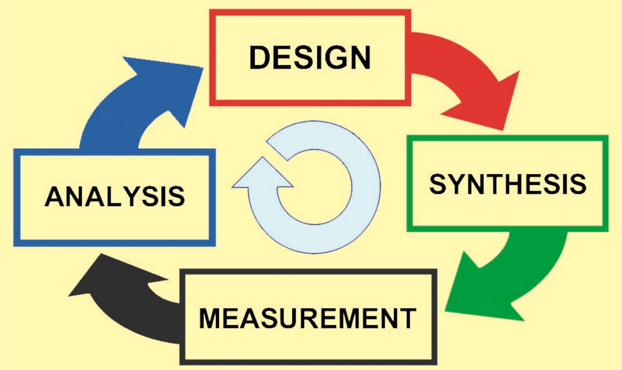
nanoscience

The properties of matter at nanoscale dimensions can be dramatically different from the bulk or the constituent molecules. The differences arise through quantum confinement, altered thermodynamics or changed chemical reactivity. The richness of this field and its potential benefits to the national economy and to national security are recognized in the establishment by the Department of Energy of five national Nanoscale Science Research Centers (NSRCs), one of which is the Molecular Foundry at Berkeley Lab.

The development cycle for nanoscience is an iterative one, involving design, synthesis, measurement, and analysis. The philosophy of the Molecular Foundry is to bring under one roof these four principal elements of the research cycle.

The Molecular Foundry enjoys close proximity to the Advanced Light Source, the National Center for Electron Microscopy and the National Energy Research Scientific Computing Center. There will be a coordinated proposal-submission mechanism, so that users wishing access to more than one facility need submit only a single proposal.

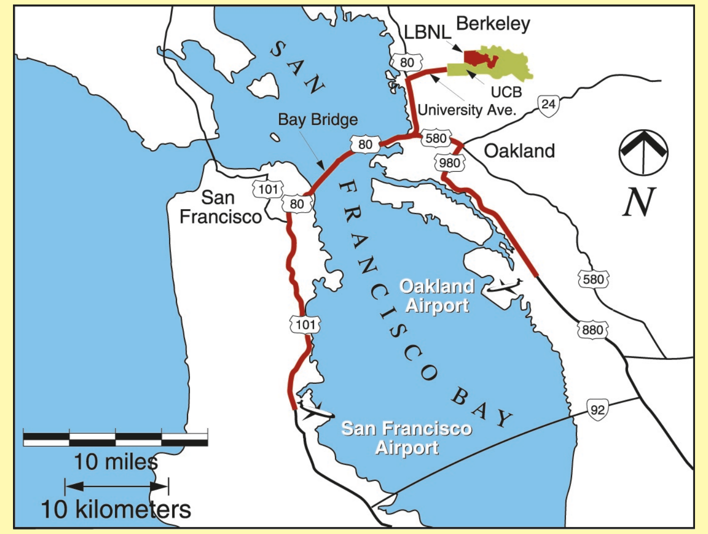


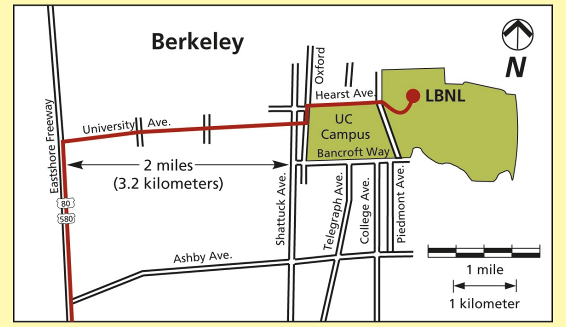
The iterative development cycle for nanotechnology. The ALS will complement the Molecular Foundry by providing tools for measurement and characterization.

The Molecular Foundry at Berkeley Lab will be ready for occupancy in 2006.

reaching the advanced light source

Berkeley Lab is located on a site in the hills directly above the campus of the University of California, Berkeley, and is readily accessible by automobile from anywhere in the San Francisco Bay Area and by limousine or taxi from the San Francisco and Oakland airports. The Bay Area Rapid Transit (BART) system also provides convenient access from the airports via its station in downtown Berkeley. Berkeley Lab operates weekday shuttle service: an off-site shuttle between locations around the UC campus and downtown Berkeley to the Laboratory and an on-site shuttle.





