CENTER FOR HOMELAND DEFENSE AND SECURITY
NAVAL POSTGRADUATE SCHOOL

Argonne NATIONAL LABORATORY

HSx: GROWTH OF MULTIDISCIPLINARY SCIENTIFIC RESEARCH

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CONTEXT

- Current global access to knowledge and rapid pace of technology development makes scientific innovation important in today's military and national security efforts.
- Multidisciplinary research:
  - Collaborative research requiring knowledge associated with several academic disciplines.
  - Developed from the need to answer complex questions, which a single discipline is unable to handle.
- The recent trend towards multidisciplinary scientific research suggests that this approach is key to innovation and scientific progress.

GROWTH OF MULTIDISCIPLINARY SCIENCE

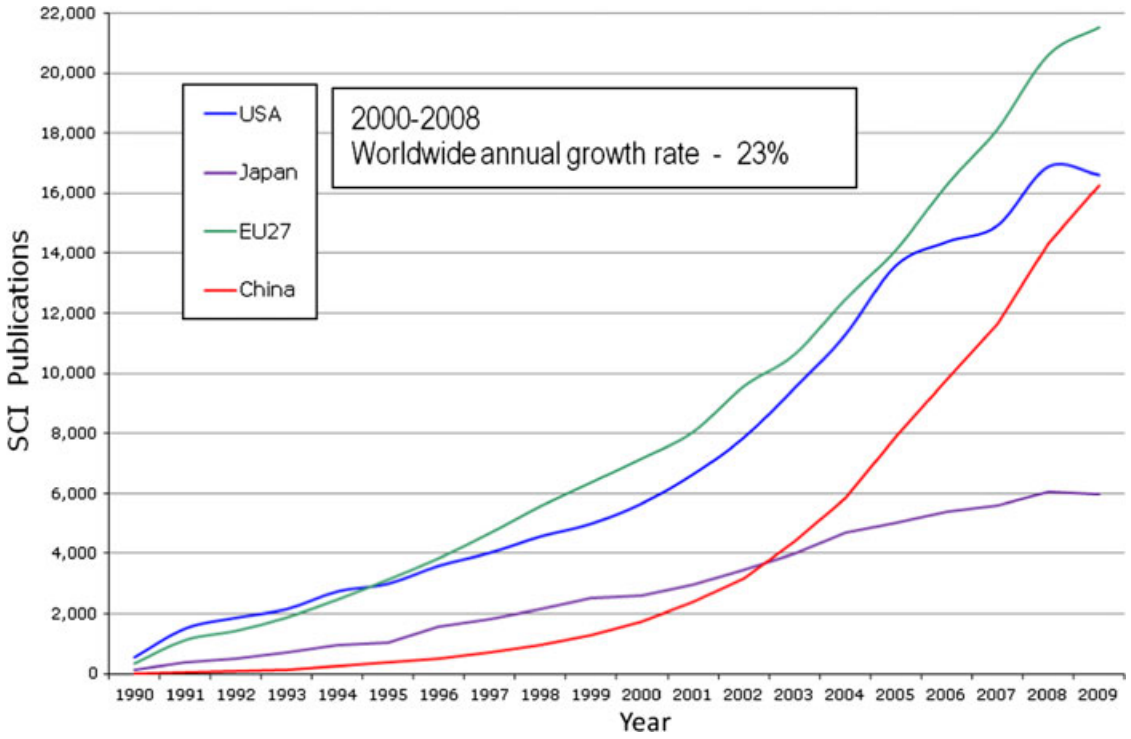
- Solving problems of today and the future requires collaboration across science disciplines, government agencies, and international boundaries.
- Multidisciplinary research is on the rise:
  - New fields of study have emerged that involve techniques from multiple disciplines (biomedical engineering, environmental sustainability, nanotechnology).
  - The idea of team science is growing: bringing together groups of investigators to collaborate on projects
  - Recent dramatic rise in funding opportunities for multidisciplinary projects and research centers.
- Evidence of growth of multidisciplinary collaboration:
  - Several multidisciplinary journals (International Journal of Multidisciplinary Research and Development, Journal of Multidisciplinary Research)
  - Multidisciplinary research centers (California NanoSystems Institute, Texas Tech Center for Multidisciplinary Research in Transportation).
  - Multidisciplinary departments at universities (Stanford's Department of Bioengineering, Indiana State University's Department of Multidisciplinary Studies).
  - Increase in funding opportunities for multidisciplinary research
    - Multidisciplinary University Research Initiatives (MURI) Program from the Office of Naval Research.

