SIZE MATTERS: Mechanical properties of materials at nano-scale

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While "super-sizing" seems to be the driving force of our food industry, the direction of materials research has been quite the opposite: the dimensions of most technological devices are getting ever smaller. These advances in nanotechnology have a tremendous impact on parts of the economy as diverse as information, energy, health, agriculture, security, and transportation. Some of the examples include data storage at densities greater than one terabit per square inch, high-efficiency solid-state engines, single-cell diagnostics of complex diseases (e.g. cancer), and the development of ultra-light yet super-strong materials for vehicles, with the component sizes comprising these technological devices reduced to the sub-micron scale. The functionality of these devices directly depends on their structural integrity and mechanical stability, driving the necessity *to understand* and *to predict* mechanical properties of materials at reduced dimensions. Yield and fracture strengths, for example, have been found to deviate from classical mechanics laws and therefore can no longer be inferred from the bulk response or from the literature. Unfortunately, the few existing experimental techniques for assessing mechanical properties at that scale are insufficient, not easily accessible, and are generally limited to thin films. In order to design reliable devices, a fundamental understanding of mechanical properties as a function of feature size is desperately needed; with the key remaining question whether materials really are stronger when the instrumental artifacts are removed, and if so then *why* and *how*.

A key focus in Professor J.R.Greer's research is the development of innovative experimental approaches to assess mechanical properties of materials whose dimensions have been reduced to nano-scale not only vertically but also laterally. One such approach involves the fabrication of nanopillars with different initial microstructures (single crystalline, nano-crystalline, amorphous, etc.) ranging in diameter from 100 nm to 800nm by using Focused Ion Beam (FIB) and micro-fabrication approaches. Their strengths in uniaxial compression and tension are subsequently measured in a one-of-a-kind in-situ mechanical deformation instrument developed in the Greer lab. This instrument is called SEMentor, as it is comprised of the Scanning Electron Microscope (SEM) and Nanoindenter, which allow for precise control of displacement and loading rates, as well as for simultaneous video capture. Some representative images of various nano-sized mechanical testing specimen are shown in Figure 1. In this seminar we will discuss the differences observed between mechanical behavior in two fundamental types of crystals: face-centered cubic (fcc) and body-centered cubic (bcc), as well as of nano-crystalline Nickel and amorphous metallic glasses with nano-scale dimensions. In a striking deviation from classical mechanics, we observe a SMALLER IS STRONGER phenomenon in single crystals manifested by the significant (~50x) increase in strength of as material size is reduced to 100nm. To the contrary, nano-crystalline materials tend to exhibit the opposite trend: SMALLER is SOFTER. Finally, metallic glasses, whose Achilles' heel has always been the occurrence of catastrophic failure at very small strains, exhibit non-trivial ductility when reduced to nano-scale. Furhtermore, unlike in bulk where plasticity commences in a smooth fashion, all of these materials exhibit numerous discrete strain bursts during plastic deformation. These remarkable differences in the mechanical response of nano-scale solids subjected to uniaxial compression and tension challenge the applicability of conventional plasticity models at the nano-scale. We postulate that they arise from the effects of free surfaces, leading to the significant differences in dislocation behavior for the case of crystals, grain-boundary activity for the case of nano-crystalline solids, and shear transformation zones in metallic glasses. and serve as the fundamental reason for the observed differences in their plastic deformation. These mechanisms and their effect on the evolved microstructure and the overall mechanical properties will be discussed.