A LASTING

IMPACT

DART, Livermore, and Planetary Defense

TRAVELING at about 6 kilometers per second (km/s) and weighing around 600 kilograms (kg), the Double Asteroid Redirection Test (DART) spacecraft slammed into Dimorphos, the secondary asteroid of the Didymos binary system, 11 million km from Earth. The impact, on September 26, 2022, successfully transferred enough energy to change Dimorphos's orbit—a first demonstration of a planetary-defense technology called "kinetic impact." DART represented years of international collaboration, and a remarkable application of Lawrence Livermore's signature scientific and technological expertise.

> "This has been a very exciting project to work on. We're doing research that not only protects the nation but the entire planet."
>
> —*Katie Kumamoto*

While asteroid deflection sounds like something out of science fiction, the potential threat of a catastrophic asteroid impact and the abundance of near-Earth objects (NEOs) has precipitated decades of scientific exploration into planetary defense. Since the 1990s, Lawrence Livermore scientists and engineers have supported NASA and other government agencies by evaluating ways to prevent or mitigate a potential asteroid impact. (See *S&TR*, December 2009, pp. 12–14.) In 2011, Paul Miller, deputy division leader for Livermore's Design Physics Division, successfully proposed a Laboratory Directed Research and Development (LDRD) project to model the deflection and disruption of asteroids by both kinetic impact and nuclear explosives. "By understanding available threat-mitigation options and outcomes, as one of the few institutions with the simulation capabilities and nuclear effects knowledge, we knew we could improve confidence in the effectiveness of a nuclear response and provide decision makers with options to address a potential threat," says Miller. At the end of the three-year LDRD project, the Laboratory received approval from the National Nuclear Security

Administration (NNSA) headquarters to continue the work with programmatic funding. The team then researched deflecting NEOs by impacting a dense, solid asteroid at the apex of its orbit or by dispersing a rubble-pile asteroid—an agglomerate of boulders, rocks, and dust. By applying uncertainty quantification techniques, hydrodynamics codes, and advanced algorithms, the team modeled the nuclear-blast strategy, including the effect of the target's material composition and the hypothetical debris path. (See *S&TR*, December 2013, pp. 12–15.)

