Class Introduction

- Webpages, wiki, projects, grades
- Books, etc.
- Self-Assembly
- Architecture (Nano and Bio)
- Vision of Nanotechnology
- What is BioNanoTech?
- Drexler vs Smalley
- Bio-inspiration
Course Web Page & Wiki

http://www.cs.duke.edu/courses/spring08/cps296.4/

Background Nanotechnology, What is BioNanoTech?
Biomacromolecules (Nucleic acid and protein structure, MAGE)
Methods and Instruments: Molecular biology, chemistry, microscopy (AFM, TEM, SEM, STM, etc.)
NanoMaterials (nanoparticles, nanotubes, nanowires, nanocrystals, block co-polymers)
DNA Engineering. DNA-Based Nanofab. Algorithmic Self-Assembly.
DNA-Based Computing. RNA Nanotech.
Protein & Peptide Design & Engineering. In vitro evolution.
BioNano with Protein, Virus, Cell Building Blocks.
Impacts: biosensors, molecular therapeutics, nanoelectronic, nanooptical, nanochemical, molecular manufacturing.
Stu Kauffman

- Self-organization in complex systems
- “Order for free”
- Nk model
- All-against-all experiment (→ Gnostic Gnose…)

The Origins of Order
SELF-ORGANIZATION AND SELECTION IN EVOLUTION

Stuart A. Kauffman
Ribbon Diagrams

(A) (B) (C)

Jane & Dave Richardson, Duke

Goodsell, Bionanotechnology (Jan. 04)

- The Quest for Nanotechnology.
- Bionanomachines in Action.
- Biomolecular Design and Biotechnology.
- Structural Principles of Bionanotechnology.
- Functional Principles of Bionanotechnology.
- Bionanotechnology Today.
- The Future of Bionanotechnology.
Architecture

- Post & Lintel
- Construction
- Buildings
- Design
- Trends
- Styles
- Periods
- Materials
- Vision of what is possible

Birth of Architecture
Length Scales

Nano range  Micro range  Macro range
Top-Down and Bottom-Up

**TOP-DOWN**

“Sculpt” from bulk

- Classical semiconductors

**BOTTOM-UP**

Assemble from nano-scale building blocks

- Molecular electronics
- Biomolecular electronics

---

Moore’s Law Motivation

Moore’s Law: the growing power of silicon chips, measured in millions of instructions per second.
Feynman, 1959

- There's Plenty of Room at the Bottom
  - Encyclopaedia Britanica on the head of a pin requires only 25,000 fold reduction
  - Read- stamp, evaporate, shadow, EM
  - Write- focused ion beam, lithography
  - Atomic info: 2D surface, 3D atomic crystal
  - Biological information density
  - Need better EM
  - Physical arrangement of atoms -> chemistry
  - Miniturize computers (heat, power, speed)
  - Miniturize machines (smaller->smaller->smaller)
    - Parallalism
  - Molecular electronics
  - Mechanical tolerance

Only TOP-DOWN view [no self-assembly]
Supramolecular Chemistry

- Covalent bonds
- Non-covalent
Why Build with DNA?

- Readily self-assembles.
- Programmable interactions.
- Large set of specific codes.
- Predictable local geometry.
- Fairly rigid polymer rods.
- Developed synthesis chemistry.
- Enzymes and reagents available.
- High density of functional groups.
- Fairly stable chemistry.
- Externally readable sequence.
- Aptamers = specific binders.
- Deoxyribozymes = catalysts.
Proteins

See: Anatomy & Taxonomy of Protein Structure
http://kinemage.biochem.duke.edu/~jsr/
Goodsell, cellular machinery

- Molecular machines
- Bioinspired engineering
Nano and BioNano

- Nanotech--atomic control of matter
- Bionanotech--control of matter on low nanometer scale with inspiration, principles, or materials borrowed from biology.
THE PROCESS BEGINS
with a large population of viruses, called phage (close-up, below), that infect bacteria. The phage's genes have been genetically engineered so that each part has a different coat of proteins. The coat on the shaft, at the tip, and on the ends of its filaments can be genetically engineered separately.

