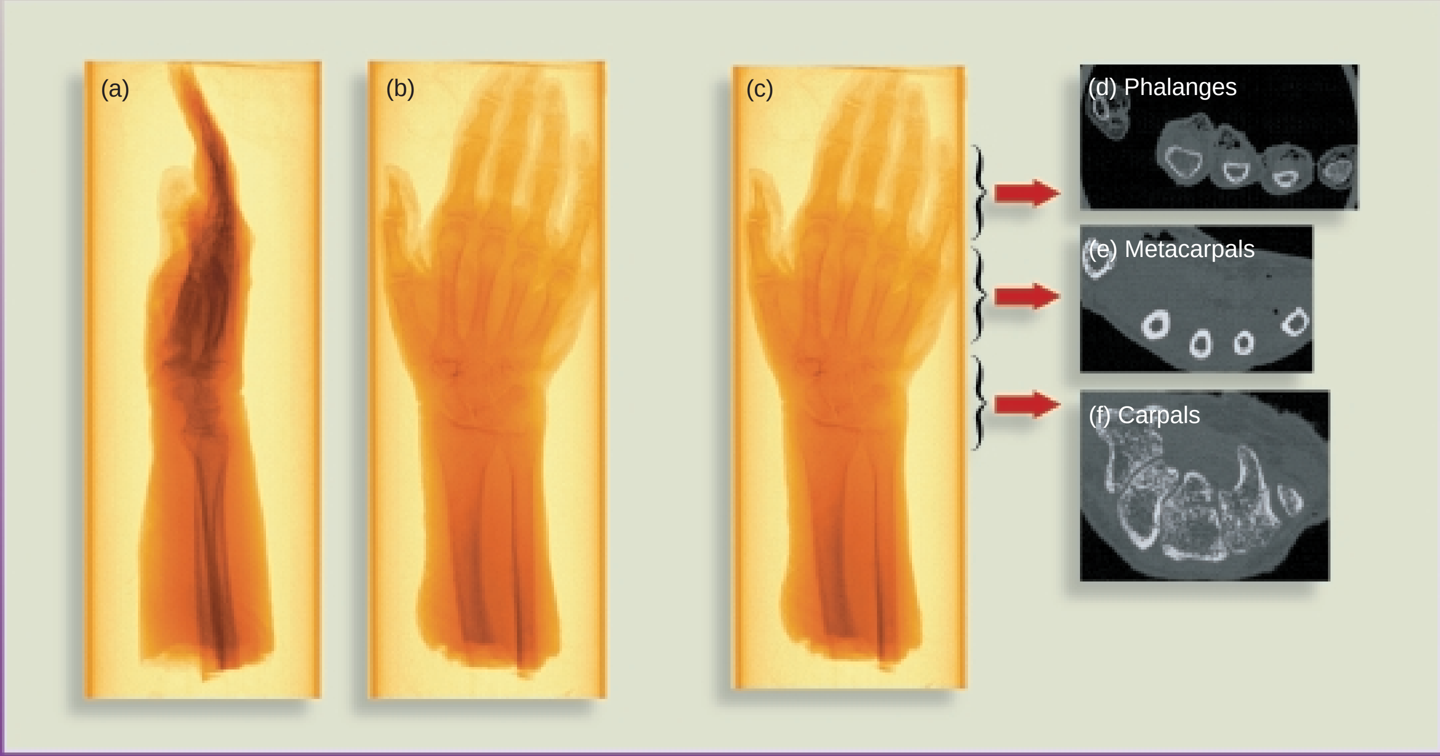
Looking into the Shadow World

THE x-ray image of your daughter's broken arm is really a picture of shadows. If the image is caught on film, dense material like bone will appear lighter because it absorbs more of the x rays than organs or soft tissue. The x ray, or radiograph, easily reveals the broken bone, showing where it needs to be reset.

To obtain the image, the technician places your daughter's arm between the radiation source (x-ray machine) and a detector, which may be film or a digital device. The end result is that three dimensions are compressed to produce a two-dimensional image of your daughter's arm. There will be a bit of blur, but the image meets the doctor's needs just fine.

Computed tomography (CT) takes the radiography process several steps further. A tomograph, whether made for a medical, industrial, or scientific application, starts out as radiographic views—as many as 1,000 of them—taken around a given plane. The measurements in those two-dimensional radiographic projections are mathematically reconstructed into a three-dimensional volume of data. When the reconstruction is complete, doctors or researchers can view individual cross-sectional planes of the object with all other planes eliminated.