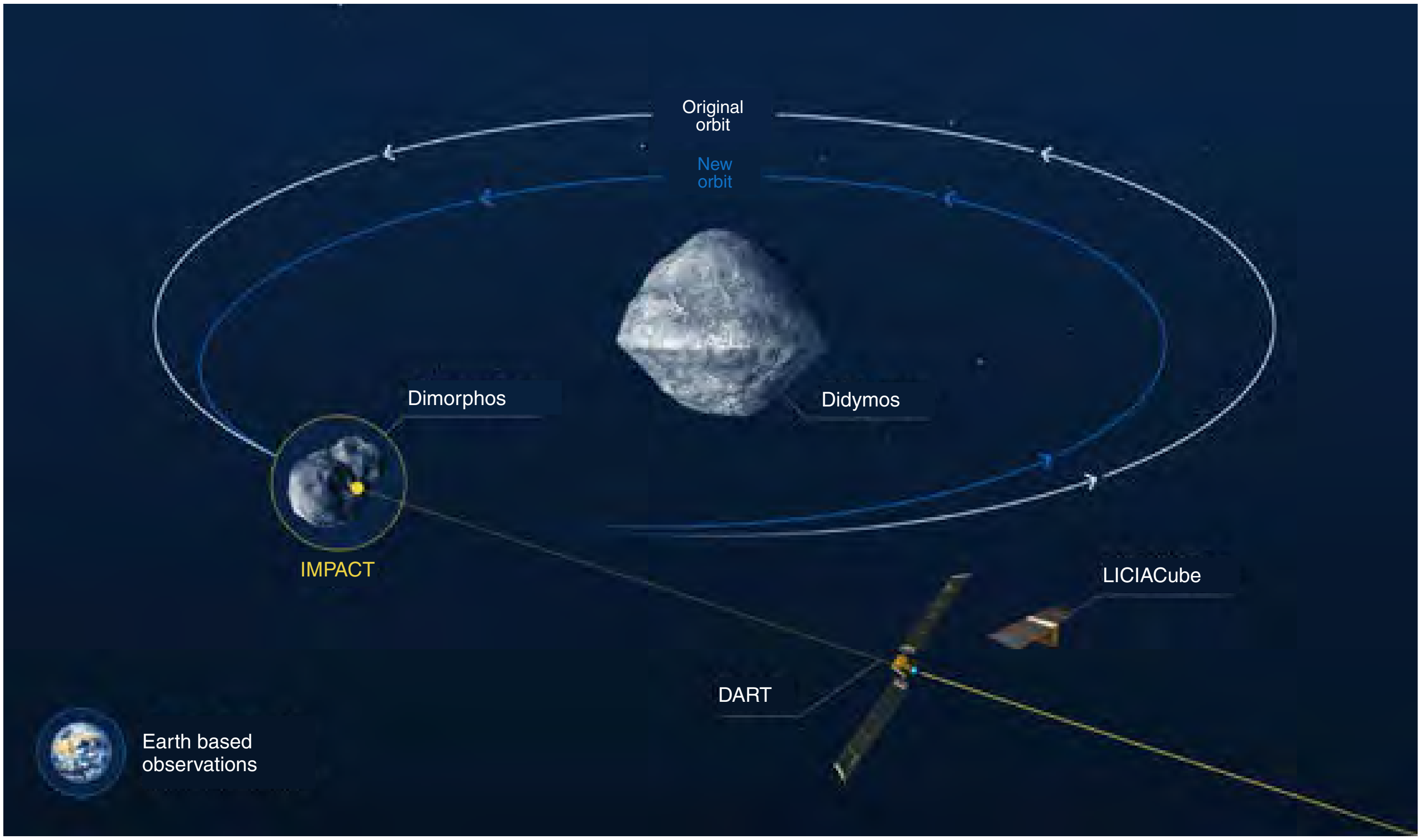
Colliding with Unknowns

On February 15, 2013, an asteroid about 20 meters in diameter moving at 19 km/s, entered the Earth's atmosphere and exploded above Chelyabinsk, Russia, with 20 to 30 times more power than the atomic bomb dropped on Hiroshima, Japan. The explosion broke windows in six Russian cities, and collapsed several buildings, injuring 1,500 people. It also catalyzed the creation of DART—a mission to change the trajectory of an actual asteroid by kinetic impact—a test collision between a spacecraft and an asteroid about 160 meters in diameter but not on an orbit threatening to Earth.

Funded by NASA's Planetary Defense Coordination Office and led by the Johns Hopkins University Applied Physics Laboratory (JHUAPL), DART engaged the international planetary science community, rallying worldwide cooperation around the issue of planetary defense. Around the same time, Miller led a related project, the Planetary Defense Team NA-10 Project, which received an NNSA Award of Excellence. He also contributed to the National Near-Earth Object Preparedness Strategy as a member of the Interagency Working Group for Detecting and Mitigating the Impact of Earth-bound Near-Earth Objects of the National Science and Technology Council.

Lawrence Livermore's role in DART became formalized as a Strategic

The Double Asteroid Redirection Test (DART) included observation from multiple vantage points: from Earth and, before impact, from the DART spacecraft, which also deployed the Light Italian Cubesat for Imaging Asteroids (LICIACube) to record the kinetic impact that altered Dimorphos's orbit around Didymos. (Image courtesy of Johns Hopkins University Applied Physics Laboratory (JHUAPL).)

