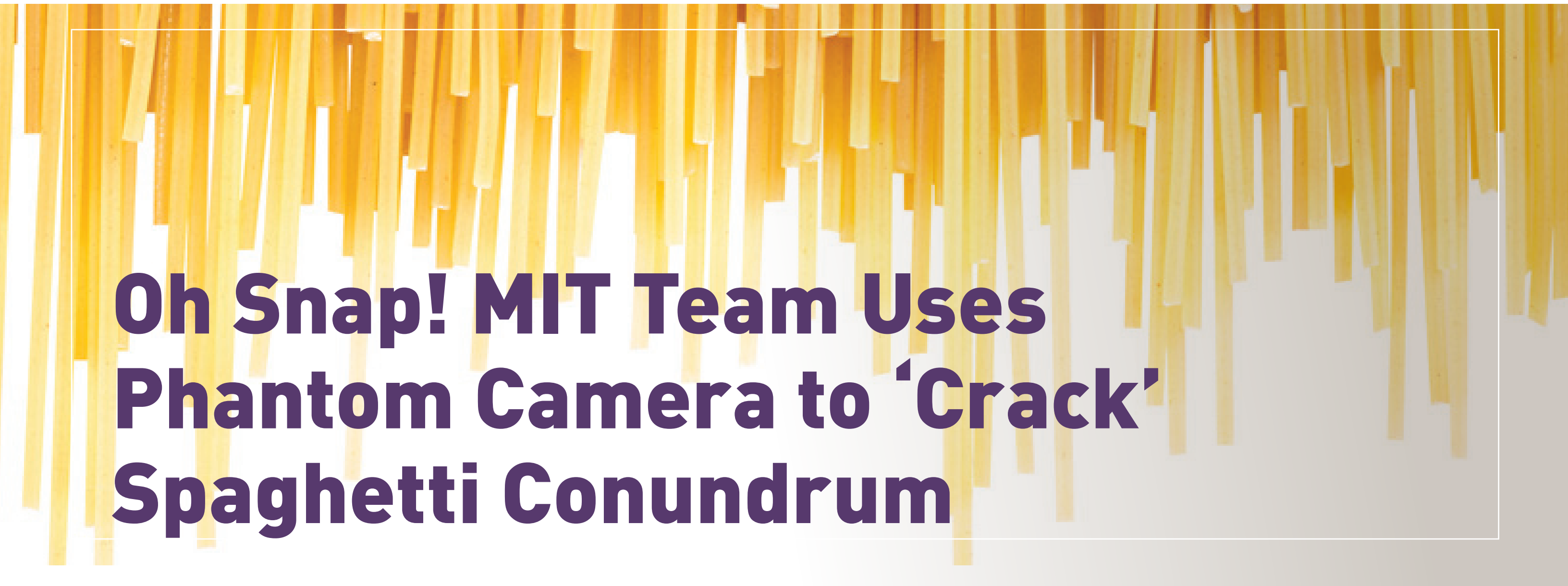
2019
CASE STUDY



Oh Snap! MIT Team Uses Phantom Camera to 'Crack' Spaghetti Conundrum

High-speed footage reveals how spaghetti can be made to crack into two versus multiple pieces—shedding light on the fracture mechanics of elastic rods.

Have you ever wondered why you can't break a piece of dry spaghetti into two pieces? Richard Feynman wondered the same thing. The physicist and Nobel Prize winner noted that holding a spaghetti stick at both ends and bending it until it breaks always yields at least three pieces. But the reason why eluded him—and dozens of other scientists—for decades.

Turns out this is not some trivial matter, and its implications extend beyond the kitchen. Spaghetti is key to understanding the fracture mechanics of elastic rods (ER), making Feynman's observation an enticing puzzle for a group of researchers at the Massachusetts Institute of Technology (MIT). With the help of a Phantom high-speed camera, the team tested a mathematical model explaining how a piece of spaghetti can be made to break into two pieces—adding a new "twist" to the time-old pasta puzzle.