Medical radiographs and tomographs are concerned with contrast—the degree of difference between dark and light in images—as well as the shape and location of bone, internal organs, tumors, and so on. But many industrial applications and the National Nuclear Security Administration's Stockpile Stewardship Program—to preserve the reliability and safety of nuclear weapons—require more than contrast and geometry. Many stockpile stewardship applications require reconstructed tomographs that researchers can use to determine the density of an object and accurately identify minute voids and other changes. The data produced by current radiographic methods and tomographic reconstruction techniques have just not been good enough to meet such requirements.

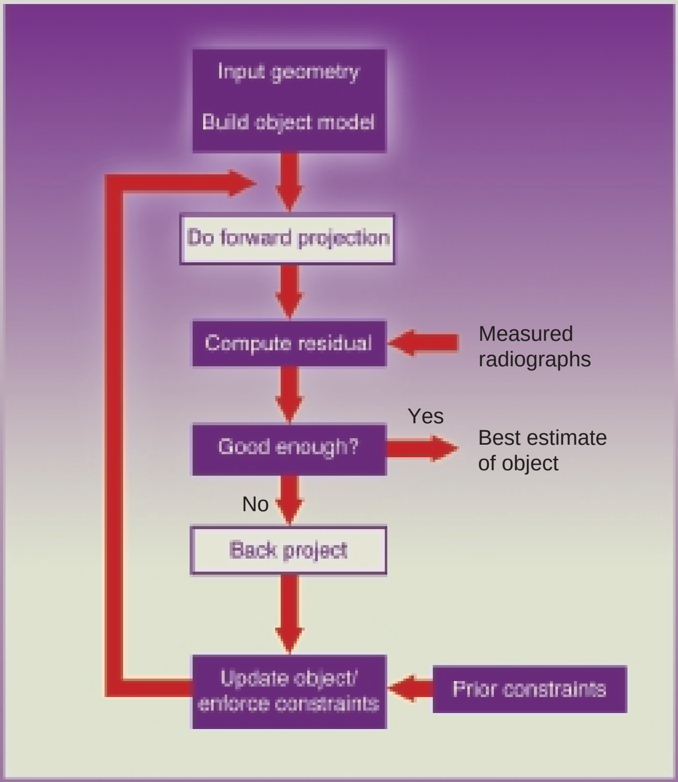


(a), (b) Radiographs of a woman's hand. Because radiographs compress three dimensions into two, in (a) it is possible that the woman has just two fingers and not five. But (b) shows that she indeed has five fingers, although it provides no information on her hand's internal workings. (c) One of many radiographs taken of the same hand as part of a tomographic scan. (d), (e), and (f) Cross-sectional images of the hand that are only possible with three-dimensional computed tomography.

For useful tomographic reconstructions, researchers must be able to model and simulate the radiography process to provide good data for the reconstructions. Right now, researchers can simulate two-dimensional radiographs for Livermore applications to about a 10-percent accuracy. Future applications will require an accuracy of about 1 percent, that is, differences in image contrast as small as 1 percent should be perceptible. Tomographic reconstruction is also problematic. The best reconstruction software available today cannot calculate the blurring effects caused by the detector and the radiation source; the software accounts for blurring after the fact, through a deconvolution process. X rays come in a spectrum of energies that attenuate differently in different materials, but current reconstruction methods ignore the differences. Noise, artifacts from x-ray scatter, and the spectrum of x rays from the source further diminish tomographic results. With current limitations, the accuracy of computed tomography is typically about 15 percent.

To attain 1-percent accuracy, Livermore's Center for Nondestructive Characterization set up a team headed by physicist Harry Martz to achieve that goal. The team's first order of business was to improve the radiographic imaging process to get the best data possible for tomographic reconstructions. Martz and team members improved the data acquisition system of Livermore's 9-megaelectronvolt linear accelerator, changing it to better account for radiation scattering and blur from the radiation source. Equally important, they modeled the detector using a Monte Carlo code so they would understand detector response and be able to reduce or eliminate blur caused by the detector.

Then they began to develop software that incorporates the real effects of blur, attenuation differences, noise, and artifacts at the front end of a reconstruction to achieve the tomographic accuracy that Livermore needs.



Flowchart of the HADES–CCG tomographic reconstruction process. Items with a purple background are operations that CCG performs. Items with a gray background are operations that HADES performs. All results are passed between the codes using shared files.

Challenges for Software

"Even with a pure material, we cannot get a perfect radiograph or tomographic reconstruction," says Martz. "So it is hardly surprising that we cannot get high-quality reconstructions of objects made of several different kinds of materials."

One challenge is that for some tomographic reconstructions, only a limited amount of data is available, sometimes as few as 4 to 20 radiographic views. "The manner in which we do tomographic reconstruction is different with a smaller number of views," says Morry Aufderheide, creator of HADES, a ray-tracing code for simulating the radiographic projections. Martz, Aufderheide, and the rest of the team members are working on coupling HADES with an optimization algorithm to perform tomographic reconstruction with a limited number of radiographic views.