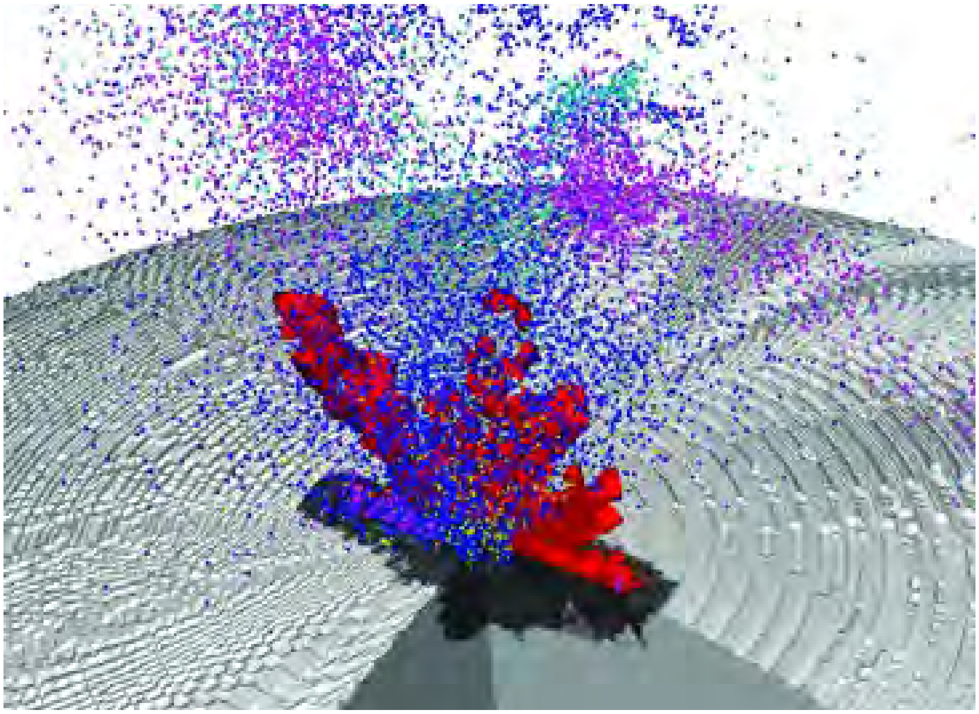


Partnership Project in 2016, joining a mission that has support from several NASA centers—the Jet Propulsion Laboratory, Goddard Space Flight Center, Johnson Space Center, Glenn Research Center, and Langley Research Center—and international partners such as the European Space Agency, the Italian Space Agency, and the Japan Aerospace Exploration Agency. "The DART mission is important because it is the first test of kinetic deflection of an asteroid providing validation data for our computer modeling of the amount of deflection," says Miller. "Validation is important because in the event of a future need to deflect an asteroid, the models will be utilized to assess the adequacy of any planned deflection efforts."

The concept of kinetic impact seems relatively simple. The collision delivers a significant momentum impulse to the asteroid, but the overall effect of the spacecraft collision on Dimorphos was not assured. Even after impact, the asteroid's mass remains unknown; one of many DART unknowns addressed by Livermore modeling.

The effectiveness of the kinetic nudge depends on more factors than the masses and velocities of the spacecraft and its target. The materials and other unknown properties of the asteroid also contribute to a momentum multiplier: the escaping crater ejecta. The unknowns about ejecta in DART, and any future kinetic-impact missions, are a reason Lawrence Livermore has a key interdisciplinary role in planetary defense, with scientists and engineers from across the Laboratory exploring the nexus of geology, physics, forensics, and data science.

"I came to the Laboratory to work on planetary defense as a postdoctoral scientist in 2014, and this project continues to attract new scientists who want to work on interdisciplinary problems at the intersection of design physics and urgent national security matters," says Megan Bruck Syal, planetary-defense project lead and a group leader in the Design Physics Division at Livermore.



Ejecta (dots) rise above an asteroid less than 1 second after impact in one of the Lawrence Livermore team's computer simulations, which helped quantify the predicted contribution of ejecta to the post-impact velocity of Dimorphos. The simulations helped researchers interpret DART data and are integral to planning future planetary defense strategies. (Image by Mike Owen; capture by Mark Gartland.)

A Terrific Toolbox

For the DART mission, the Laboratory's planetary defense team focused on modeling DART-like kinetic impacts. "Preparing numerical impact modeling is crucial to making the most out of the DART experiment," says Livermore design physicist Mike Owen. "We needed to investigate the effects of possible target properties, such as material strength and porosity." The Laboratory applied its impact-modeling expertise using Spheral, a mesh-free (particle-based) code for evaluating impact, damage, and fragmentation of materials undergoing extreme shocks and deformation. "I started developing the current version, Spheral++, in 1998 as a side project and learning exercise," says Owen. "We needed a code that was very flexible to test new ideas for discretizing hydrodynamics and other sorts of physics on mesh-free approaches, both to try new methods and to accommodate a wide variety of computing systems."

