Importance of Clean Water

- Waterborne illnesses major cause of death
- Emerging pollutants in water supplies
- Population growth globally increases demand

![Graphs showing life expectancy and infant mortality over time](chart.png)
Nano = Dwarf (Greek) = $10^{-9}$

“Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications.”

-National Nanotechnology Initiative
Vision: Nano-Enabled Water Treatment & Reuse

“Nano” particles:
• High surface areas
• Hyper-catalytic functions
• Tunable physical properties
• Multifunctional membranes
• Faster kinetics

Transformative Technologies to

Enable high-performance water treatment and remediation systems with
(1) Less infrastructure,
(2) Less materials/reagents (selective targeting)
(3) Lower costs & energy

clean water, enhance water infrastructure, & enable integrated water management & reuse
Conceptual Improvements to Water Treatment Through Nanotechnology

Nano-Enabled Water Treatment @ Rice

- Sand filter coated with nano-magnetite to remove As (pilot in Mexico, reported by BBC, NY Times, Forbes and CBC).
- Fouling-resistant membranes that also inactivate virus (nAg, nano-TiO$_2$)
- Pd/Au hypercatalysts to treat TCE (Pilot at Dupont site)
- Novel amino-fullerene photocatalysts to enhance UV and solar disinfection and advanced oxidation processes
Photocatalytic MS-2 Virus Inactivation by Aminofullerene

Immobilization of amino-C$_{60}$ onto silica beads facilitates separation, reuse and recycling

3-(2-Succinic anhydride)propyl functionalized silica gel
200-400 mesh, extent of labeling: 0.7 mmol/g loading

EDC, pH = 5.5 (MES buffer)

No loss of photo-activity

Fluidized Photocatalytic Reactor (Swaziland)

- **Water in**
- **Air in**
- **Clean Water out**

- **UV lamp or other light source**
- **Photocatalyst attached to suspended beads**
Photocatalytic degradation of emerging pollutants (pharmaceuticals, endocrine disruptors) to polish effluents from wastewater treatment plants

Photocatalytic *Pre-treatment* of Weathered Oil to Enhance Bioavailability and Bioremediation

Sunlight

\[ \text{H}_2\text{O}, \text{O}_2 \]

\[ \text{OH}^\bullet, ^1\text{O}_2 \]

Weathered Oil (Recalcitrant)

Hydroxylated Residue (Bioavailable)

\[ \text{CO}_2 \]
Photocatalysis Increased Solubilization and Biodegradation of Weathered Oil

* statistically significant ($p < 0.05$) after 1-day exposure

37% more BOD removed
Responsible Nanotechnology

"With Great Power, Comes Great Responsibility"

Uncle Ben to Peter Parker in Spider Man

Paul Hermann Muller
Thomas Midgley
Microbial-nanoparticle Interactions to Inform Risk Assessment

- Bacteria are at the foundation of all ecosystems, and carry out many ecosystem services

- Disposal/discharge can disrupt primary productivity, nutrient cycles, biodegradation, agriculture, etc.

- Antibacterial activity may be fast-screening indicator of toxicity to higher level organisms (*microbial sentinels?*)
Example- Silver Nanoparticles (nAg): Effect of Size, Coating, and Ag⁺
Bioavailability and Toxicity of nAg

Ag⁺ is released only if nAg(0) is oxidized: 

\[ 4\text{Ag}^0 + \text{O}_2 + 4\text{H}^+ \rightleftharpoons 4\text{Ag}^+ + 2\text{H}_2\text{O} \]

(Solubility of Ag⁰ ≈ 0)

- Oxidized NPs (Ag₂O)
- Toxic
- Bacteria
- Bioavailable?
- Toxic?
- Ligands: \( \text{Cl}^-, \text{S}^{2-}, \text{Cysteine}, \text{CO}_3^{2-}, \text{HCO}_3^-, \text{SO}_4^{2-}, \text{PO}_4^{3-} \)
- Complexation?
- Precipitation?
No Ag$^+$ release under Anaerobic Conditions
(Faster release for air-exposed smaller NPs)

No Toxicity Without Ag$^+$ Release

nAg Toxicity Can Be Explained by Dose-Response of Released [Ag⁺]

R² = 0.95

“What does not kill you makes you stronger”

Friedrich Nietzsche

Stimulatory effect after 6 h exposure to low Ag$^+$ concentration (Hormesis?)

Quo Vadis, Nano?

“Nanohype” - Berube
Cost of Purification

- High purity requirements increase separation cost due to higher energy, solvent, & process time requirements (consider tradeoffs)

Need market-driven decrease in ENM price

- Few commercial applications = low demand → prices stay high

- Most production is done for research (small quantities of highly purified material)
Less pure amino-C$_{60}$ cost less (20x) without significantly sacrificing reactivity
Conclusions

The convergence of nanotechnology & microbiology has a great potential for meaningful disruptive innovation:

- DBP-free disinfection
- Advanced (photo) oxidation
- Fouling- and corrosion-resistant surfaces
- Multi-functional membranes
- Responsive materials
The Clarke Prize

Thanks!
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Any Questions?