THE PHAGE POPULATION is exposed to a substance of interest, such as a wafer of zinc sulfide (ZnS). Those whose protein coats have a natural affinity for the material stick to the wafer.

THE PROCESS IS REPEATED several times using the newly grown population of phage and an ever stronger wash. Ultimately, the relevant genes of the best-binding phage are sequenced, and the phage is duplicated many times over through genetic engineering.

THE FEW PHAGE LEFT are removed from the wafer and allowed to multiply by infecting bacteria.

THE WAFER AND STUCK PHAGE are washed in dilute acid or other chemical bath. Phage that do not bind well to the wafer are washed away.
Belcher, virus $\rightarrow$ circuit

IN A DROP OF WATER, the virus is placed on a wafer that has gold source and drain electrodes patterned on its surface, as well as a gate and an insulator.

THE VIRUS automatically binds to the gold, bridging the source and drain and forming a transistor channel. The wafer is a platform for the device.

THE CHIP IS DOUSED in a solution of ZnS precursor chemicals. The virus's specially designed protein coat causes the ZnS to precipitate into uniform crystals along the viral shaft, forming a ZnS nanowire.

INA BLAST OF HEAT the virus itself is vaporized, leaving only the nanowire bonded to the gold electrodes, essentially yielding a nanotransistor.
### Selected Biological Self-Assembly Projects

<table>
<thead>
<tr>
<th>RESEARCH GROUP</th>
<th>MICROBES AND BIOMOLECULES</th>
<th>NANOPARTICLES</th>
<th>PROPOSED APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angela Belcher (MIT/Semzyme)</td>
<td>Bacteriophage virus and peptides</td>
<td>Quantum dots and nanowires</td>
<td>Electronics, sensors, displays, magnetic storage</td>
</tr>
<tr>
<td>DuPont</td>
<td>Peptides and DNA</td>
<td>Carbon nanotubes</td>
<td>Electronics, sensors, nanotube sorting</td>
</tr>
<tr>
<td>Dow Corning/Genencor</td>
<td>Peptides</td>
<td>Silicon-based chemicals and particles</td>
<td>Materials manufacturing</td>
</tr>
<tr>
<td>Daniel Morse (UCSB)</td>
<td>Peptides</td>
<td>Silica and titanium oxide nanoparticles</td>
<td>Materials manufacturing</td>
</tr>
<tr>
<td>Mehmet Sarikaya (Univ. of Wash.)</td>
<td>Peptides</td>
<td>Gold and platinum</td>
<td>Electronics</td>
</tr>
<tr>
<td>M.G. Finn (Scripps Research Institute)</td>
<td>Plant viruses and DNA</td>
<td>Gold nanowires</td>
<td>Electronics, materials manufacturing, sensors</td>
</tr>
<tr>
<td>Chad Mirkin (Northwestern University)</td>
<td>Fungus and DNA</td>
<td>Gold nanowires</td>
<td>Electronics, sensors</td>
</tr>
<tr>
<td>Susan Lindquist (Whitehead Institute)</td>
<td>Prions</td>
<td>Silver and gold nanowires</td>
<td>Electronics</td>
</tr>
</tbody>
</table>
Nay-Sayers

- Nano OOC scenario
- Evolutionary-group-chaos-theory-alife
- BioNano-back-to-bio
- Far-fetched but based on sound science…
Nay-Sayers: ETC group

From Genomes to Atoms

The Big Down
Infocast is pleased to announce the dates of February 25-27, 2004, for the 2nd Annual NBIC Convergence conference, to be held at the New York Marriott Financial Center in New York City.

The prospect of unparalleled improvements in human health and performance, as well as the unification of science, were the over-arching themes at Infocast’s first NBIC (Nanotechnology + Biotechnology + Information Technology + Cognitive Science) Convergence conference held in February 2003, at UCLA in Los Angeles, CA.
Stepping Down: Some Major Milestones in Atomtech

1959 Nobel Prize-winning physicist Richard Feynman gives his now-famous speech, “There’s Plenty of Room at the Bottom,” describing the future possibility of atomic engineering.

1964 Glenn Seaborg, Nobel Prize Laureate for Chemistry, wins two US patents on elements he discovered—Americium #95 and Curium #96—a little known milestone that sets a dangerous precedent for the patenting of elements and atomically-engineered matter.