MULTIDISCIPLINARY SCIENCE

- Examples of multidisciplinary science fields important to defense and infrastructure (this list is not exhaustive):
  - Nanotechnology
  - Metamaterials
  - Battery improvement
  - Biochemistry/bioengineering

NANOTECHNOLOGY BACKGROUND

- The ability to control and restructure matter at the atomic and molecular levels to create materials, devices, and systems with new properties and functions by engineering their small structure.
- Multi-disciplinary: combines physics, chemistry, material science, engineering (electrical, mechanical, chemical).
- Nanotechnology research has increased dramatically in the 21st century.



Number of Science Citation Index papers reflecting discoveries in the area of nanotechnology, based on a title-abstract keyword search

Image source: Roco, 2011. The Long View of Nanotechnology Development: The National Nanotechnology Initiative at 10 years. Journal of Nanoparticle Research, 13: 427-445.

NANOTECHNOLOGY APPLICATION

- Defense
  - U.S. is currently the leader in development of nanotechnology-based applications for military and national defense.
    - Will revolutionize modern warfare: nanosensors, artificial intelligence, nanomanufacturing, nanorobotics.
  - Stronger and lighter battle suits
    - Magnetorheological (MR) fluid: a fluid that can be controlled to change from liquid to solid state using magnetic fields.
  - Nanorobotics
    - Robots designed at the nanoscale that can swarm together and be used for reconnaissance, communication, and sensing
  - Nano-enabled medicines to cure field wounds
- Infrastructure
  - MR fluid dampers can be used to control vibrations of bridges and buildings in earthquakes.

Image sources: https://sites.google.com/a/temple.edu/semi-active-dampers/ and http://www.spatialrobots.com/2009/09/i-swarm-robots/#more-1202

METAMATERIALS

- Artificially engineered materials exhibiting unique or unusual electromagnetic properties that cannot be found in natural materials.
- Multidisciplinary: combined material physics, electromagnetics, optics, radio engineering, electronics.

- Defense Applications:
  - Cloaking devices
    - Acoustic cloak: A U.S. Navy research project evaluated the use of metamaterials to cloak underwater naval vehicles from active sonar.
  - Antenna technology
    - Antenna miniaturization
  - Threat detection
    - Split-ring resonators (SRRs) made of metamaterials can detect many biological and chemical agents.

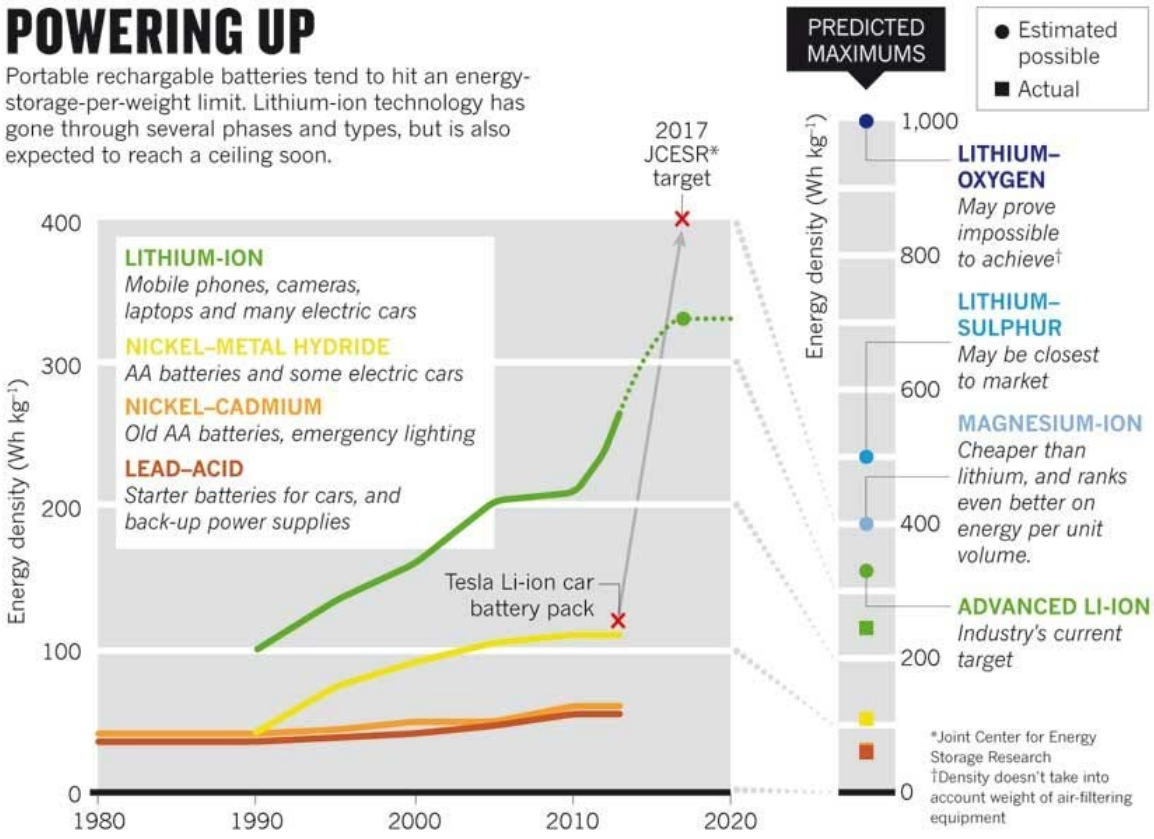
- Infrastructure Applications:
  - Earthquake shields made of mechanical metamaterials to deflect acoustic waves generated in an earthquake.