Spheral deploys multiple kinds of mesh-free discretizations, such as adaptive smoothed-particle hydrodynamics, which models solid and fluid dynamics including strength, elastic–plastic flow, shock physics, damage evolution, and fragmentation according to the Lagrangian evolution equations. "Spheral allows researchers to accurately follow materials through large deformations and topological changes, at the cost of increased complexity and higher computational expense, compared with ordinary meshed fluid-flow discretizations. Spheral also works with supercomputer clusters, so we can tackle 3D challenges like the DART impact and get results in days instead of weeks," says Owen.

Initially released in 1998 and rereleased in 2012 on Github as the open source Spheral++, the code provides a steerable, parallel environment for performing coupled hydrodynamic and gravitational numerical simulations using particle-based methods that can be adapted or extended by users by writing new physics packages in Python. "These realistic models with all the potential variables are very challenging to set up and run. We had to develop new capabilities in our modeling tools for DART," Owen adds.

Jason Pearl, a design physicist at the Laboratory, developed a new solver in Spheral, which improved ability to model highly heterogeneous materials. This capability came in handy, as Dimorphos turned out to be a rubble pile with significant local variations in bulk density and porosity. "Spheral's modular nature allows for the rapid development of new capabilities. It's a terrific toolbox," Pearl says. "The new solver leans heavily on many tools that were already present." He also built a discrete element method (DEM) package into Spheral. DEM is useful for simulating the motion of boulders and gravel at low speeds and is a natural extension of Spheral's mesh-free algorithms. Owen has since used the new DEM package to generate more realistic rubble-pile initial conditions for impact simulations.

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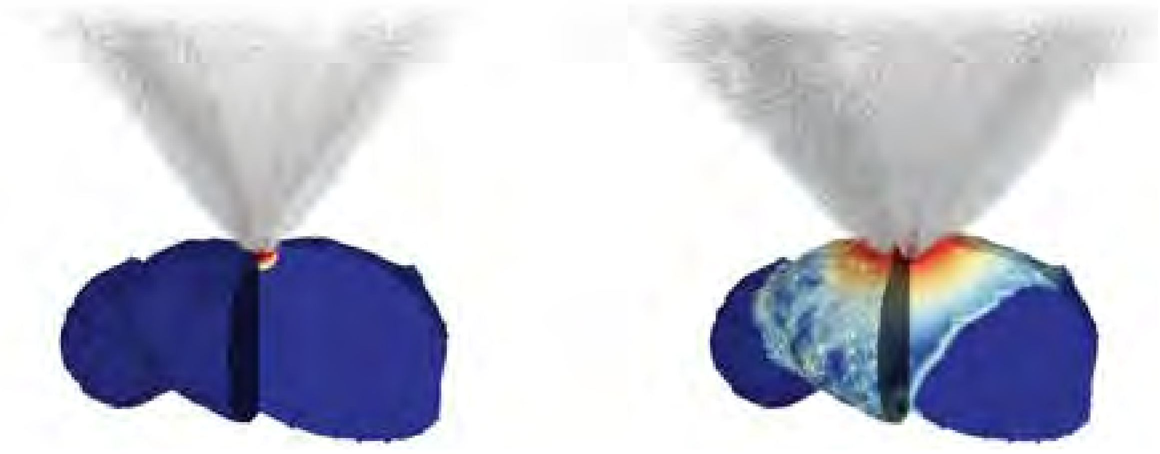
>
> *—Megan Bruck Syal*