SPAGHETTI AND ER FRACTURE BEHAVIOR

The fracture behavior of spaghetti sheds light on how ERs, which include building columns, trees, bones and even nanotubes, respond to extreme stresses—making the study of rod fracture and fragmentation critical to a wide range of applications, including the material sciences. "According to the story, Feynman observed that upon bending, spaghetti breaks into at least three pieces," says Vishal Patil, mathematics graduate student. "We became interested in the role of twist—and if twist could be used to break spaghetti into only two pieces."

Patil also wanted to investigate the role of nonadiabatic quenching—a process that, in this case, involved moving the ends of a piece of spaghetti towards each other. He developed a predictive model explaining how controlled twisting and nonadiabatic quenching can cause a rod to break into two pieces versus multiple pieces. According to this model, the unwinding of a twisted spaghetti after it fractures helps dampen the forces that would otherwise cause additional breaks.

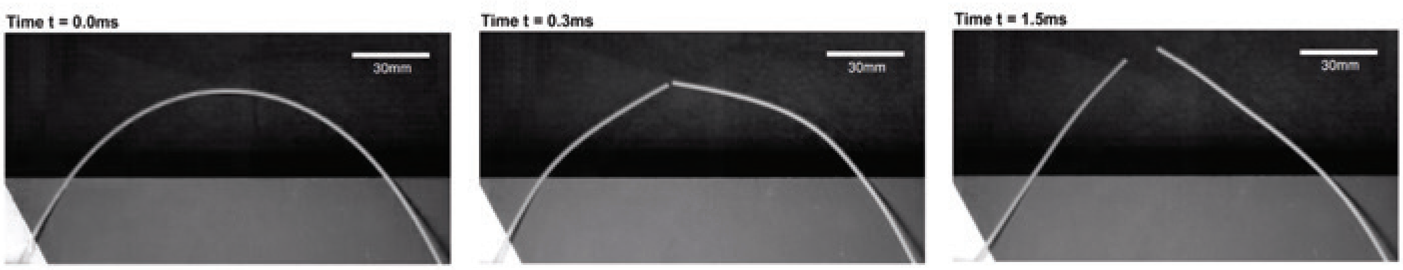
NONADIABATIC QUENCHING

While quenching typically means the rapid cooling of a system, in statistical physics it refers to a change in a control parameter that pushes the system through a phase transition. In this case, the parameter is the speed at which the spaghetti-snapping device moves the ends of the spaghetti sticks together. Nonadiabatic refers to the fact that the quench adds energy to the system.

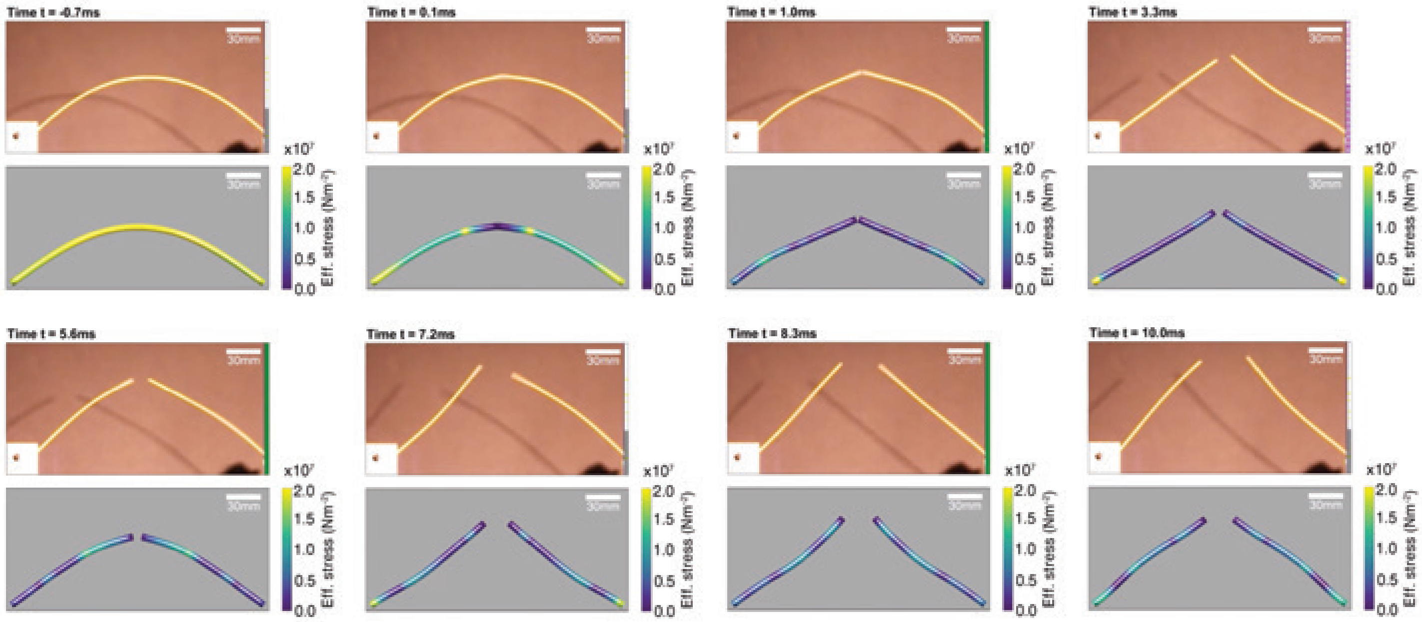
The model itself is based on Kirchhoff's equations, which describe the dynamics of thin rods. Patil and his team employed a discrete differential geometry algorithm to numerically solve the equations—with each rod discretized into 50 elements and with one step of simulation time corresponding to 1 μs of real time.