BATTERIES: INCREASED ENERGY DENSITY

- Multidisciplinary: combines chemical sciences, engineering, high-energy physics, materials science, mathematics, computer science, nanoscience.
- Energy density is how much energy can be supplied per unit weight.
- The greater electric power demand required by advanced weapons and sensors drive the need for increased energy density in batteries.
- Commercial demand has driven battery innovation in recent years, but the commercial and military needs for batteries differ.
  - Consumers need inexpensive, rechargeable batteries while soldiers need light-weight, long-lasting batteries for radios, GPS units, and night vision systems.
  - Non-rechargeable batteries currently offer better energy density than rechargeable batteries.
- New research areas:
  - Looking beyond lithium-ion batteries
    - Magnesium-Ion, Lithium-Sulphur, lithium-Oxygen
  - Betavoltaics: generate power from radioactive materials
    - Have up to 5X the energy density of traditional chemical batteries.

BATTERIES: INCREASED ENERGY DENSITY

- Increased energy density means:
  - Batteries could be used to supplement or replace diesel engines as a silent energy source for missions.
  - Extending operating times of unmanned missions (unmanned aerial vehicles, unmanned ground vehicle, unmanned surface vehicle, and unmanned underwater vehicles)



Graphics source: http://www.nature.com/news/the-rechargeable-revolution-a-better-battery-1.14815

BIOCHEMISTRY/BIOENGINEERING

- Biochemistry: the study of the chemical substances and vital processes occurring in living organisms.
  - Multidisciplinary: combines cell biology, molecular biology, microbiology, genetics, molecular medicine.
- Bioengineering: the application of engineering principles and techniques to problems in medicine and biology.
  - Multidisciplinary: combines math, physical sciences, chemical sciences, engineering.

BIOCHEMISTRY/BIOENGINEERING APPLICATIONS

- Anticipating and detecting new threats: emerging infectious diseases, synthetic biology, and engineered diseases.
  - Counter threats with detection systems, protective equipment, and vaccines.
- Biomimicry: uses natural biological systems or material as an inspiration for solving engineering problems.
  - Gloves based on gecko's feet that allow soldiers to scale walls.
  - Stronger, lighter armor for soldiers based on spider silk and abalone shell
  - Self-cleaning materials based on the water-repellency of lotus leaves.
    - Can be used for protective equipment to reduce threat from chemical warfare agents.