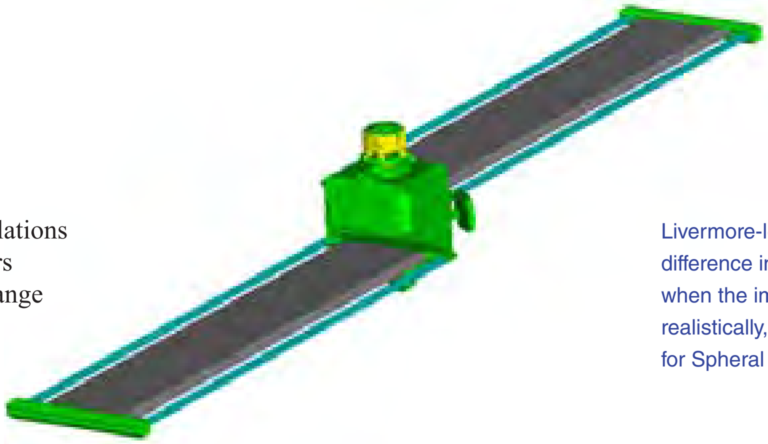
A Detailed Dress Rehearsal

To prepare for the data generated by the DART impact, JHUAPL and Los Alamos National Laboratory (LANL) ran full-impact simulations and gave some of the data—idealized spacecraft and asteroid shape, impact location, and velocity change—to the Lawrence Livermore team but omitted any information about the simulated asteroid's material properties. "Our job was to take this limited data set and reverse-engineer what kind of asteroid would produce this velocity change. This inverse test was a detailed dress rehearsal. We had to figure out how to make the most of the data using the tools we had on-hand to prepare impact modelers to interpret the real DART experimental data after the actual impact," says Cody Raskin, a design physicist and device-reconstruction lead at the Laboratory who works on reverse engineering and nuclear forensics.

Katie Kumamoto, a Livermore geologist and mineral physicist who studies rock deformation, ran 338 Spheral simulations in support of the inverse test for DART. "We know so little about asteroids. Most of the material that we study in laboratories had to survive atmospheric entry and impact, so we are working with a biased sample. How rocks react or deform on Earth is going to be different from how they behave in outer space. Asteroids also include rubble piles with significant macroporosity, and they're not going to behave like a solid boulder," says Kumamoto. Numerous characteristics can affect how an asteroid will react to an impact, including mass, strength, porosity, shape, internal structure, spin state, and equation of state. These aspects were



In Spheral-simulated impacts, the region of deformed material grows slower at near right, in a solid-rock, more porous asteroid (less bulk density). By contrast, at far right, a less porous, weaker (fractured, sedimented) asteroid deforms more and produces more ejecta. Plastic strain is shown increasing from blue to yellow to red. The change in velocity after impact is the same in both scenarios.



Livermore-led studies showed a measurable difference in the amount of predicted ejecta when the impactor spacecraft was modeled more realistically, as in this polyhedral representation for Spheral simulations.

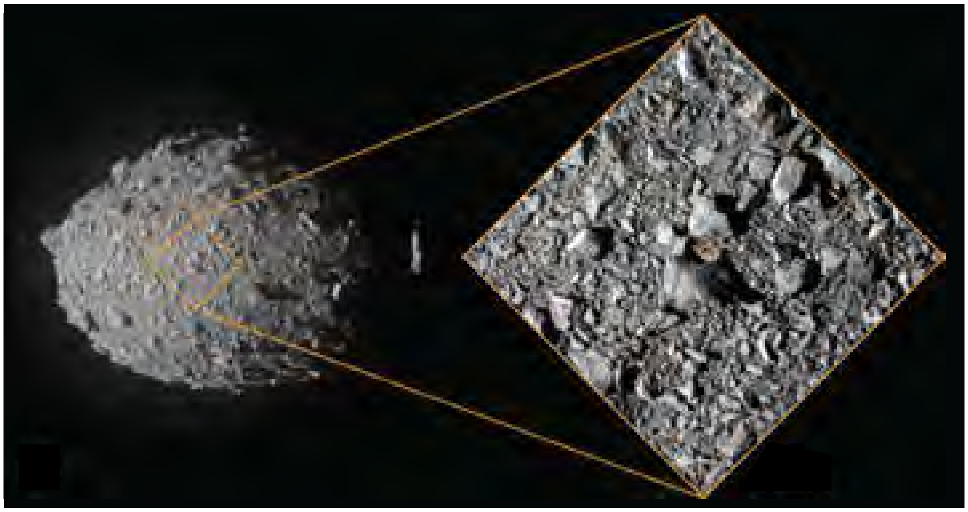
incorporated into the team's simulations to find combinations of parameters that would satisfy the velocity change provided by JHUAPL and LANL. "The goal of our simulations was to constrain the target asteroid's properties as much as possible from this limited data set. We set up the problem, tested it out, and confirmed the results with what we received, so that when we had data from the impact, we could plug those numbers in and have a degree of confidence in the findings," says Kumamoto.