1974 Norio Taniguchi of Tokyo Science University first uses the word “nanotechnology.”

1981 Gerd K. Binnig and Heinrich Rohrer at IBM’s Zurich Research Laboratory invent a scanning tunneling microscope that enables researchers to see and manipulate atoms for the first time. The researchers won a patent on the microscope in 1982 and a Nobel Prize in Physics in 1986.

1981 Eric Drexler publishes the first technical paper on molecular nanotechnology in the Proceedings of the National Academy of Sciences.


1989 IBM physicists manipulate atoms precisely by spelling the letters IBM with thirty-five xenon atoms.

1991 Sumio Iijima, a physicist at NEC Research Labs in Japan discovers multi-wall carbon nanotubes.

1993 Warren Robinett of the University of North Carolina and R. Stanley Williams of the University of California create a virtual reality system connected to a scanning tunneling microscope that enables researchers to "see" and touch atoms.

1993 Rice University establishes the first laboratory dedicated to nanotechnology in the USA.

1996 Curl, Kroto and Smalley win Nobel Prize in chemistry for discovering buckyballs.

1997 The first nanotechnology venture capital company established in the USA.

1998 Researchers at the Delft University of Technology (Netherlands) create a transistor from a carbon nanotube.

2000 Lucent and Bell Labs, working with Oxford University, create the first DNA motors, demonstrating the convergence of biotech and nanotech.

Milestones 3/3

2001 Researchers at both IBM and Delft University use carbon nanotubes to develop nanometer-sized logic circuits—the components that perform processing in computers.  

2001 Mitsui & Co. of Japan announce plans for mass-manufacture of carbon nanotubes.  

2002 In June IBM’s nanotechnologists demonstrated data-storage density of 1 trillion bits per square inch, equal to a 100-gigabyte hard-drive—enough to store 25 million printed textbook pages on a surface the size of a postage stamp.  

2002 In August IBM announces the development of a new electron microscope with resolving power less than the radius of a single hydrogen atom. 


- Engines of Construction
- Engines of Abundance
- Engines of Destruction
  - “gray goo problem”
Drexler vs Smalley

- **Drexler**
  - Molecular assemblers will provide atom-by-atom manufacturing

- **Smalley**
  - “fat fingers problem”
  - “sticky fingers problem”
OBITUARY

Richard E. Smalley (1943–2005)

Chemist and champion of nanotechnology.
Drexler, 1981

- Drexler (1981) PNAS
  - Microtechnology
  - Protein design and engineering
  - Protein enzymes = molecular robots
  - Prediction: protein-based assemblers will be the tools needed to advance molecular manufacturing

- Bottom-up approach
- [http://www.foresight.org](http://www.foresight.org)
- “Visionary proponent of a new technology”
- “Hype-man for the-next-big-flop”
Molecular assemblers will perform molecular manufacturing.
Atom-by-atom control via mechanical positioning of reactive molecules (not by manipulating individual atoms). “Smalley fingers” are not required.

No by-products. No pollution.

“Replicating assemblers and thinking machines pose basic threats to people and life on earth.” Gray goo hypothesis.

Potential for abuse of advanced nanotechnologies means peaceful countries should invest and stay ahead.
Molecular assemblers are not physically possible.

Talks about the impossibility of computer controlled assemblers. Enzymes required.

Talks about the need for water. States that enzymes can not work in organic solvent.

Speculation about unrealistic potential dangers of nanotechnology threaten public support for it.
Good point: “when a scientist says something is possible, they’re probably underestimating how long it will take. But if they say it’s impossible, they’re probably wrong.”

Some simple “machine phase” chemistry using STM manipulation of atoms has already been achieved.
Single-atom manipulation

Chemistry by STM

Schematic drawing of the sequence of steps by which an STM probe can
(a) dissociate a C6H5I molecule on a terrace;
(b and c) draw iodine atom away;
(d) pull one C6H5 (phenyl) molecule toward another;
(e) weld them together; (f) pull one phenyl to confirm the association
Wrong about enzymes’ need for water.
Wrong about biological systems not utilizing metals.
“If [there can be] a non-water-based life form, then there is a vast area of chemistry that has eluded us for centuries.” (His own work demonstrates that there are vast areas of chemistry that have eluded us for centuries!)
If nanobots use enzymes and water then they cannot perform chemistry with materials that are unstable in water.