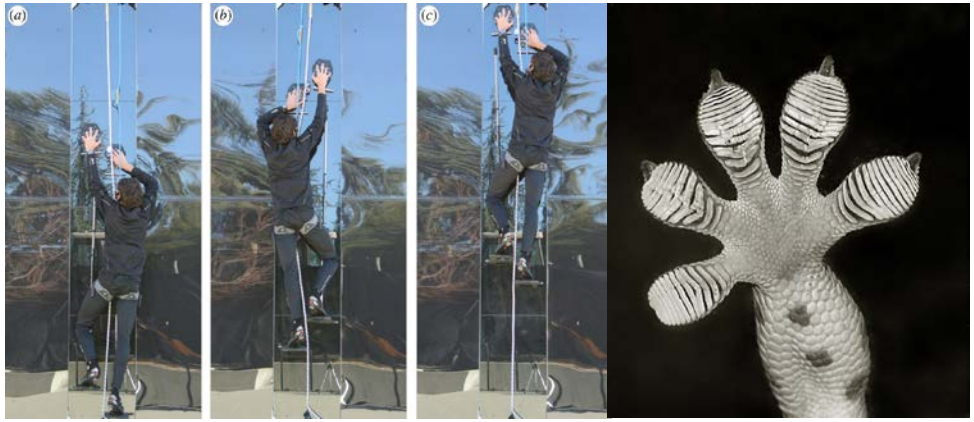


Image sources:
http://rsif.royalsocietypublishing.org/content/12/102/20140675.figures-only and
http://www.popsci.com/scitech/article/2008-04/gecko-tech

NATIONAL SECURITY IMPLICATIONS

- Maintaining U.S. leadership in research and technology is crucial to America's success.

- The U.S. has lead the world in scientific research since WWII, but it is no longer assured leadership in technology critical to national security.
  - The European Union, Japan, and North America currently account for the majority of global science and technology investment.
  - But substantial growth in several Asian economies could shift leadership in some areas.
  - Decreased U.S. federal funding for research in recent years threatens the country's global position in research and development.

- Increased international collaboration can lead to security issues.
  - Example: Allegations of cyberespionage made by both China and the U.S. have led to increased apprehension about scientific collaboration.
    - Chinese interests in collaboration seem to be targeted at specific fields and facilities where China hopes to enhance capabilities.

RESOURCES

- The following resources provide further information on this topic:
  - **Boston University, 2012**. Innovation for the New Front Line: Security & Defense Technology Research. Available at: https://www.bu.edu/systems/files/2012/10/BUCE_Security.pdf. Accessed April 2017.
  - **Holdren et al., 2016**. A 21st Century Science, Technology, and Innovation Strategy for America's National Security. Committee on Homeland and National Security of the National Science and Technology Council.
  - **O'Connor et al., 2009**. Collaboration in the National Security Arena: Myths and Reality – What Science and Experience Can Contribute to its Success. Topical Strategic Multi-Layer Assessment (SMA) Multi-Agency/Multi-Disciplinary White Papers in Support of Counter-Terrorism and Counter-WMD.
  - **Sarewitz et al., 2012**. Energy Innovation at the Department of Defense: Assessing the Opportunities. Available: http://bipartisanpolicy.org/wp-content/uploads/sites/default/files/Energy%20Innovation%20at%20DoD.pdf. Accessed March 2017.

- Additional research materials and information sources regarding this topic can be found in the associated *Literary & Scholastic Resource List*.

Literary and Scholastic Resources – Growth of Multidisciplinary Scientific Research

Date of information: April 2017

Overview: While not exhaustive, the following resources provide an overview of the growth of multi-disciplinary scientific research and how that research applies to defense and infrastructure rapid technological advancement. These resources provide a baseline of understanding, but as the scientific research continues to evolve, new data will become available and resource lists will require updates.

Module Resource Lists to Cross-Reference: Artificial Intelligence & Machine Learning, Role of Big Data

Organizations:

- International Journal of Nanotechnology (IJNT): IJNT offers a multidisciplinary source of information in all subjects and topics related to Nanotechnology, with fundamental, technological, as well as societal and educational perspectives. Special issues are regularly devoted to research and development of nanotechnology in individual countries and on specific topics. Main page at: http://www.inderscience.com/jhome.php?jcode=ijnt.

- European Physical Journal Applied Metamaterials (EPJ AM): EPJ AM is an open access platform for multidisciplinary researchers to exchange information on metamaterials with a focus on high impact engineering applications. Main page at: http://epjam.edp-open.org/

Recent Publications and Journal Articles:

- Fundamental Research and U.S. National Security: A journal article that discusses the role of scientific research in U.S. national security. The article highlights several recent technological advances that were funded by the DoD and explains that a decrease in federal funding for research has resulted in the United States no longer leading the world in science and technology.
    - *Citation:* Godfrey, B., 2016. Fundamental Research and U.S. National Security. Proceedings of the IEEE, 104(2): 215-219. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7386802. Accessed April 2017.

