National Science Foundation
National Nanotechnology Coordinated Infrastructure (NNCI)

University of Washington
with Oregon State University

Montana State University
with Carlton College

University of Nebraska-Lincoln

University of Minnesota Twin Cities
with North Dakota State University

Northwestern University
with University of Chicago

University of Louisville
with University of Kentucky

Georgia Institute of Technology
with North Carolina A&T State University and
University of North Carolina-Greensboro

University of Texas at Austin

Harvard University

Cornell University

University of Pennsylvania
with Community College of Philadelphia

Virginia Polytechnic Institute and State University

North Carolina State University
with Duke University and
University of North Carolina-Chapel Hill

Stanford University

University of California, San Diego

Arizona State University
with Maricopa County Community College District
and Science Foundation Arizona

$81 Million
16 National Sites
5 Years of Funding
Earth’s nanomaterials
Major Technological Revolutions in Human History (cont.)

- Molecular Biology Revolution
- Cognition Revolution, “Decades” of the Brain
- Nanotechnology Revolution
- Digital / Information Revolution

Timeline:
- 1930
- 1940
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
The President’s 2019 Budget supports nanoscale science, engineering, and technology R&D at 12 agencies (approx. $1.5B). The five Federal organizations with the largest investments (representing 95% of the total) are:

**HHS/NIH** (nanotechnology-based biomedical research at the intersection of life and physical sciences).

**NSF** (fundamental research and education across all disciplines of science and engineering).

**DOE** (fundamental and applied research providing a basis for new and improved energy technologies).

**DOD** (science and engineering research advancing defense and dual-use capabilities).
Gold

Melting temperature
= 1,064°C

Melting temperature
= 427°C
Color = gold

Color = pink, orange, red, purple, violet
Inert gold in 1,000 year old shipwreck.

Catalytic gold in gas reaction research

\[ \text{CO} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2 \]
How small is “nano”?

1 nm = 10\(^{-9}\) m

Piece of paper = 100,000 nm thick
Human hair = 80,000 nm thick
DNA = 2.5 nm diameter
Gold atom = 0.3 nm diameter
So what’s the big deal for the Earth sciences!?  OK, an example . . .

Phytoplankton: half of all photosynthesis on Earth!

**EARTH COMPONENTS**
- Soils/regolith
- Continents
- Factories
- Farms
- Watersheds
- Oceans
- Wastewater treatment plants
- Atmosphere
- Machines
- Coal burning power plants

**PRECURSORS**
- Electrons & protons
- Small molecules/clusters
- Elements & ions
- Polyatomic ions

**NANOMATERIAL CYCLE**
- Dispersion & diffusion transport
- Weathering, Deposition, Aggregation reactions
- Natural & engineered processes
- Redox, Hydrolysis, Dissolution, Precipitation

**NANOMATERIAL EXAMPLES**

**INCIDENTAL**
- Magneli phases
- Nanoplastics
- Welding fumes
- Soot

**NATURAL**
- Metal oxides
- Clay minerals
- Viruses
- Sulfides

**ENGINEERED**
- Liposomes
- Carbon nanotubes
- Metals
- Quantum dots
Natural, incidental, and engineered nanomaterials and their impacts on the Earth system

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BACKGROUND: Natural nanomaterials have always been abundant during Earth's formation and throughout its evolution over the past 4.54 billion years. Incidental nanomaterials, which arise as a by-product from human activity, have become unintentionally abundant since the beginning of the Industrial Revolution. Nanomaterials can also be synthesized using unusual, tunable properties that can be used to improve products in applications from human health to electronics, and in energy, water, and food production. Nanomaterials are very much a recent phenomenon, not yet a century old, and are just a small mass fraction of the natural and incidental varieties. As with natural and incidental nanomaterials, engineered nanomaterials can have both positive and negative consequences in our environment.

Despite the ubiquity of nanomaterials on Earth, only in the past 20 years or so have their impacts on the Earth system been studied extensively. This is mostly due to a much better understanding of the distinct behavior of materials at the nanoscale and to multiple advances in analytic techniques. This progress continues to expand rapidly as it becomes clear that nanomaterials are relevant from molecular to planetary dimensions and that they operate from the shortest to the longest time scales over the entire Earth system.

ADVANCES: Nanomaterials can be defined as any organic, inorganic, or organometallic material that present chemical, physical, and/or electrical properties that change as a function of the size and shape of the material. This behavior is most often observed in the size range between 1 nm up to a few to several tens of nanometers in at least one dimension. These materials have very high proportions of surface atoms relative to interior ones. Also, they are often subject to property variation as a function of size owing to quantum confinement effects. Nanomaterial growth, dissolution or evaporation, surface reactivity, and aggregation states play key roles in their lifetime, behavior, and local interactions in both natural and engineered environments, often with global consequences.

It is now possible to recognize and identify critical roles played by nanomaterials in vital Earth system components, including direct human impact. For example, nanomaterial surfaces may have been responsible for promoting the self-assembly of protocols in the origin of life and in the early evolution of bacterial cell walls. Also, weathering reactions on the continents produce various bioavailable iron (oxy)hydroxide nanomaterials and accidental nanomaterials, which are transported to the oceans via riverine and atmospheric pathways and which influence ocean surface primary productivity and thus the global carbon cycle. A third example involves nanomaterials in the atmosphere that travel locally, regionally, and globally. When inhaled, the smallest nanoparticles can pass through the alveolar membranes of the lungs and directly enter the bloodstream. From there, they enter vital organs, including the brain, with possible deleterious consequences.

OUTLOOK: Earth system nanoscience requires a convergent approach that combines physical, biological, and social sciences, as well as engineering and economic disciplines. This convergence will drive developments for all types of intelligent and anticipatory conceptual models assisted by new analytical techniques and computational simulations.

Ultimately, scientists must learn how to recognize key roles of natural, incidental, and engineered nanomaterials in the complex Earth system, so that this understanding can be included in models of Earth processes and Earth history, as well as in ethical considerations regarding their positive and negative effects on present and predicted future environmental and human health issues.
Nano-hematite, HAADF-STEM tomography, aggregate, 30 nm

Echigo et al. (2013) Am. Min.
Purely quantum mechanical considerations

Quantum Mechanics?

Ugh.

Well, not anymore
Weak quantum confinement regime:

\[ a_e, a_h < a \]

Intermediate quantum confinement regime:

\[ a_e < a < a_h \]

For hematite: 7.0 nm 3.8 nm

Strong quantum confinement regime:

\[ a < a_e, a_h \]
\( a_B \) written in terms of \( a_0 \):

\[
a_B = \frac{\varepsilon m_0}{\mu} a_0
\]

Quantum Confinement in Hematite

For PbS galena:

\[
a_B = 18 \text{nm}
\]