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links to DOE nanoscience user facilities

NANOSCIENCE FACILITIES AT BERKELEY LAB

Molecular Foundry — *www.foundry.lbl.gov*

Advanced Light Source (ALS) — *www-als.lbl.gov*

National Center for Electron Microscopy (NCEM) — *ncem.lbl.gov*

National Energy Research Scientific Computing Center (NERSC) — *www.nersc.gov*

U.S. DOE NANOSCALE SCIENCE RESEARCH CENTERS

Molecular Foundry, Berkeley Lab — *www.foundry.lbl.gov*

Center for Functional Nanomaterials, Brookhaven National Laboratory — *www.cfn.bnl.gov*

Center for Integrated Nanotechnologies, Sandia National Laboratories and Los Alamos National Laboratory — *cint.lanl.gov*

Center for Nanophase Materials Sciences, Oak Ridge National Laboratory — *www.cnms.ornl.gov*

Center for Nanoscale Materials, Argonne National Laboratory — *nano.anl.gov*

U.S. DOE SYNCHROTRON RADIATION FACILITIES

Advanced Light Source, Berkeley Lab — *www-als.lbl.gov*

Advanced Photon Source, Argonne National Laboratory — *www.aps.anl.gov*

National Synchrotron Light Source, Brookhaven National Laboratory — *nslsweb.nsls.bnl.gov/nsls/*

Stanford Synchrotron Radiation Laboratory, Stanford Linear Accelerator Center — *www-ssrl.slac.stanford.edu*

U.S. DOE NEUTRON SCATTERING FACILITIES

High Flux Isotope Reactor Facility (HFIR), Oak Ridge National Laboratory — *www.ornl.gov/sci/hfir*

Intense Pulsed Neutron Source (IPNS), Argonne National Laboratory — *www.pns.anl.gov*

Los Alamos Neutron Scattering Center (LANSCE), Los Alamos National Laboratory — *lansce.lanl.gov*

Spallation Neutron Source (SNS), Oak Ridge National Laboratory — *www.sns.gov*

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nanoscience

at the ADVANCED LIGHT SOURCE

ALS

MOLECULAR FOUNDRY

NERSC

NCEM

Ernest Orlando Lawrence Berkeley National Laboratory

synchrotron radiation

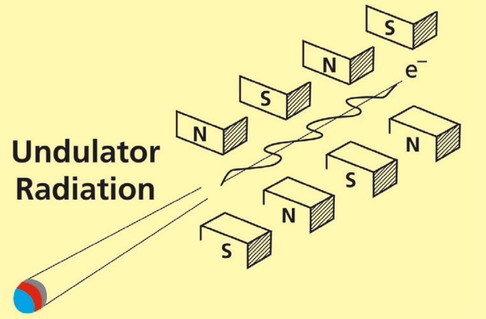
Synchrotron radiation is the light emitted by electrons as they circulate around a high-energy accelerator. This light covers the spectrum from hard (short-wavelength) x rays through soft (long-wavelength) x rays, ultraviolet, visible, and infrared. Once thought of as an energy-sapping by-product of circular accelerators, synchrotron radiation has become an indispensable tool in many areas of science. The U.S. Department of Energy operates four synchrotron radiation facilities, one of which is the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory.

The ALS is a "third-generation" source. The storage ring has long straight sections designed to accommodate special magnetic devices called undulators that generate an extremely bright beam confined to a narrow cone in the forward direction.