They will be restricted to biologic-like materials: rock, wood, flesh, bone.

They could not make Si crystals, steel, aluminum, titanium or other “key materials on which modern technology is built”… 

Smalley
Magnetosomes in Bacteria


Fig. 3a–c Electron micrographs of *M. gryphiswaldense* cultures grown in the oxystat at defined pO\(_2\) tensions of 0.25 mbar (a), 10 mbar (b), and 20 mbar (c). Arrows indicate the magnetosome chains (*M*) and the electron-dense particles (*EP*) found in magnetic and non-magnetic cells. The bright inclusions represent polyhydroxyalkanoate globules. Bar 0.5 \(\mu\)m.
Nearly half of essays from high school and middle school students assumed that self-replicating nanobots were possible and most were worried about what would happen when the spread around the world.

“You and people around you have scared our children.”
ETC group - What’s to fear?

- Below ~50 nm quantum size-effect means quantum mechanics takes over from classical mechanics.

- Unpredictable properties - macro-gold is yellow, nano-gold is red.

- Powerful chemistry - Catalyst material made of particles 10 nanometers in diameter is about 100 times more reactive than the same amount of the same material made of particles one micrometer in diameter.

- “Green Goo”
Laws of Technology Introduction

1. It takes a full human generation to comprehend the ramifications of a new technology. Therefore, decisions about whether or not or how to use a new technology will necessarily be ambiguous. Society must be guided by the Precautionary Principle.

2. In evaluating a new technology, the first questions must be: Who owns it? Who controls it? By whom has it been designed and for whose benefit? Who has a role in deciding its introduction (or not)? Are there alternatives? Is it the best way to achieve a particular goal? In the event of harm, with whom does the burden of liability rest and how can the technology be recalled?

3. The extent to which a new technology may be beneficial to society will be in proportion to the participation of society in evaluating the technology—including and especially those people who are most vulnerable.

4. A new technology cannot definitively be assessed as “positive,” “negative” or “neutral,” although certain technologies—in an equitable environment—may be intrinsically decentralizing, democratizing and helpful.

5. For every so-called “Luddite” attempting to establish social controls over the introduction of a technology, there is a powerful elite using social controls to impose new technologies on society.

6. The introduction of a new technology is not inevitable.

7. Any new technology introduced into a society that is not itself a just society can exacerbate the gap between rich and poor—and may even directly harm the poor.

8. A new technology cannot be a “silver bullet” for resolving an old injustice. Hunger, poverty, social disablement and environmental degradation are the consequences of inequitable systems—not of inadequate technologies.

9. The leaders of a society who permit injustice are the least likely to introduce a new technology that will correct injustice.
There's Plenty of Room at the Bottom

- Encyclopaedia Brittanica on the head of a pin requires only 25,000 fold reduction.
  - 1/25,000 pixel = 80 Å (8 nm) = ~32 metal atoms in 2D or 1000 atoms in 3D
- Read- press metal stamp into soft plastic mold, evaporate silica onto plastic to make a thin film, shadow at low angle with gold to highlight raised letters, then examine using electron microscope.
- Write- focused ion beam (TV cathode ray spot), suggests photo process with light shining through holes in a screen could effect metal atoms on surface or some other chemical which could be patterned and recognized later (lithography).
- All books in the world would fit on 1 million pin heads (about 3 square yards). Can we encode to improve information density?
- Atomic info: 2D surface, 3D atomic crystal. If a bit could be encoded in a cube 5x5x5 atoms then “all books in world” would require $10^{15}$ bits and would fit in a cube 1/200 inch wide.
- Biological information density (~50 atoms per bit).
- Need better EM

