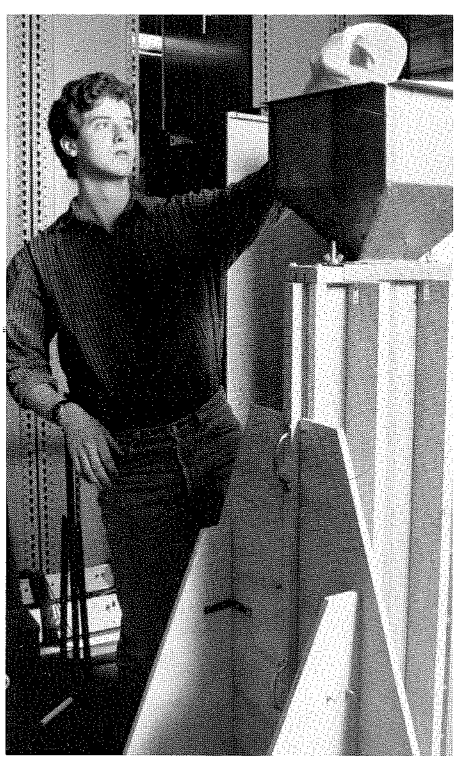
The trickle of sand through an egg timer is anything but steady as a ticking clock when seen up close, but spurts and dribbles instead.

Chute the Works

Erik Taylor loads beads into the chute.

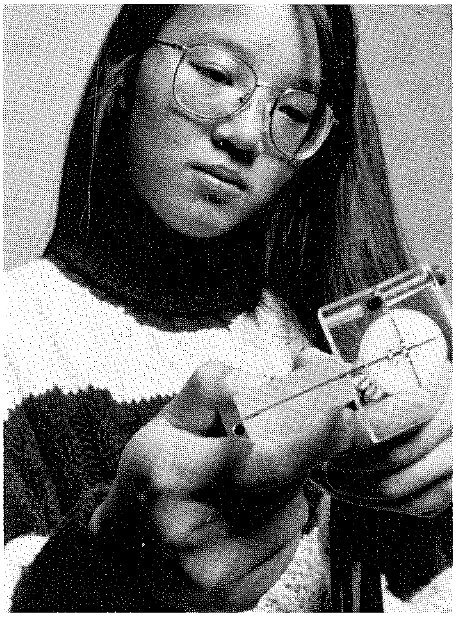


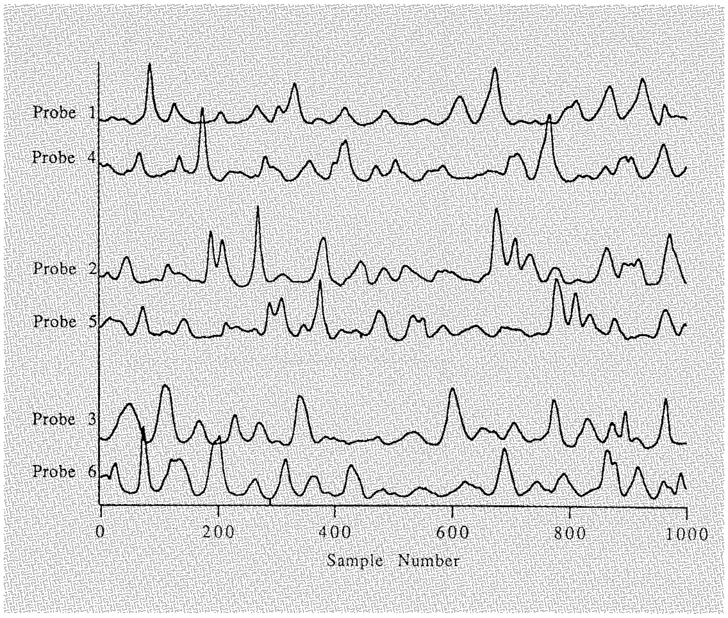
The next time you pass a gravel quarry or a grain elevator, take a look at those huge chutes. You know nearly as much about what's happening inside them as the people who designed them. Fluid flows have been studied rigorously since at least Newton's time, but "it's only recently that people have started to make any scientific measurements of flows of solid material" according to Assistant Professor of Mechanical Engineering Melany Hunt. There are elaborate mathematical treatments that assume that the coal lumps, fertilizer clods, frozen broccoli tips, or what have you are just very large gas molecules, and apply the principles of gas dynamics to them. But the models are on shaky ground without real-world observations to test their assumptions. Says Hunt, "We aren't even sure how to define the flow's properties—things like viscosity or shear stress, which we measure easily in fluids." Take flow rate, for example—the trickle of sand through an egg timer is anything but steady as a ticking clock when seen up close, but spurts and dribbles instead. And the flow varies from place to place as well as from time to time as individual sand grains tumble into each other, jostling their neighbors sideways as they flow downstream.