With seven variables describing material properties of the asteroid, the team was working with a large-dimensional space too computationally expensive to process in the limited time available. "To constrain the parameter space, we used a machine-learning decision-tree algorithm to select parameter combinations," says Raskin. In a series of hundreds of simulations with varied asteroid physical properties, the algorithm produced tens of thousands of possible parameter combinations in which impact changed velocity as in the JHUAPL/LANL simulations). "Each output was used to inform and fine tune the next simulation," says Raskin. "Ideally, each time we update the model, it homes in on a more reliable prediction."

In this inverse test, the more porous targets produce a greater change in velocity. Conversely, solid rocks produce smaller changes in velocity. A large part of this relationship to porosity is due to the realistic set up of the model. The target asteroid is modeled in a specified shape and size, but the mass is unknown, as in the DART mission. The porosity therefore has a large effect on the mass and momentum and on the post-impact velocity change. Porosity also affects the amount of ejecta from the impact crater: In more porous targets, more of the material is compacted rather than ejected. After accounting for the parameters and running a battery of simulations, the team correctly predicted the material properties of the JHUAPL/LANL simulation. "In addition to understanding the effects of asteroid material properties, we've also learned that asteroid geometry and impact location may be critical in analyzing disruption risk," says Bruck Syal.

The Spacecraft Itself

The inverse test identified trends across the deflection magnitude and asteroid material parameters as well as the challenges of predicting properties from limited data. "We also wanted to explore accurate representation of the spacecraft in our models," says Owen. "The momentum produced by ejecta is influenced by the spacecraft geometries, in addition to how that impactor interacts with the asteroid's material properties, the angle of impact, and the terrain of the impact site." Previous impact modeling—including for the inverse test—represented the spacecraft as an idealized, uniform aluminum sphere or other highly simplified geometries. The actual DART spacecraft bus, however, was shaped somewhat like a vending machine composed of thin-walled structures, open spaces, and various components, including solar arrays that stretched 20 meters, and presented a very different mass distribution and effective surface area than an idealized sphere. "Ironically, what we know most about the DART mission is the spacecraft itself," says Owen. The team decided to compare high-fidelity computer-aided design (CAD) models of the DART spacecraft including its electronics, tanks, and antennae—all the components most relevant to impact—and three kinds of idealized impactors with the