5 atoms = 125 atoms
Feynman, 1959

- There's Plenty of Room at the Bottom
  - Encyclopaedia Britanica on the head of a pin requires only 25,000 fold reduction.
  - Read- press metal stamp into soft plastic mold, evaporate silica onto plastic to make a thin film, shadow at low angle with gold to highlight raised letters, then examine using electron microscope.
  - Write- focused ion beam (TV cathode ray spot), suggests photo process with light shining through holes in a screen could effect metal atoms on surface or some other chemical which could be patterned and recognized later (lithography).
  - All books in the world would fit on 1 million pin heads (about 3 square yards). Can we encode to improve information density?
  - Atomic info: 2D surface, 3D atomic crystal. If a bit could be encoded in a cube 5x5x5 atoms then “all books in world” would require $10^{15}$ bits and would fit in a cube 1/200 inch wide.
  - Biological information density (~50 atoms per bit).
  - Need better EM
Feynman, 1959

- There's Plenty of Room at the Bottom
  - Physical arrangement of atoms -> chemistry
  - Miniturize computers (heat, power, speed)
  - Miniturize machines (smaller->smaller->smaller)
    - Parallalism
  - Molecular electronics
  - Mechanical tolerance

Only TOP-DOWN view [no self-assembly]
Nano and BioNano

- Nanotech--atomic control of matter
- Bionanotech--control of matter on low nanometer scale with inspiration, principles, or materials borrowed from biology.
Top-Down vs Bottom-Up

**TOP-DOWN**
“Sculpt” from bulk
- Classical semiconductors

**BOTTOM-UP**
Assemble from nano-scale building blocks
- Molecular electronics
- Biomolecular electronics

Classical engineering scale
- 1 µm
- 100 nm
- 10 nm
- 1 nm

Atomic/subatomic scale

“top-down”

“bottom-up”
# Organic Synthesis
# Self-Assembly

Ernst Haeckel (1834-1919) Jena
“The Tree of Life”

- Anatomical systematics
- Haeckel’s line of descent
- 5 Kingdom Model
- 3 Domain (Woese 1990, Pace)
Materials found in nature combine many inspiring properties such as sophistication, miniaturization, hierarchical organizations, hybridization, resistance and adaptability. Elucidating the basic components and building principles selected by evolution to propose more reliable, efficient and environment-respecting materials requires a multidisciplinary approach.
Famous examples of bio-inspired engineering

• **Velcro** - (1948) Swiss engineer George de Mestral was removing burdock burrs from his dog when he realized how the hooks of the burrs clung to the fur.

• **Cat’s Eye Reflectors** - (1935) Percy Shaw studied the reflecting cells in the eyes of cats, tapetum lcidium, known for reflecting the tiniest amounts of light.

• **Smart Clothing** - (2004) Julian Vincent used pinecones as his inspiration for "smart" clothing that adapts to changing temperatures. Pinecones respond to warmer temperatures by opening their scales (to disperse their seeds). The smart fabric does the same thing, opening up when it is warm, and shutting tight when cold.
Mercedes Benz Bionic Car

- The vehicle is modelled after the boxfish (ostracion cubicus) - a tropical fish that lives in coral reefs

- Sets record for lowest vehicle drag coefficient with 0.19, previous record was 0.195 from GM EV1 (a car with much smaller internal volume)

- 60% of energy required to keep car moving at highway speeds originates from aerodynamic drag

- Car gets 70mpg and 140hp, 220ft-lbs torque at 1600rpm
**Biomimetics in the News**


- **Movie**
  - Outermost layer contains chromatophores
  - Muscle contraction increases size of various chromatophores
  - Number of chromatophores range, 40 for deep water species to over a million for octopuses and cuttlefish.
  - Nerves connect the chromatophores directly to the animals brain, eliminating the need for hormones to trigger the color change
  - Middle layer contains iridophore cells
    - Reflect color and produce blue, green, and silver shades for the animal.
  - Innermost layer contains leucophore cells reflect ambient light
    - A base coat to help match surroundings

- Iridophores usually generate iridescent or metallic colors while leucophores produce reflective white hues

- Iridophore reflectance is usually from purine crystals, but in cephalopods it comes from reflectin proteins
- Proteins stack to form pancake structures (platelets)
- Platelets create thin-film interference that the creature can use to manipulate incident light
- Thin films cast from reflectins have the highest known index of refraction of films made from any naturally occurring protein
- Reflectins cast into a thin film from an ionic liquid solution will organize themselves into diffraction gratings that are defect-free over a length of several millimeters
More than two thousand years ago it was observed that some plants have clean leaves despite their dirty habitats.