Aufderheide named HADES for the Greek underworld, where the dead were sometimes referred to as shadows. HADES can accurately simulate the radiographic process—from radiation source to image formation and detection. With the recent huge increase in computing power, HADES can include radiographic physics—blur from both the detector and the radiation source, differing energy attenuations, and noise—in its calculations. HADES incorporates detailed models of various radiation sources and detectors to understand blur, noise, and scattering.

HADES can also operate with an optimization algorithm known as constrained conjugate gradient (CCG), developed by Livermore engineer Dennis Goodman several years ago. CCG has been used for adaptive optics systems on large telescopes and was first applied to tomographic reconstruction a few years ago. Goodman took a standard conjugate gradient code and modified it so that a researcher can specify constraints. For example, in a tomographic reconstruction, totally opaque portions of an object can be ignored. The code also performs well with limited data sets.

Reconstructing a CT image entails solving a large matrix equation that relates simulations of the object being reconstructed to the many radiographic projections taken of it. First, CCG creates a model of the object, which may be based on some known data or may simply be all zeros. HADES then simulates a radiograph of this modeled object. The CCG search algorithm compares the simulated radiograph to an actual measured radiographic projection, seeking what is known as a maximum likelihood solution. This search continues iteratively, efficiently modifying the model using conjugate gradients and user-specified constraints, until the difference between the actual measured radiographs and the simulated or calculated radiographs is satisfactorily small. This reconstruction technique also minimizes, but does not eliminate, the possibility of introducing spurious features.

CCG and HADES are both complex codes, created and maintained separately. Attempting to actually merge the two codes would be time-consuming and inefficient. Merging them could also make maintenance and upgrades to either code more difficult. The most effective solution so far has been to run them in parallel and exchange information between them in shared files.

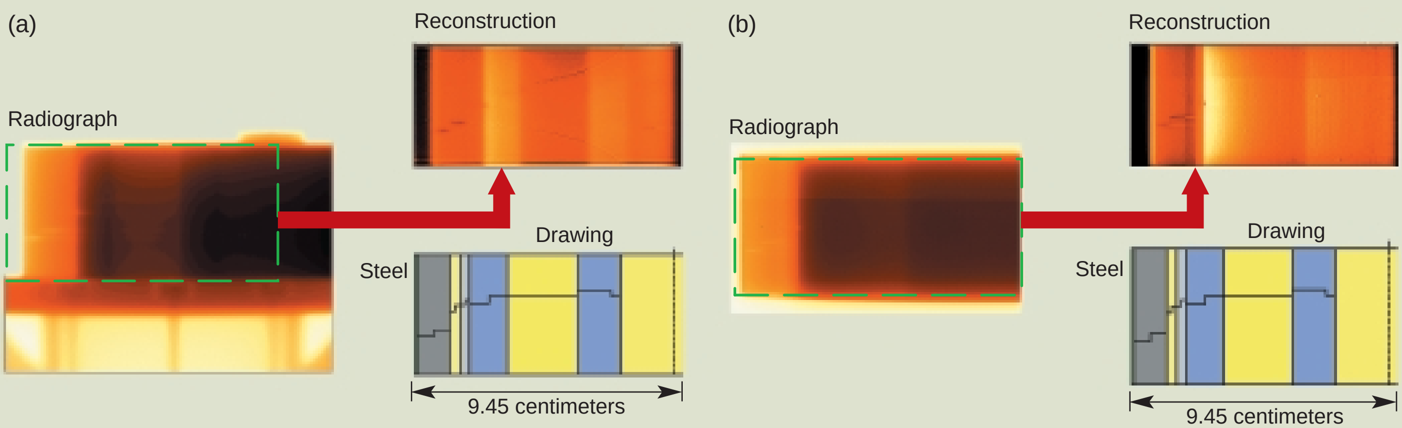
Experiments Validate Codes

Martz and his team have performed several experiments to test their new capability in experimental and simulation radiography as well as the new CT image reconstruction technique. They used a variety of test objects because each one tests a different aspect of the simulation and tomographic reconstruction process.