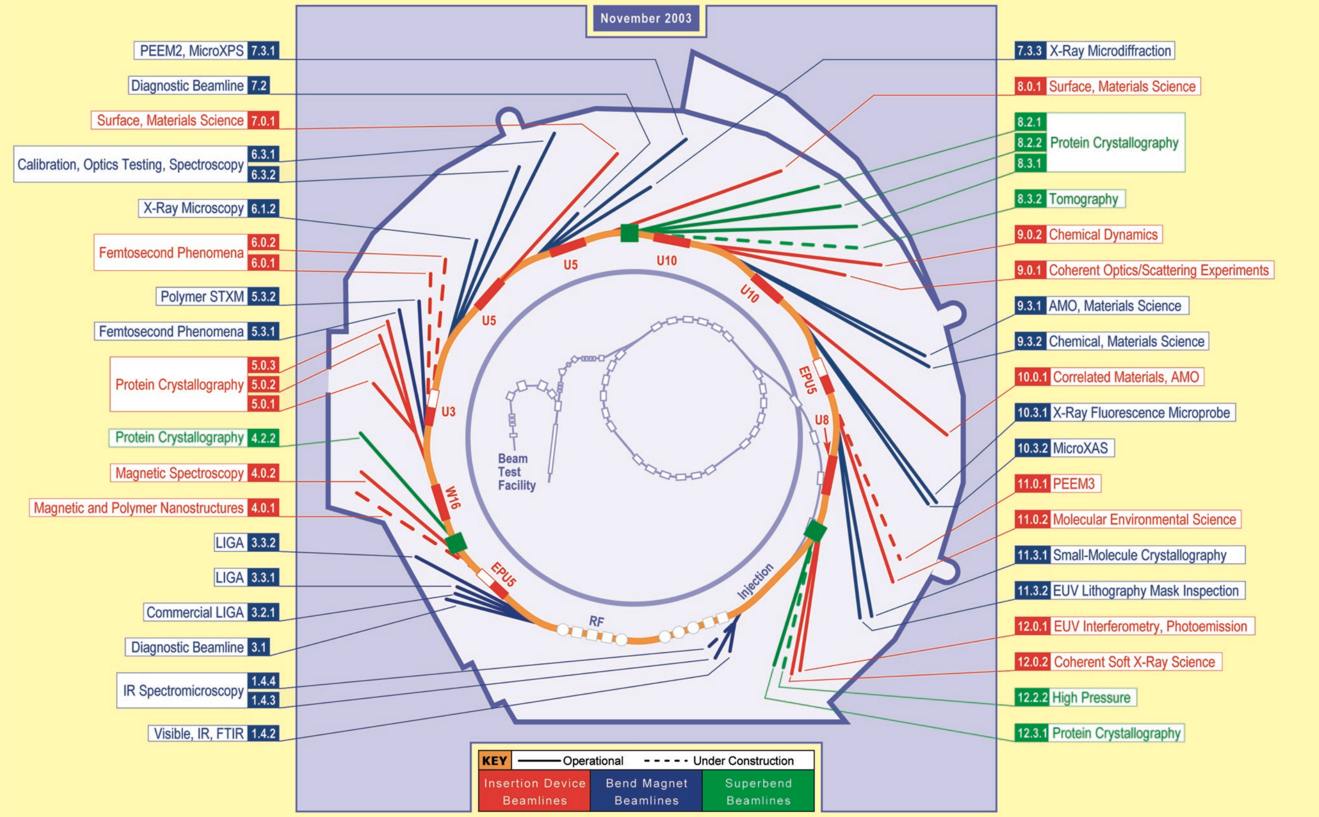
High brightness confers three major advantages:

- High resolving power for spectroscopy
- High spatial resolution for microscopy
- High coherence for speckle and imaging

These features make the ALS an ideal choice for research on both physical and biological systems with characteristic length scales measured in nanometers.



The alternating magnetic fields in an undulator cause the electrons in the accelerator to oscillate about the central trajectory, thereby generating intense radiation in a narrow cone in the forward direction.



To serve a broad spectrum of applications, beamlines at the ALS make use of four types of light sources. Undulator beamlines are the brightest but are limited to lower photon energies (<2 keV). Wiggler beamlines from straight sections and superconducting bendmagnet (superbend) beamlines from curved arcs cover the widest spectral range with intense broadband radiation. Bend-magnet beamlines also emit broadband radiation, but it is less intense than that from superbends.