The Lotus Flower is a species that typically grows in swamps in eastern Asia and eastern North America. The fact that Lotus emerges totally clean from muddy water prompted Buddhists to declare it a symbol of purity.

- Contamination, dirt, and pathogens are washed off the surface of Lotus with small amounts of water
- In addition to their superhydrophobic surfaces these plants retain a layer of air under water

The emergence of the SEM allowed scientists to understand the Lotus effect.
Formation of Glass Microstructures

*Patterned Solid:* A 50 nm thick gold film was prepared on a (100) silicon wafer primed with 2 nm of titanium by electron-beam evaporation. A monolayer of hexadecanethiolate was patterned on the wafer using micro-contact printing so that the resulting pattern presented uncovered 2 μm squares. The unprotected gold was removed with a cyanide etch. The native silica oxide layer was then removed by etching in 2% HF for 30 s. The silicon was etched in a 40 wt.-% solution of KOH in water and isopropanol; this anisotropic etch generated pyramidal pits. The remaining gold was removed with aqua regia. The surface of the resulting textured solid was treated by putting the wafer under static vacuum with a drop of (tridecafluoro-1,1,2,2-tetrahydro-octyl)-1-trichlorosilane for 30 min. This compound polymerized on the surface and made a layer that reduced adhesion to the surface.

Fig. 1. Schematic outline of the molding method used to fabricate structures supported on a flat substrate. A droplet of precursor was compressed between the silicone mold and the surface by applying a pressure of roughly 10 psi (ca. 0.7 atm). The high interfacial free energy of the solution caused the precursor to dewet the substrate completely where the mold and the substrate were in contact.

Pearl Drops

Fig. 5. – SEM images of microstructured hydrophobic surfaces designed for quantifying the influence of the surface pattern on the contact angle. The three different surfaces (spikes, shallow cavities and stripes) are criculated on a micrometer scale.

Fig. 6. – Water drop on a hydrophobic surface decorated with spikes (see the microscopic pattern in fig. 5). The drop has a radius of 100 μm.

Advantages of Superhydrophobicity in Nature

• A water film affects the gas exchange which is crucial for many physiological processes—photosynthesis and plant growth

• Water films significantly increase leaching of nutrients

• Prevention of a water film has an important side effect: the period during which dissolved air pollutants can damage the plant is distinctly shortened

• Dust that is deposited on photosynthetic plant organs causes shading, enhanced reflection, increased leaf temperature, decreased gaseous diffusion and increased transpiration through stomata and cuticle

Pathogen Defense
Spores of pathogenic fungi are completely washed off surfaces of certain crops with well-developed epicuticular waxes

• A dense layer of wax crystals makes it more difficult for fungi to penetrate a plant surface

• The almost permanent dryness of superhydrophobic self-cleaning surfaces is an obstacle particularly to pathogens producing spores which require free water for germination
Numerous studies have shown that certain bacteria, fungi and algae are able to colonize facades, roof tiles, building stone, concrete and even glass. These organisms not only produce optical disturbances; due to the release of organic and inorganic acids, they also cause serious damage.

The common way to prevent biodeterioration so far has been to add biocides to building materials, particularly to façade paints. Since these biocides are gradually leached and, due to their toxicity, give cause for environmental concern, an ecofriendly alternative has been overdue.

• Self cleaning glasses in surveillance camera lenses

• Residue-less containers for medical and research industries

• It is proposed that such surfaces can reduce significantly the drag of large ships.

1/17/08 CPS 296.4/NANO 316
Savings on water, energy, cleaning agents, and waste can be had if active cleaning becomes unnecessary.

Optical properties of glasses are changed

Micro and nanostructure alterations to surface increase fragility

All materials developed to date lack self-healing capability and long term stability.
**Vascular Networks**
Biological organisms have a highly developed multifunctional vascular network to distribute fuel, remove waste, control internal temperature, effect self-healing, etc.
--Goal of current research is to create continuous healing network embedded within a composite laminate that delivers healing agent from a reservoir to regions of damage.