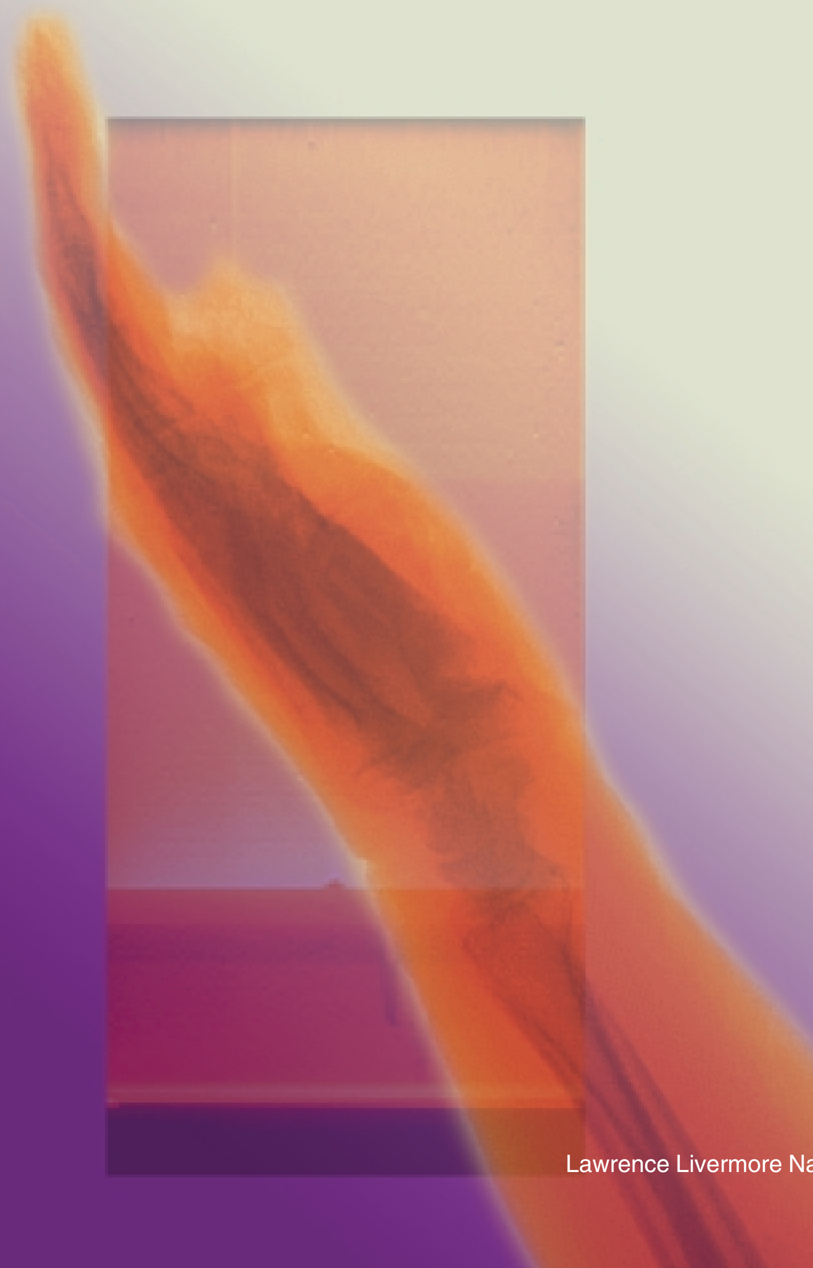
In one experiment, they imaged two copper step wedges to quantify their improvements to the radiography experimental and simulation process. The experiment showed that new collimators have indeed reduced scattering at the detector. It also showed a better agreement with simulations by accounting for the response of the digital amorphous-silicon detector, which they had modeled with a Monte Carlo code and incorporated into HADES. Of the experiments with these test objects, fabricated of a single pure material, a pleased Martz says, “We got between 1- and 2-percent radiographic accuracy.”

Continuing the evaluation of the new radiography modeling process, the team tested a more complicated object, a disk made of eight layers of five different materials. The first experiment used neutron radiography (see *S&TR*, May 2001, pp. 4–13) and was performed at the Ohio University Accelerator Laboratory, one of the few neutron sources in the country. The team took 64 radiographic images of the disk. One radiographic image and a two-dimensional reconstruction of its radiographic projection are shown in the top figure on p. 24. The quality of the reconstruction is remarkable, considering that it was made with just one rather than all or even several of the 64 images.

Top view of eight-layer test object.



(a) Reconstruction of eight-layer test object with neutrons and (b) reconstruction of eight-layer test object with x rays.



When few projections are available, the quality of the input data must be as high as possible. The high quality of the CT reconstruction is also a measure of the effectiveness of the HADES-CCG reconstruction process.

When the same disk was tested using Livermore's 9-megaelectronvolt x-ray source, the results were quite different, as shown in the figure above. The x rays could not penetrate as far as the neutrons, just to the fourth or fifth layer of the disk, producing only noise beneath those layers. However, in the layers they did penetrate, the x rays provided better contrast than neutron imaging. Neutron and x-ray imaging complement each other to provide more complete tomographic reconstructions.

The team has just begun working on full three-dimensional tomographic reconstructions of objects made from multiple materials. This most complex version of the tomographic process is what Livermore really needs for stockpile stewardship and other projects. It's a long way from the radiograph of your daughter's arm.

—Katie Walter

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