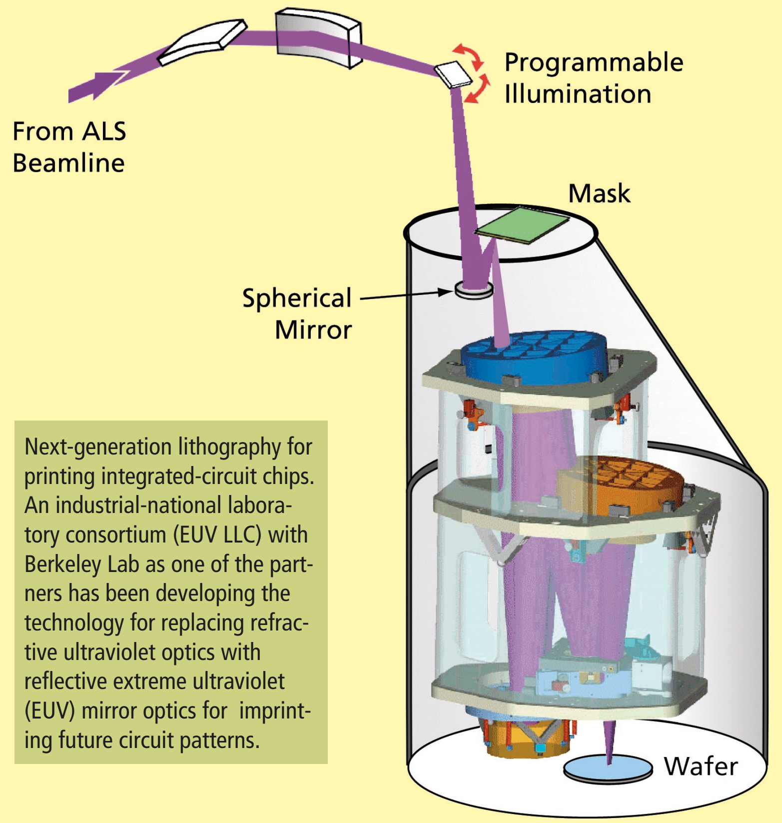
nanotechnology

The investment in nanoscience carries the expectation that there will ultimately be a payoff in the form of new nanotechnologies. At the ALS, this process has already begun with critical contributions to the development of extreme ultraviolet (EUV) lithography.

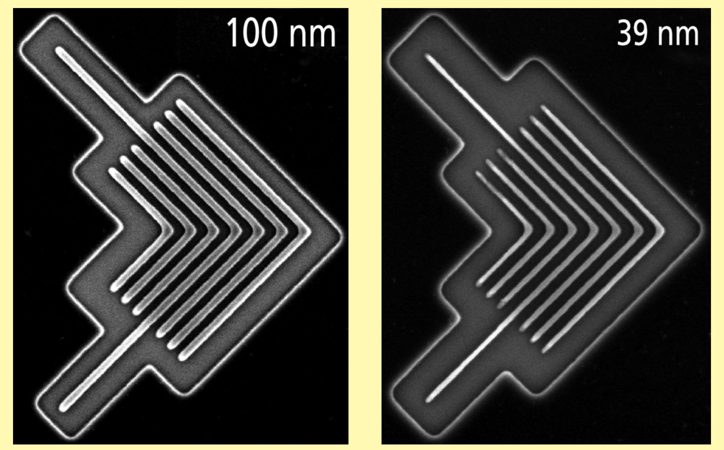
The density of circuit elements on microchips has doubled roughly every 18 months for more than 30 years, resulting in ever smaller, faster, and cheaper computers. The traditional technique for printing circuit patterns, optical lithography based on refractive optics (lenses), cannot continue indefinitely on this course. Today's leading candidate for a successor, known as EUV lithography, relies on reflective optics (mirrors) to image patterns from masks onto the surface of a silicon wafer that will ultimately be diced into microchips.

Metrology beamlines for interferometry, reflectometry, and mask inspection built and operated at the ALS by Berkeley Lab's Center for X-Ray Optics (CXRO) have been instrumental in a 5-year, $250-million industry–national laboratory effort to bring EUV lithography to the commercial stage.