**Healing Agents**
Biomimetic hollow-fiber self-healing mimics mammalian self-healing in that a liquid healing agent leaks from a region of mechanical damage that has resulted in the fracture of an enclosed conduit.
In living networks the relatively rapid response addresses the need to arrest bleeding; the actual tissue and skin healing is a more lengthy process. In biomimetic self-healing, a reasonably rapid response is required to restore some degree of structural integrity or prevent crack propagation since; for example, an aircraft in flight could potentially experience a limit load at any time after a damage event.

**Compartmentalization**
While a cut to mammalian flesh triggers the blood clotting process, in other natural systems, e.g., trees, it is internal scabbing or the formation of internal impervious boundary walls that develop over time to protect the tree from further damage (healing vs injury management).

**Blood Cells**
Artificial cells (nanoparticles) that deposit their payload into regions of damage.

**Skeletal Healing**
Deposition, resorption, and remodelling of fractured reinforcing fibres.

Most materials in nature are themselves self-healing composite materials.
Terrestrial arthropods negotiate demanding terrain more effectively than any search-and-rescue robot.

1) Microcontact-printing of thiol groups.

2) Controlled nucleation of calcite at these functionalized sites.

→ Individual plates of calcium carbonate formed by coccolithophores (exact function is unknown)

→ Creation of ceramics or semiconductors whose mechanical, optical, and electrical properties can be regulated by controlling the size, distribution, crystallographic orientation, and morphology of the constituent crystals.

Gecko Tape

Setae cover the gecko's feet
- each setae branches into spatulae
- spatulae rely on van der Waals forces for adhesion
- each spatulae can exert an adhesive force of 10nN

Wikipedia Factoid - If a typical mature 70g gecko had every one of its setae in contact with a surface, it would be capable of holding aloft a weight of 133 kg.
Gecko Tape

Dhinojwala’s lab used carbon nanotube bundles (100mm wide) to produce tapes with 4x sticking power of a gecko foot

1) Photolithographic Mask
2) Aluminum deposition
3) 1.5nm iron layer
4) CVD

Geim’s lab used a mold (created through lithography) to produce polyimide columns (2mm long).

1) Polyimide bed
2) Aluminum mask (bed then e- beam)
3) Etching


Ge et al. *PNAS* 104(26), 10792-10795 (2007)
Photonic butterfly wing scales

Papilio Butterfly Wings
- covered with textured scales
- zooming in on the scales produces the image to the right
From a distance the butterfly appears green.

Applications in anticounterfeiting, LED design improvements

Wikipedia Factoids –
- Males are strongly attracted to green objects which they mistake for females.
- When in flight the butterfly can be seen hundreds of metres away as sudden bright blue flashes.
- This butterfly is used as an emblem for Queensland tourism.
JOURNAL CLUB

More Examples of Bioinspiration

1

**Capsaicin Tested On Surgical Wounds**

“Bite a hot pepper, and after the burn your tongue goes numb. The Baltimore Sun reports that Capsaicin, the chemical that gives chili peppers their fire, is being [dripped directly into open wounds](https://www.baltimoresun.com/health/2017/02/06/surgery-capsaicin-surgical-nerve-pain.html) during highly painful operations, bathing surgically exposed nerves in a high enough dose to numb them for weeks. As a result patients suffer less pain and require fewer narcotic painkillers as they heal. ‘We wanted to exploit this numbness,’ says Dr. Eske Aasvang, a pain specialist who is testing the substance. Capsaicin works by binding to C fibers called TRPV1, the nerve endings responsible for long-lasting aching and throbbing pain. Experiments are under way involving several hundred patients undergoing various surgeries, including knee and hip replacements using an ultra-purified version of Capsaicin to avoid infection. Volunteers are under anesthesia so they don’t feel the initial burn.”

2

Man-made sonar systems do not function well in shallow, reverberant, near-shore regions of the ocean….However, observations suggest dolphin sonar performs very well.

3

Swarm Intelligence - Georgia Tech researchers developed a honeybee dance-inspired communications system to help single-task Internet servers move between tasks as needed, reducing the chances of a Web site being overwhelmed with and locking out potential visitors. When compared with the way server banks normally run, the honeybee method improved service between 4- and 25 percent in tests based on real Internet traffic.