- Earthquake Resistance of Structures Using Dampers – A Review: A journal article about vibration mitigation of structures subjected to environmental and manmade loads. The article includes magnetorheological fluids as one type of mitigation used for bridges.
    - *Citation:* Gowda and Kiran, 2013. Earthquake Resistance of Structures Using Dampers – A Review. International Journal of Advances Structures and Geotechnical Engineering, 2(1): 31-35. http://basharesearch.com/IJASGE/1020106.pdf. Accessed April 2017.

- A 21st Century Science, Technology, and Innovation Strategy for America's National Security: A strategy that reflects input from and deliberation among the science, technology, and innovation components of the Departments and Agencies responsible for carrying out the Nation's national security mission. This strategy sets forth how the U.S. national security science, technology, and innovation enterprise should evolve to address the challenges and opportunities imposed by a new landscape of national security technology concerns in the 21st century.
    - *Citation:* Holdren, et al., 2016. A 21st Century Science, Technology, and Innovation Strategy for America's National Security. Committee on Homeland and National Security of the National

Science and Technology Council. http://www.defenseinnovationmarketplace.mil/resources/National_Security_ST_Strategy_2016_FINAL.PDF. Accessed April 2017.

- Career Paths in Multidisciplinary Research: An opinion paper released by the Life, Environmental and Geo Sciences Committee that discusses the importance of multidisciplinary research and makes recommendations about the lack of clear evaluation metrics for scientists working in multidisciplinary teams.
    - *Citation:* Inzé, et al., 2014. Life, Environmental and Geo Sciences Committee Opinion Paper: Career Paths in Multidisciplinary Research.http://www.scienceeurope.org/wp-content/uploads/2014/09/2-LEGS_Careers_OpinionPaper_FIN.pdf. Accessed April 2017.

- Atomic Batteries: Energy from Radioactivity: An article about various atomic batteries with perspectives of development and comparisons of performance parameters and cost.
    - *Citation:* Kumar, 2015. Atomic Batteries: Energy from Radioactivity. arXiv:1511.07427. http://arxiv.org/abs/1511.07427. Accessed April 2017.

- Large Scale Mechanical Metamaterials as Seismic Shields: A journal article about a novel approach that uses large-scale mechanical metamaterials to address the problem of earthquake damage from acoustic waves. The article describes how 3D simulations were used to test the feasibility of a passive isolation strategy for seismic waves.
    - *Citation:* Miniaci, M., A. Krushynska, F. Bosia, and N.M. Pugno. 2016. Large Scale Mechanical Metamaterials as Seismic Shields. New Journal of Physics, 18: 083041. doi:10.1088/1367-2630/18/8/083041. http://iopscience.iop.org/article/10.1088/1367-2630/18/8/083041/pdf. Accessed April 2017.

- Collaboration in the National Security Arena: Myths and Reality – What Science and Experience Can Contribute to its Success: An inter-agency/multi-disciplinary white paper that includes 35 articles addressing U.S. Government agency and operational perspectives, scientific disciplines studying collaboration, common barriers to collaboration, findings from applied research on collaboration, and finally potential enablers for collaboration. It is primarily intended for the operational and policy community in DoD, the Intelligence Community (IC), DHS, and other U.S. Government agencies. The authors are from the IC, Services, USG agencies, FFRDCs, academia, and the private sector.
    - *Citation:* O'Connor, et al., 2009. Collaboration in the National Security Arena: Myths and Reality – What Science and Experience Can Contribute to its Success. Topical Strategic Multi-Layer Assessment (SMA) Multi-Agency/Multi-Disciplinary White Papers in Support of Counter-Terrorism and Counter-WMD. https://www.usna.edu/Users/math/wdj/_files/documents/teach/CollaborationWhitePaperJune2009.pdf. Accessed April 2017.

- The Long View of Nanotechnology Development: The National Nanotechnology Initiative at 10 years: A journal article about the development of the National Nanotechnology Initiative (NNI) since 2000 in the international context, the main outcomes of the R&D programs after 10 years, the governance aspects specific to this emerging field, lessons learned, and most importantly, how the nanotechnology community should prepare for the future.
    - *Citation:* Roco, 2011. The Long View of Nanotechnology Development: The National Nanotechnology Initiative at 10 years. Journal of Nanoparticle Research, 13: 427-445. https://www.nsf.gov/crssprgm/nano/reports/MCR_11-0201_JNR13_NNI+at+10+years_11051_2010_192_print.pdf. Accessed April 2017.