THE THEORY BEHIND FEYNMAN

In 2005, a group of French physicists finally posited a theory explaining Feynman's observation that dry spaghetti always breaks into three or more pieces. The team discovered that when long, thin rods are bent evenly from both ends, they will break near the center where the rod is most curved. This initial break causes a "snap-back" effect, or bending wave, that further fractures the stick. But despite their Ig Nobel Prize-winning theory, the question remained: could a piece of spaghetti ever be made to break into only two pieces?



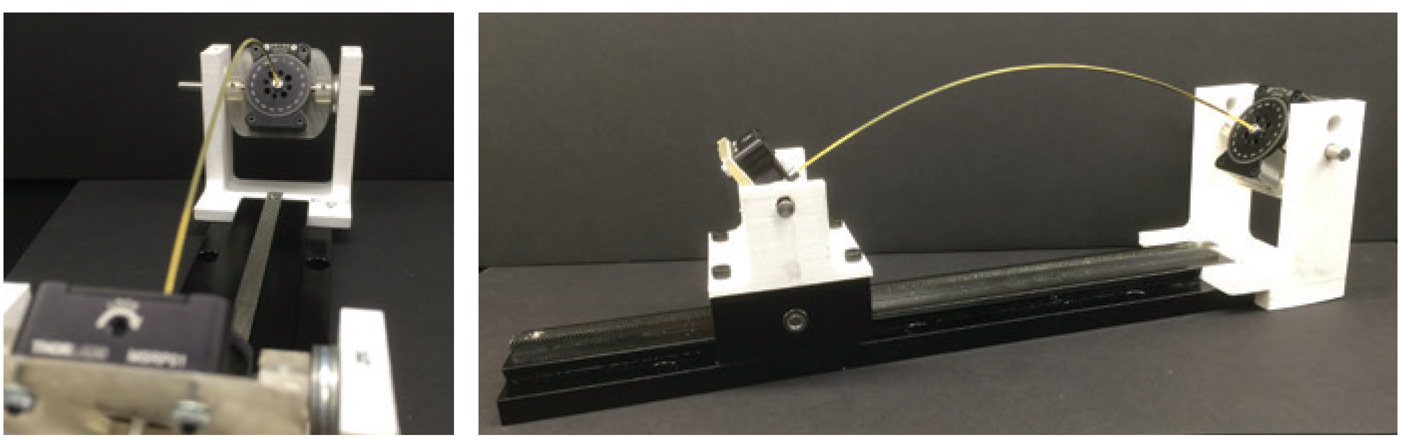
Binary fracture of spaghetti may be induced at low quench speeds (2 mm/s). Frame rate = 75,000 fps.