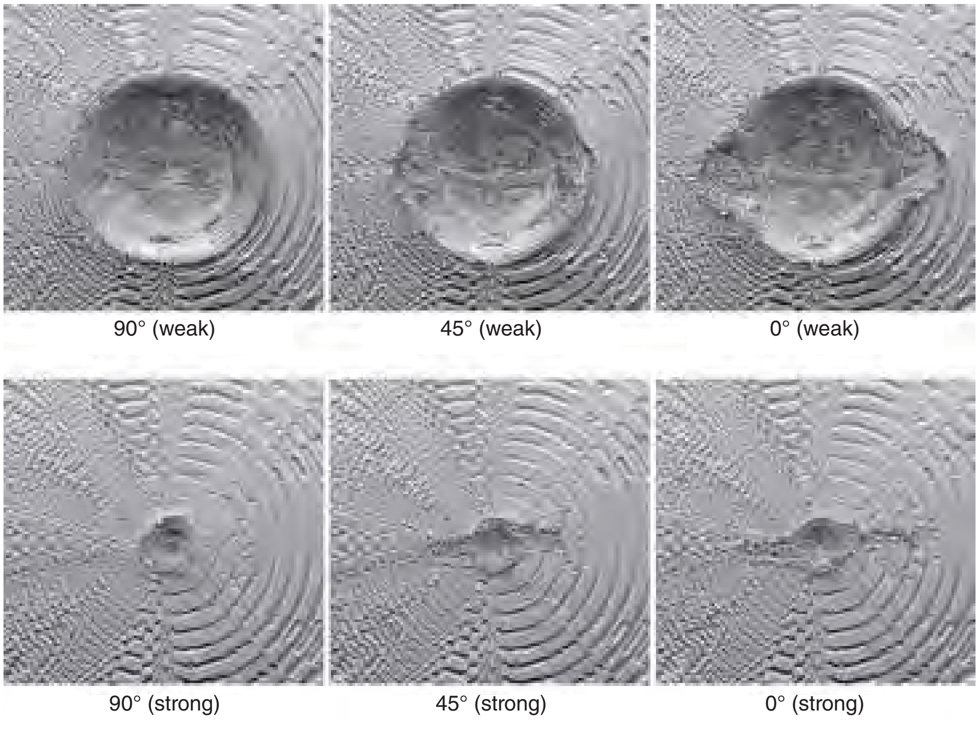


The DART spacecraft's on-board camera showed the rubble-pile appearance of Dimorphos, consistent with weak-asteroid simulations made earlier by Livermore scientists. The close up was two seconds before impact near the yellow circle. (Image courtesy of NASA/JHUAPL.)

same relative mass (535 kg): cylinders of different diameters; a solid, uniform sphere; and a set of three solid spheres composed of a central solid sphere (with a mass equal to the spacecraft bus) and two smaller solid spheres on either side (with the masses of the spacecraft solar arrays). The researchers then ran three kinds of impact simulations using three different codes—Spheral; CTH, a large deformation, strong shock-wave Eulerian adaptive-mesh-refinement physics code developed by Sandia National Laboratories; and iSALE-2D, a mesh-based Eulerian approach—to compare the results across a range of numerical methodologies.

The simulations across all three codes were set at the same velocity, 6.65 km/s, at multiple impact orientations: along the asteroid face (0°); partially along surface, with the full length of the bus and solar arrays impacting across the asteroid surface sideways, (45°); and head-on along an idealized z-axis (90°). Previous spectroscopic observations had suggested that Dimorphos may be composed of silicate, and a uniform porosity was set at 30 percent with two material-strength variables for strong (solid boulder) and for weak (granular or regolith) rock. "Our primary goal was to better understand how these different projectiles produced different results and see what trends, discrepancies, and consistencies the codes revealed," says Owen. "We were also examining the ejecta each model produced: how high it went, how far, how fast, and the size and depth of the resulting crater. These data tell us a lot about the possible deflection velocity of Dimorphos, which, depending on its material properties and the impact site, could have been anything from nothing much to significant." The team found that the difference among the impactors, from a simple, idealized solid sphere to the DART spacecraft, was significant. The three-sphere set, however, produced similar results to the spacecraft, suggesting that the spacecraft acted more like multiple impactors. The models also revealed that the single sphere overestimated ejecta momentum, while cylinder impactors reduced momentum from strong ejecta and increased weak-ejecta momentum.

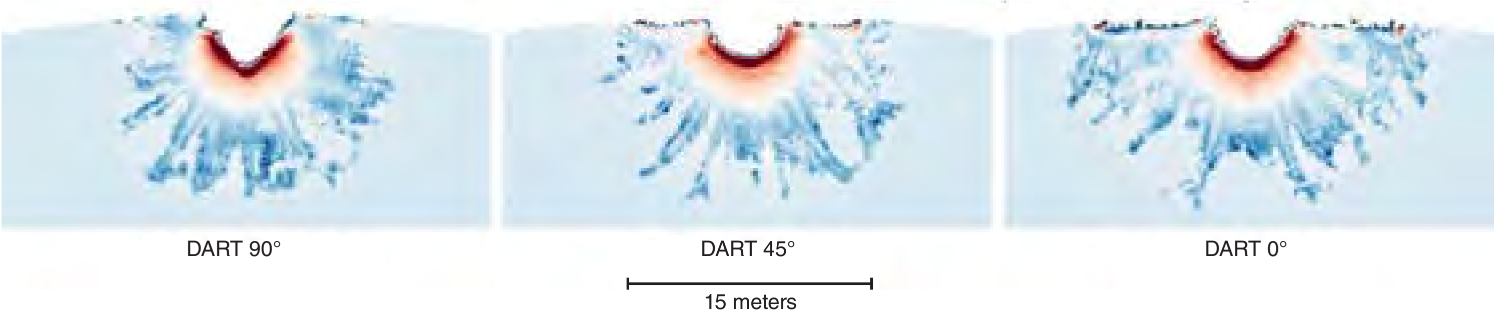
Lawrence Livermore scientists used Spheral code with computer-aided design geometry of the DART spacecraft to simulate the craters made at different impact angles. The top row represents a weak, rubble-like Dimorphos, and the bottom row represents a strong, boulder-like asteroid material in which the imprint of solar panels is etched beside the central crater. (The rings beyond the craters are modeling artifacts.)