- Energy Innovation at the Department of Defense: Assessing the Opportunities: A report that provides an overall synthesis of key issues surrounding energy innovation at DoD, and then presents four papers that explore distinctive perspectives and elements of the DoD innovation process.
    - *Citation:* Sarewitz, et al., 2012. Energy Innovation at the Department of Defense: Assessing the Opportunities..http://bipartisanpolicy.org/wp-content/uploads/sites/default/files/Energy%20Innovation%20at%20DoD.pdf. Accessed March 2017.

- Trends in U.S.-China Science and Technology Cooperation: Collaborative Knowledge Production for the Twenty-First Century?: A report on the scientific collaboration that has occurred between the U.S. and China and how that relationship has evolved over the course of 35 years.
    - *Citation:* Suttmeier, R.P. 2014. Trends in U.S.-China Science and Technology Cooperation: Collaborative Knowledge Production for the Twenty-Frist Century? Research Report Prepared on Behalf of the U.S.-China Economic and Security Review Commission. https://www.uscc.gov/sites/default/files/Research/Trends%20in%20US-China%20Science%20and%20Technology%20Cooperation.pdf. Accessed April 2017.

- Military and National Security Implications of Nanotechnology: A journal article about recent advancements in nanotechnology in the U.S. and how they are revolutionizing modern warfare.
    - *Citation:* Tate, et al., 2015. Military and National Security Implications of Nanotechnology. The Journal of Technology Studies, 41(1): 20-29. https://scholar.lib.vt.edu/ejournals/JOTS/v41/v41n1/pdf/tate.pdf. Accessed March 2017.

- Metamaterials: A Leading Edge of Science and Technology: A review paper that gives a brief history of metamaterials and describes their various uses in different fields.
    - *Citation:* Thakur, V. and D. Chaudhary, 2014. Metamaterials: A Leading Edge of Science and Technology. International Journal of Computer Applications, 98(9): 29-34.
    - *Citation:* Link to pdf at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.680.8653&rep=rep1&type=pdf

- Nanotechnology-Based Therapies for Skin Wound Regeneration: A journal article that presents an overview on the current applications of nanotechnology to wound healing and wound care.
    - *Citation:* Tocco, et al., 2012. Nanotechnology-Based Therapies for Skin Wound Regeneration. Journal of Nanomaterials. doi:10.1155/2012/714134. https://www.hindawi.com/journals/jnm/2012/714134/. Accessed April 2017.

- A Better Battery: Chemists are Reinventing Rechargeable Cells to Drive Down Costs and Boost Capacity: A journal article that discusses the changes in battery technology in recent years and the current research being conducted.
    - Citation: Van Noorden, 2014. A Better Battery: Chemists are Reinventing Rechargeable Cells to Drive Down Costs and Boost Capacity. Nature, 507: 26-28. http://www.nature.com/news/the-rechargeable-revolution-a-better-battery-1.14815. Accessed April 2017.

Other Resources:

- Defense Department Science and Technology: The U.S. Department of Defense Science and Technology webpage. This site provides descriptions of the latest scientific studies and advancements made that are relevant to the DOD.
    - *Citation:* DOD, 2017. Defense Department Science and Technology. Accessed April 2017.
    - *Citation:* Link to website at https://www.defense.gov/News/Special-Reports/0715_science-tech\

- The Next Step in Nanotechnology: A TED Talk by IBM's George Tulevski about possible future applications of nanotechnology for computing.
    - *Citation:* Tulevski, G. 2016. The Next Step in Nanotechnology. TED Talk. Recorded Nov 2016.
    - *Citation:* Link to video at https://www.ted.com/talks/george_tulevski_the_next_step_in_nanotechnology

- The Magnificence of Spider Silk: A TED Talk by biologist Cheryl Hayashi about spider silk and its potential applications in medicine and military armor.
    - *Citation:* Hayashi, C. 2010. The Magnificence of Spider Silk. TED Talk. Recorded Feb 2010.
    - *Citation:* Link to video at https://www.ted.com/talks/cheryl_hayashi_the_magnificence_of_spider_silk