Binary fracture of spaghetti is observed in both trials and simulations at high twist angles (330°). Frame rate = 1,972 fps.

THE SPAGHETTI-SNAPPING SETUP

To test Patil's model of controlled binary fracture, the research team constructed a custom device designed to break hundreds of 24-cm spaghetti sticks with controlled twisting forces and nonadiabatic quenching. The apparatus featured a manual linear stage and two freely pivoting rotary stages on either side. Each rotary stage included aluminum clamps that held the spaghetti samples close to the torsional and bending axes of rotation. For their twist experiments, the team completed 73 trials at various twist angles up to 360 degrees. The kinetic quench experiments consisted of 20 trials, during which the device moved the ends of each spaghetti stick together at various speeds between 0.1 and 50 cm/s. The team found that twisting the spaghetti stick nearly 360 degrees and then slowly bringing the two ends together to bend it caused the stick to break into two pieces.



For their experiments, the MIT team constructed a custom device to controllably break hundreds of 24-cm spaghetti sticks with controlled twisting forces and nonadiabatic quenching.

FRACTURE MECHANICS THROUGH A HIGH-SPEED LENS

In addition to achieving controlled binary fracture, the researchers wanted to capture the fragmentation process to explore why the spaghetti sticks broke into six or more pieces during the higher-speed kinetic quench trials. "There were many questions which we could only definitively resolve by filming the spaghetti at a very high frame rate," Patil says. "When the spaghetti broke into multiple pieces, we wanted to resolve the time between the fractures in the rod."

Because crack propagation occurs on very fast timescales, the team recorded their twisting and quenching trials using a Vision Research Phantom v2511 high-speed camera, which is capable of filming up to 1,000,000 frames per second (fps). To observe the fragmentation process, the team filmed their quench trials at 75,000 fps. By upping the frame rate even further, the camera provided useful insights into spaghetti fracture mechanics at the microsecond scale. "By going to 1,000,000 fps, we saw how a crack propagates through the material and how the beam relaxes immediately post fracture," Patil says.

In many cases, the high-speed footage confirmed Patil's theoretical predictions, which can apply to other rodlike structures—from cellular microtubules, to advanced composite materials. The footage also raised some additional questions. "Using the camera, we observed that crack formation and propagation in spaghetti is itself a multistage process," Patil says. "It appears as if a small pre-crack forms and then persists for a relatively long time before the crack ruptures the spaghetti. This process is quite interesting in its own right and could help us understand some of the randomness inherent in fracture."

In addition to shedding light on ER fracture mechanics, the high-speed footage opens new doors for further study—particularly in elasticity, where interesting phenomena occur on very short timescales. "I look forward to using the camera again when we find our next question," Patil says. Patil and his fellow mathematicians published their findings in the Proceedings of the National Academy of Sciences.

THE PHANTOM v2511: BALANCING HIGH FRAME RATE AND LOW EXPOSURE

At its full 1-megapixel resolution (1,280 x 800), the Vision Research Phantom v2511 high-speed digital camera can record up to 25,000 fps, making it a useful tool for scientists looking to obtain images at full or near-full resolution at very high speeds. At lower resolutions, it can record up to 1,000,000 fps—an exceptionally high frame rate that enabled the MIT mathematicians to take their research a step further by analyzing spaghetti fracture propagation at the microsecond level.

Because the nature of the twist and quench experiments required short exposure times, the research team needed a high-speed camera that could maximize light exposure without sacrificing speed or image quality. This is where the Phantom v2511 shines. The camera utilizes a custom CMOS sensor with 28-micron pixels for high light sensitivity. Each pixel has a bit depth of 12 bits—yielding 4,096 gray levels. Additionally, the camera includes a global electronic shutter capable of exposures as fast as 500 ns. Even at a frame rate of 1 million fps, the exposure time can go down to 265 ns. This capability sufficiently freezes motion while eliminating the motion blur typical of ultra-fast applications.

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