A Huge Validation Experiment

As the live feed from the Didymos Reconnaissance and Asteroid Camera for Optical Navigation (DRACO) revealed the rubble-pile surface of Dimorphos seconds before impact in September 2022, team members from Lawrence Livermore's planetary defense project, Bruck Syal, Kumamoto, and Owen, watched in awe with colleagues from JHUAPL, LANL, and NASA. "We had no idea what Dimorphos would look like. All we had were radar observations to detect its presence. But to see its actual shape and texture, this new exotic extraterrestrial object nobody had ever seen before, was thrilling," says Bruck Syal.

Not knowing what Dimorphos looked like was just the beginning. Uncertainty had pervaded preparations for the test—the asteroid's characterization including shape, density, porosity, strength, and structure, as well as how it would respond to the impact—remained a mystery. Within weeks, Earth-based observations confirmed that the DART spacecraft had changed Dimorphos's orbit. "In truth, if we ever identified an asteroid headed straight for Earth in 10 years' time, if we could nudge it just one centimeter per second, that would be enough to change its orbital trajectory so it would miss the Earth. It sounds small, but it adds up over time. Testing this approach with the Didymos binary of Dimorphos gives us a measurable benchmark," says Bruck Syal.



Crater cross sections from Spheral simulations show that strong, boulder-like asteroids are resistant to compaction. The impact of a DART-like spacecraft leaves a shallow, dense layer (red) with fractures below (blue, lower density). DART data suggest that Dimorphos's material was weaker, which would produce a larger crater.

Two weeks after the impact, Earth- and space-based telescopes began delivering data. The LICIACube (Light Italian Cubesat for Imaging Asteroids), a small satellite deployed from the DART spacecraft 15 days before impact, flew about 55 km behind DART prior to impact and then recorded images of the ejecta cone, which provided additional information about the subsurface material properties of Dimorphos. In early 2027, the European Space Agency's Hera mission will measure the mass of Dimorphos, image the crater created by the DART impact, and provide an additional data set that will reveal even more information about its material properties that will inform future missions and validate contemporary simulations.

"DART is a huge validation experiment. It allows us to reconcile our computer simulations with the behavior of a real asteroid to find out how accurate they are. We get to find out how well we model," says Bruck Syal. "The more information we have on likely impact scenarios prior to a deflection, the more successful it's likely to be." The team from Lawrence Livermore helped push the envelope of modeling the DART impact deflection with tremendous success. The impact showed a "momentum enhancement factor" measured at 3.6, meaning that ejecta multiplied the momentum effect of the kinetic impact far beyond simply imparting the momentum of the spacecraft to the asteroid, more than tripling the result. This result is well within the modeled scenarios that put the momentum-enhancement factor in a range from 1 to 6.

DART has also opened new research areas for the Laboratory to explore with the development and application of new capabilities. "This has been a very exciting project to work on. We're doing research that not only protects the nation but the entire planet. We sent a spacecraft into outer space, and it moved a rock. That's incredible," says Kumamoto. "As much as we have learned from DART, there's so much more to go." In 2022, before the DART impact, the National Academies of Sciences, Engineering, and Medicine released a decadal plan for planetary sciences that emphasizes a need for continued work in the areas of expertise Livermore has contributed to DART, such as modeling impact and characterizing asteroid composition.

"It's important that people know that Dimorphos is not a threat. We've taken a big step towards figuring out what to do if an asteroid ever does threaten the Earth," says Pearl. "We have a proof of concept that we can do this. It's pretty exciting."

—Genevieve Sexton

Mike Owen, Katie Kumamoto, and Megan Bruck Syal at the DART Impact Event at Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland, September 26, 2022. (Photo credit: Mike Owen.)

Key Words: asteroid, deflection, Didymos, Dimorphos, Double Asteroid Redirection Test (DART), Johns Hopkins University Applied Physics Laboratory (JHUAPL), kinetic impact, Laboratory Directed Research and Development (LDRD) Program, near-Earth object (NEO), planetary defense, predictive modeling, Spheral.

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