This past summer, Hunt and SURF (Summer Undergraduate Research Fellowships) students Garland Lee (senior, engineering and applied science) and Erik Taylor (junior, applied physics) worked on ways to measure an individual particle's motion in detail—a first step to abstracting the flow's bulk properties. Existing methods, including a fiber-optic system devised by Hojin Ahn (BS '85, MS '86, PhD '89), measure a particle's down-the-chute velocity but not its side-to-side buffeting, and tend to give average readings rather than specific data on individual particles. Lee modified Ahn's system to work in two dimensions, while Taylor wrote an image-processing program that tracks particles from a series of video images. "We wanted to try two different approaches, because we weren't sure which one would work better," Hunt explains.

Both detection systems track the flow of a column of beads down a vertical wooden chute about three feet tall, three inches wide, and three-quarters of an inch thick—thin enough to assume the beads only moved downward and side-to-side. The front and back walls are glass, and the replaceable side walls allow various flows to be set up. The beads are three millimeters—a shade less than an eighth of an inch—in diameter. A valve at the chute's bottom controls its flow rate. Graduate student Shu-San Hsiau built the chute and assisted Lee and Taylor with their projects.

Lee's detector, which mounts flush





Above: Garland Lee's detector consists of six fiber-optic probes in two horizontal rows of three each.

Right: A bead falling in front of a probe registers as a spike. Probe 1 is directly above probe 4, 2 is above 5, and 3 is above 6. A distinctive set of peaks appearing first at an upper and then at a lower probe marks the passage of a group of beads.

against the glass, consists of six fiber-optic probes. Each probe is 1.6 millimeters in diameter—about half the size of a bead—and consists of two semicircular bundles of optical fibers, one to emit light and one to collect it. The probes are grouped in two horizontal rows of three. Each row is one bead wide, so a bead partially crossing the central probe will trip its neighbor as well. The lower row's probes lie, like a snowman's smile, in an arc centered on the upper row's middle probe. The two rows are a bead's width apart—far enough for a falling bead to move sideways a bit, but not enough to get clean away. A bead passing directly through a probe's line of fire will reflect most of its light back to the collector, while an off-center bead won't register as strongly. (Clear glass beads work best.) Thus each probe generates a pattern of irregular peaks. A computer compares the patterns, looking for a distinctive set of peaks from an upper probe to reappear in a lower probe. To be sure that the peaks were actually related to the beads, Lee placed a dishful of beads on a spinning turntable to carry them past the probe at a known rate. The correlation between a first-row detector and the one directly downstream from it was quite good, but sideways motion wasn't so tractable—correlations between diagonal probes weren't as strong.

Taylor uses a video camera to follow a few individual beads in the stream. Black beads against a background flow of bilious Day-Glo yellow-green beads give the best contrast. A frame-grabber converts the video feed into a series of still pictures. After various processing steps to remove graininess and enhance contrast, each pixel in the image is given a value of 1 if it's part of a high-contrast bead or 0 if it's part of the background. Taylor's program then searches the 200-by-200-pixel image for round blobs containing 15 to 20 pixels, rejecting oblongs and other odd shapes. When the program finds a blob it likes, it draws a tall, thin rectangle from the bead down. The program then searches for the bead in the corresponding rectangle in the next image by a process called "autocorrelation," superimposing the second rectangle on the first and multiplying the corresponding pixel values. Since bead pixels are 1's and background pixels are 0's, only those pixels containing a bead in both frames will give a nonzero product. The program adds all the products to get an "autocorrelation value," which it remembers, and then shifts the second image by one pixel and repeats the process. The peak autocorrelation value happens when the bead is superimposed exactly on itself, and the amount of offset the process took gives the bead's velocity. The program stores the velocity and looks for the next bead. On