The first computer processors produced with EUV technology beginning around 2007 are expected to be almost ten times faster than today's most powerful chips. But before that day arrives, there is the matter of producing accurate EUV lithography cameras. CXRO researchers have verified that the optics fabricated for a prototype camera are indeed on the path to the required performance by adding small-field printing capabilities to their interferometer on ALS Beamline 12.0.1 and using the optics to print actual test patterns with ultrathin line widths.



Next-generation lithography for printing integrated-circuit chips. An industrial-national laboratory consortium (EUV LLC) with Berkeley Lab as one of the partners has been developing the technology for replacing refractive ultraviolet optics with reflective extreme ultraviolet (EUV) mirror optics for imprinting future circuit patterns.



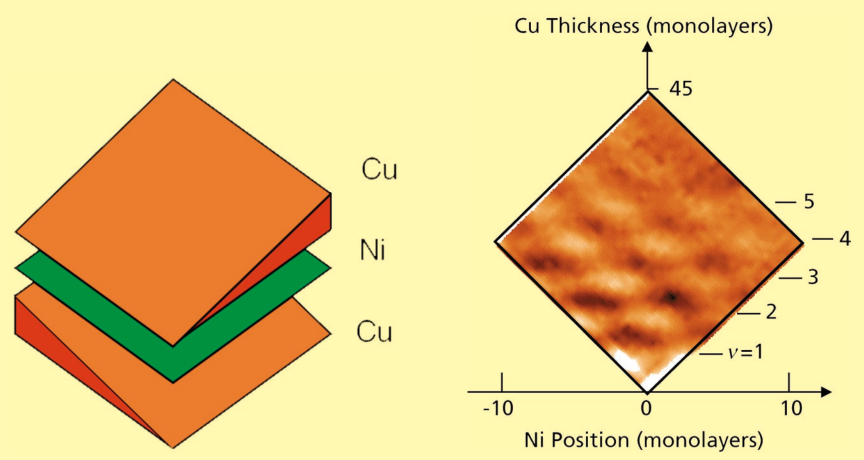
Exposures by the CXRO team have achieved the design performance of 100-nm feature sizes in a standard pattern. With the use of resolution-enhancement techniques, the team was able to print line widths down to 39 nm. Courtesy of P. Naulleau and K. Goldberg, Berkeley Lab.

quantum confinement

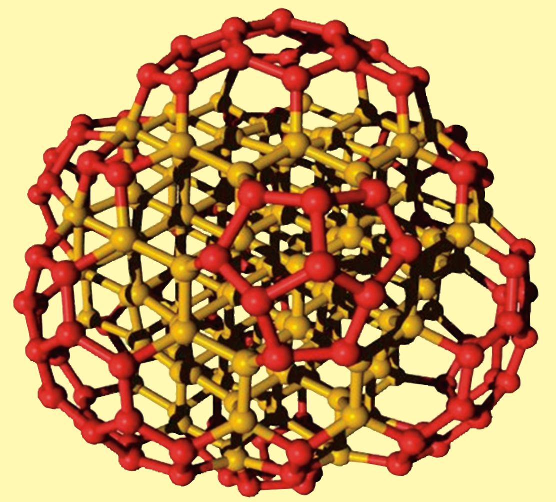
Quantum size effects are the most commonly known processes that affect nanostructures. When at least one dimension of a solid sample becomes comparable to the electron de Broglie wavelength, new properties appear.

The ALS offers a range of spectroscopic techniques for the study of electronic properties and atomic structure of nanosystems. With angle-resolved photoemission spectroscopy (ARPES), it is possible to map out the energy–momentum, E(k), dispersion relations for electronic states. The occurrences of electron standing waves in nanometer-thick and subnanometer films have been investigated in this way. With the use of double-wedge samples, it has proved possible to measure the effect of tunneling between layers and to detect the envelope function of quantum-well states.

