
  - DOD (2009 budget) $464M
    (2011 PBR) $349M

- Significant private investment
  - "guestimation" of $2T sales by 2015

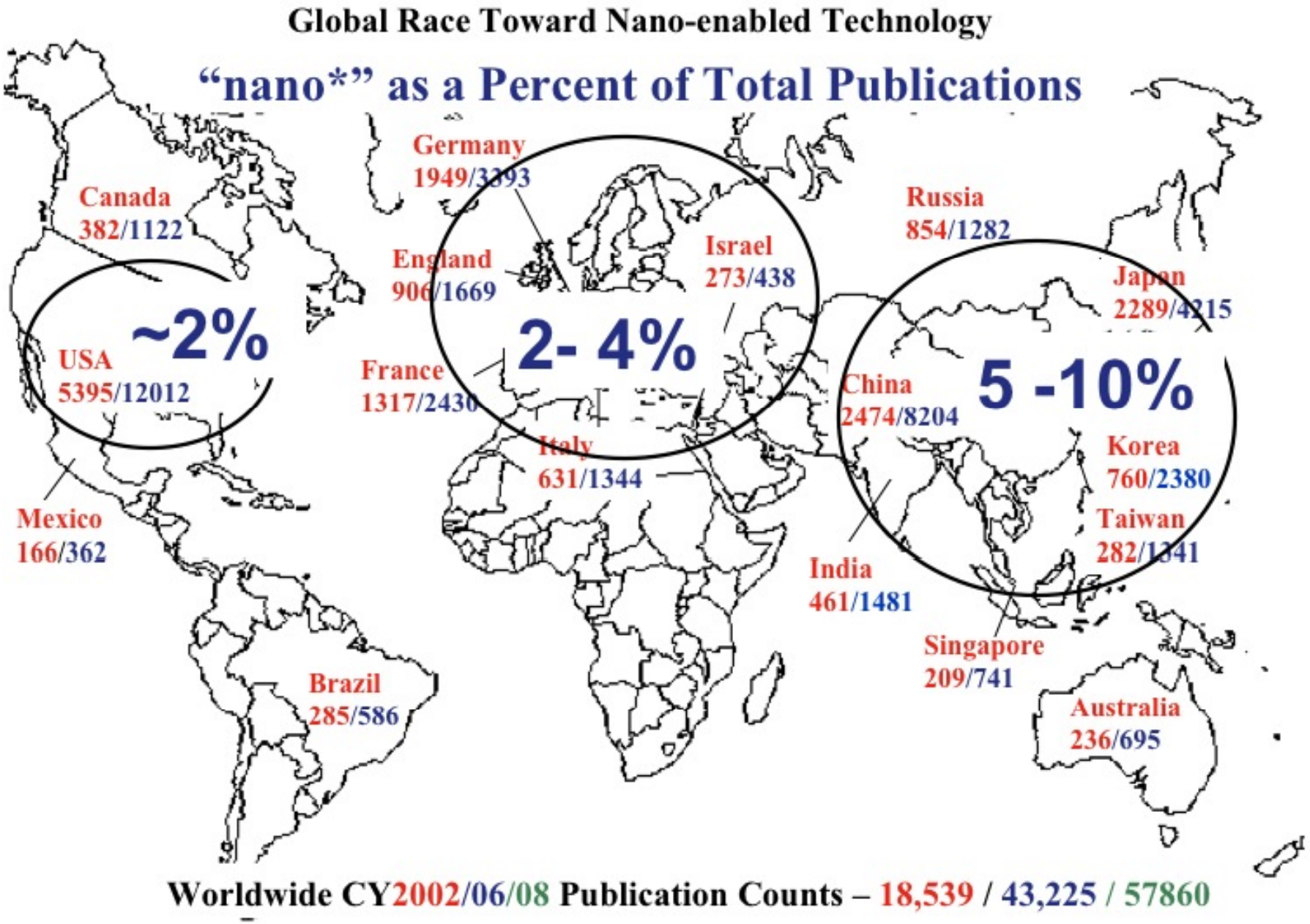


Image courtesy Jim Murday, USC

U.S. Overview

Federal

- 21st Century Nanotech Act (2003-2008) $3.7B/5years *(planned)*
- NNI (2001-08) $8.3B *(actual)*
- US federal nanotech

  (2000) $710**M**

  (2011 PBR) $1.7**B**

NNI Strategic Plan *(Dec 07)*

- *Early Detection of Life Threatening Diseases*
- *Engineered Nanoscale Materials*
- *Nanobiotechnology*
- *Nanotechnology-Based Water Purificatic & Testing*
- *Information Processing & Advanced Electronics*
- *Predictive Toxicology*
- *Societal Dimensions of Nanotechnology*

DOD

2009 $431M PBR

$464 appropriated

2011 $349M PBR

- DARPA
- Air Force: electronics, computing, communication, sensors (AFOSR)
- Army: energetics, ballistic protective materials, power/energy (ARO)
- Navy: electronics, materials, sensors (ONR)
- CBDP: passive defense
- DDR&E
- MDA

- OSD Emerging Contaminants Working Group

International Security Regimes

- Biological Weapons Convention (BWC)
- Chemical Weapons Convention (CWC)
- Export Controls

Case Study: Zyvex

– Richardson, Texas $10M revenues in 2005

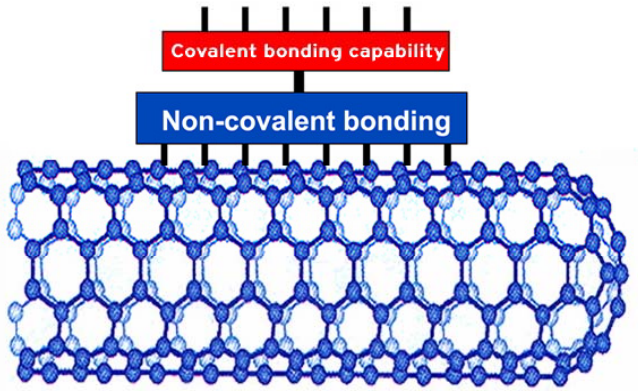
– Nanoworks – nano tools, electron microscopes & photovoltaic applications

– Kentara™ – CNT dispersions in resins

– Current market
  - CNT-reinforced mountain bikes
  - Easton baseball bats

– Required to submit ITAR licenses for CNT-product exports to China

– In response, founder suggests may relocate to SE Asia



Key Security Factors

- Deniability & Lack of Transparency
  - Most of the dual-use concerns raised regarding biotechnology risks are *potentially* applicable to malfeasant co-option of nanotechnology *

    Except, biological agents require damp environments with moderate temperatures, moderate pressures and ambient oxygen

    * *Nano-engineered materials do not replicate*
  - Lack of explicit norms
  - Lack of explicit category for international arms control regimes
- Vulnerability Perception
  - Perceived lack or limitation defensive countermeasures, e.g., limitations of stand-off biological (& to a lesser extent, chemical) detection
- International prestige
- No single discipline on which to focus
  - Chemistry to electrical engineering
  - Materials science to molecular biology
- Overwhelmingly, a state-based proliferation concern
  - Secondarily, rogue scientist scenario
- Intent must be balanced with capability
  - Offensive versus defensive not transparent
- Globalization
  - Private sector is major player global, e.g., sale or transfer of technology