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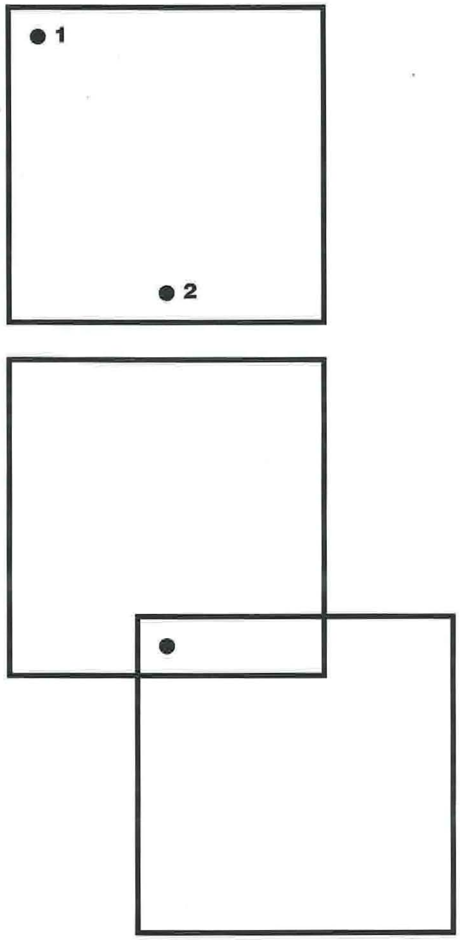
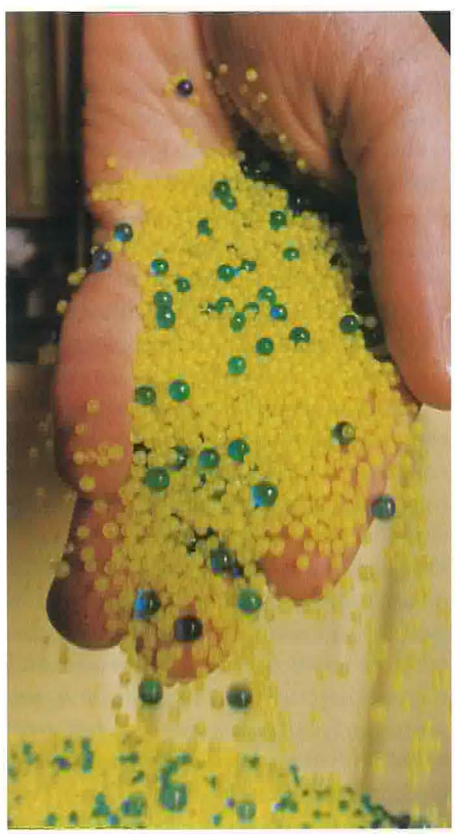


Right: How autocorrelation works. (Top): A bead (1) falls to a lower position (2) in the next video frame. (Bottom): The computer moves the two frames until the bead is superimposed upon itself, then uses that offset to calculate the bead's velocity.

Below: Lee (seated) fires up the computer as Hunt (left) and Taylor look on. Their small vertical chute stands at the right, while Patton's one-cubic-meter per minute chute awaits its turn behind Taylor.



average, each bead moves three to eight pixels down and one to three pixels sideways between images. "The trick is to have few enough beads that their rectangles don't overlap, but enough to get a significant amount of data per run," notes Taylor. "I can handle about one black bead per square centimeter." The program works, but it's slow and memory-intensive. Taylor expects to speed it up considerably by making it screen the images before storage and having it store the locations of the dark pixels only.

Both methods suffer from some of the problems that have hampered progress in this field for so long. As dust and dirt builds up on the chute's walls, the accumulating gunk slows the flow. Soon, results from one run can't be repeated in the next one as the beads begin to stick together. The paint on Taylor's Day-Glo beads chips and flakes as they clatter against each other, putting more crud in the chute. The chute has to be torn apart and the plates washed with soap every few runs in order to keep the data reproducible. Life got even more interesting one dry day, when the researchers discovered that the cascading beads can generate enough charge to succumb to the curse of static cling.

The next step will be to measure flows in a more realistic setting. Behind the little vertical chute stands a huge, inclined one, built about ten years ago by J. Scott Patton (MS '80, PhD '85) for Rolf Sabersky, now professor emeritus of mechanical engineering. This baby is rated at a deafening one cubic meter per minute, enough to start taking some real-world data. "Open-channel chutes like this one are especially complex," says Hunt. "There's room at the surface for the material to expand, so the velocity varies with depth as particles ride up and over each other. Ask anybody who designs these chutes how they behave, and they'll say, 'We just build them. Then, when they clog up, we get out shovels and unclog them.' We know so little about the fundamental equations governing these flows that we can't even scale them up—half the capital cost of a plant can be in its chutes, and a lot of that money gets spent on building larger and larger prototypes. We're hoping to begin to change that." □—*DS*