The combination of x-ray absorption spectroscopy (XAS) and x-ray emission spectroscopy (XES) reveals the fundamental bandgap in semiconducting nanoparticles, with the former displaying the conduction band minimum and the latter displaying the valence band maximum. More powerfully, these spectroscopic techniques reveal the density of states around the bandgap, which is often a sensitive fingerprint of the bonding configuration. This approach has recently been applied to the study of nanodiamonds. With evidence obtained from XAS and XES data near the carbon K edge in combination with theoretical modeling, the scientists proposed that the nanodiamonds under study are actually "buckydiamonds" that have a diamond core (yellow in the illustration) with a fullerene coating (red).



Intensity of photoemission from the Fermi level in a double-wedge-shaped sample. Vertically, the electron standing waves are characterized by the quantum number ν. Horizontally, the envelope modulation is revealed as a nickel probe layer passes through the quantum well. Courtesy of Z. Qiu, University of California, Berkeley.



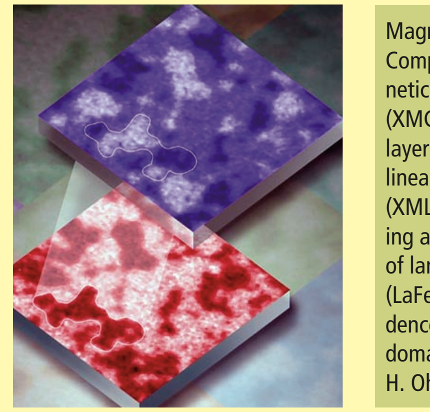
Diamond sports a new coat. As the particle size decreases, the surface of diamond nanoparticles takes on the characteristic soccer-ball structure of fullerenes (buckyballs). Courtesy of L. Terminello, Lawrence Livermore National Laboratory.

nanomagnetism

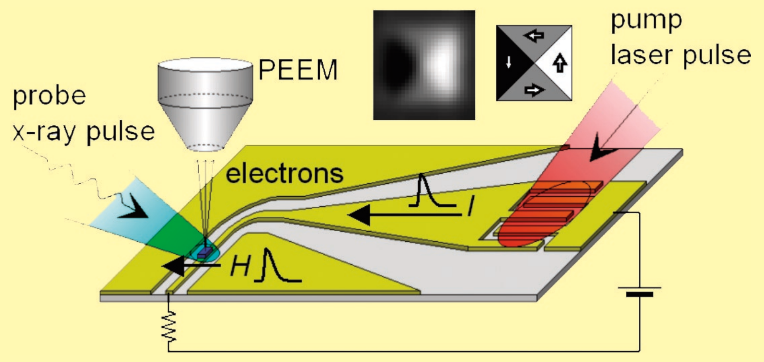
Research frontiers in nanomagnetism concern behavior at interfaces between nanolayers and behavior of domain nanostructures. High spatial resolution to study nanostructures and ultrafast methods to study dynamics are key requirements.

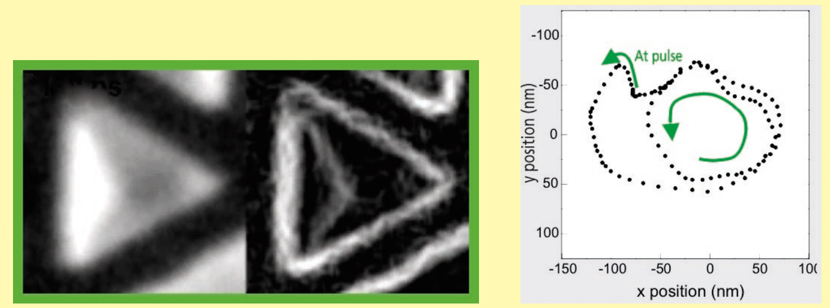
The present photoemission electron microscope at the ALS (PEEM2) has a spatial resolution (30–50 nanometers) well matched to magnetism problems. Moreover, the ALS is optimized for the soft x-ray region, which contains the important core-level L edges of the elemental ferromagnets iron, cobalt, and nickel. Contrast is provided through x-ray magnetic circular dichroism (XMCD) for ferromagnetic domains and x-ray linear magnetic dichroism (XMLD) for antiferromagnetic domains. The next-generation system (PEEM3) presently under construction should reach a spatial resolution of 5 nm.

For magnetic memory, switching speed is as important as storage capacity. At the ALS, the duration of the x-ray pulses determines the temporal resolution, which turns out to be comparable to the magnetic precession period (40 picoseconds in a 1 Tesla field). Scientists have demonstrated the ability to image magnetic vortex dynamics in 20-nanometer thick CoFe patterns excited by a pulsed magnetic field. The position of the vortex core is extracted from the images. Physical quantities such as the vortex speed, the magnetic field at the vortex core, the magnetic damping and the vortex orientation and dimension can be extracted from data and micromagnetic simulations.



Magnetic imaging. Comparison of an x-ray magnetic circular dichroism (XMCD) image of a cobalt layer with an x-ray magnetic linear magnetic dichroism (XMLD) image of an underlying antiferromagnetic layer of lanthanum iron oxide ($LaFeO_3$) shows the correspondence between the magnetic domains in each. Courtesy of H. Ohldag et al., SSRL and ALS.





Picosecond dynamics at nanometer resolution—the response of the magnetization in 20-nm-thick CoFe patterns after excitation by in-plane magnetic field pulses (~15 mT). The vortices perform 1–2 rotations during each 8-ns period between pulses, depending on their size. Courtesy of A. Scholl et al., ALS.

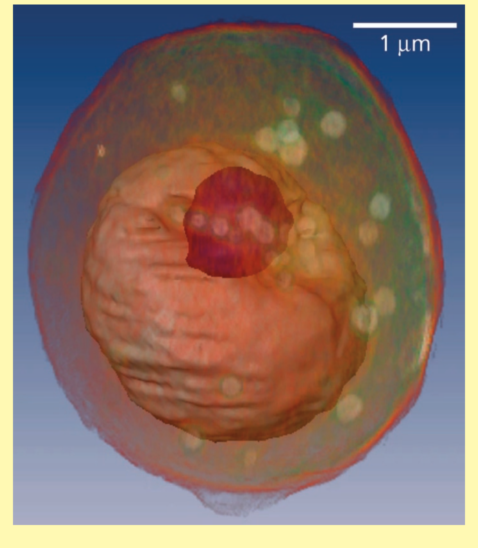
soft matter

An important area of nanoscience is the small-scale interaction between hard matter and soft matter, broadly defined to include proteins, lipids, carbohydrates, nucleic acids, and biological molecular systems.

The soft x-ray region serviced by the ALS contains the core-level K edges of the first-row elements, in particular carbon and oxygen. The region between 300 eV and 500 eV is known as the "water window" because carbon (organic material) is absorbing and oxygen (water) is transparent, thereby providing a contrast mechanism for x-ray microscopy. A spectacular demonstration of this capability is provided by recent tomography studies of biological cells.

Another contrast mechanism derives from the fine structure in the absorption spectra of organic matter near the carbon K edge. Such spectra constitute molecular fingerprints of the various organic species present and have been used with considerable success in the study of polymer blends of importance in the petrochemical industry.

Techniques, such as speckle, that exploit the strong coherence of undulator radiation are under active development at the ALS. The prospect of lensless imaging is exciting. It is known theoretically that the "phase problem" associated with reconstructing real-space images from intensity data is surmountable, so that a three-dimensional object can be reconstructed from the measured speckle diffraction pattern. Recent experiments support this prediction, and it is anticipated that an ultimate spatial resolution of 2 nm for hard matter and 5 nm for soft matter will be achieved.



Tomographic reconstruction of *Saccharomyces cerevisiae* (yeast). Courtesy of C. Larabell, University of California, San Francisco, and Berkeley Lab

Characterizing the composition and topography of annealed, cast, polymer-blend films of polystyrene and polymethylmethacrylate by atomic force microcopy (top) and scanning transmission x-ray microscopy (STXM, bottom). The images of (a) "nano-onion," (b) nanotube, and (c) clay, respectively, show that the high-aspect-ratio nanotube and clay are better at compatibilizing the polymer blend (i.e. keeping domain sizes small). The shape of the corresponding nanoparticles are shown in the insets on the top. The composition maps of the as-cast films are shown in the insets of the STXM images. Courtesy of Wenhua Zhang, Stony Brook University, Harald Ade, North Carolina State University, et al.