To planetary scientist Clark Chapman of the Southwest Research Institute in Boulder, Colorado, the findings clinch the case that S-type asteroids are the source of most meteorites. "It looks to me like the story is finished," he says. But Chapman notes, "You do need a step between the observation of a continuum [of color] and making an interpretation of what's doing it."

What may be doing it, say Binzel, Chapman, and others, is a process called space weathering. Just as exposure to the elements alters rocks on Earth, the space elements—such as the solar wind and the impacts of micrometeorites—can alter the surface of freshly exposed asteroidal rock by vaporizing part of a mineral and redepositing it elsewhere on the surface. Just how it works is a mystery, though, says meteoriticist Harry McSween of the University of Tennessee, Knoxville. "I believe in space weathering," he says, "but we don't really understand it."

As a result, some researchers hesitate to accept that S asteroids are chondrites in disguise. "I'm still skeptical, because space weathering [of asteroids] hasn't been proven," says astronomer Lucy-Ann McFadden of the University of Maryland, College Park. "It's easy to invoke space weathering but difficult to prove" that it's behind the differing appearance of S-types and ordinary chondrites. Planetary scientist Carlé Pieters of Brown University agrees, but notes that, in the lab, simulated space conditions can give ordinary chondrites at least some resemblance to S-types. And she says that space scientists are also learning how the solar wind and micrometeorite impacts alter soils on the moon—a model for what may happen to S-type asteroids.

Space weathering may not be the only process altering the look of larger S-types, Binzel adds. Because of their weak gravity, small asteroids may retain little of the finest debris generated by impacts, resulting in a coarser surface coating than is found on more massive asteroids. Particles of different sizes scatter light differently, which could contribute to the differences in color. With plenty of possible explanations at hand, Chapman and others aren't discouraged by the mystery of what reddens S-types. "There's been a major shift of opinion," says Chapman. "It's just the details that remain to be cleaned up."

Some of the details could be cleaned up starting this Valentine's Day, when the NEAR spacecraft goes into orbit around the 33-kilometer-long S-type asteroid Eros. X-ray and gamma ray instruments on NEAR will for the first time determine the elemental composition of an asteroid's surface, something that no amount of space weathering should alter. NEAR's close look could prove crucial in understanding cloaking and pinning down the link between S-types and chondrites. But if not, the frustrations could persist until a future mission to an S-type—as yet unplanned—actually scoops a sample from an asteroid and brings it back to Earth. **–RICHARD A. KERR**

DEVELOPMENTAL BIOLOGY

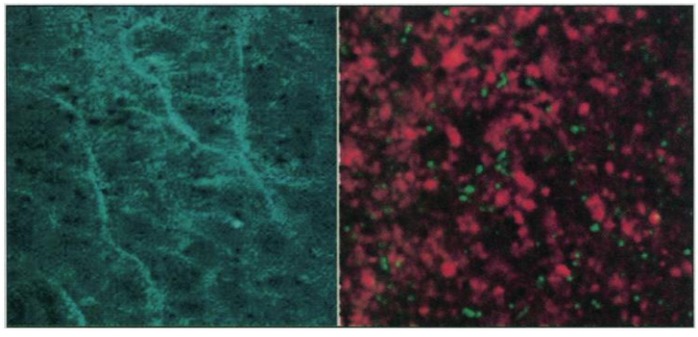
Many Modes of Transport For an Embryo's Signals

Developing embryos may actively ship key signaling molecules from place to place, instead of relying on diffusion to carry the messages

The developing embryo is a complex and ever-changing world, where landmarks quickly form and disappear and the entire geography shifts over time. Orchestrating these changes are protein messengers that constantly flow within and between cells, directing the next stage of shape change and cell division. But how do these messengers travel to their appointed destinations?

The classic paradigm is that a developmental signaling molecule diffuses freely from its source, so that nearby cells get the biggest dose and feel the strongest effects. "People have been talking about gradients since the beginning of embryology," says developmental geneticist Thomas Kornberg of the University of California, San Francisco (UCSF). But he notes that researchers have been unable to find these concentration gradients for a few key signaling molecules. And simple gradients can't explain the physical changes that accompany some crucial developmental events.

Now, thanks to an increasingly popular method of tracking proteins in space—hooking a glow-in-the-dark marker to the protein of interest—researchers can watch signals traverse cells in real time. Experiments with such methods are beginning to suggest that cells may actively ship some proteins around rather than relying on diffusion to carry the message. For example, 2 weeks ago researchers reported that frog eggs apparently haul a key signaling protein across the egg on a sort of intracellular railroad. Once at its destination, the protein helps trigger a cascade of messages that transform that side of the egg into the back of the embryo. And Kornberg's recent work on developing fly wings has sparked a bold new theory of transport: Rather than waiting for instructions to reach them, target cells may themselves send out long, skinny extensions to pick up messages from the source cells. "It's a way-out unexpected wrinkle," Kornberg says.



Railroading development. Microtubules (left, blue) guide the Dishevelled protein (green) to one side of a fertilized egg. (Each region is 35 μm across.)

CREDIT: LARABELL AND ROWNING

These and other studies offer a first glimpse into what may be a complex transportation system within the developing embryo, says developmental biologist Sergei Sokol of Harvard Medical School in Boston. "We used to have this simplistic view that different proteins diffuse readily in the cytoplasm. Now, more and more people think of it as a compartmentalized process," he says.

Still, the work is preliminary, cautions developmental geneticist Clifford Tabin of Harvard Medical School, and few papers have sewn up the details of these new modes of transport. For example, although Tabin agrees that the cell extensions Kornberg has spotted "are in a great place to be transmitting all sorts of signals," so far no one has proved that they actually do so. All the same, says developmental geneticist Andrew McMahon of Harvard University, these and other transport findings are giving development researchers "new food for thought."

Riding the egg's railroad

One of the key tasks in the life of a just-

fertilized egg is to tell its back from its belly. In frog eggs, this feat requires at least two types of developmental events. A protein called β-catenin, which turns on a host of genes, must be activated, and the egg must also undergo a major contortion: Its entire outer layer rotates 30 degrees around the cell's interior, tugged by an array of protein chains called microtubules. Now, in the 26 July *Journal of Cell Biology*, scientists link these two events, reporting that as microtubules move the outer cytoplasm, they also cart a signal in the β-catenin pathway to the embryo's future back side.

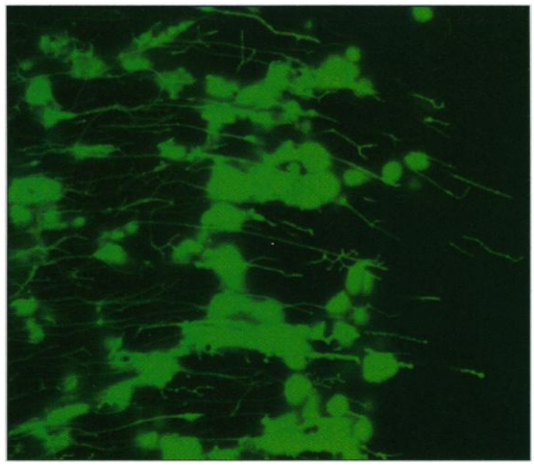
Previous research had shown that the microtubules not only drive the egg's rotation but also carry intracellular compartments called vesicles—highly suggestive evidence of protein transport. Researchers also knew that disrupting the microtubules both blocks the rotation and prevents the embryo from distinguishing its front and back sides: It becomes a blob of disorganized gut and blood cells without head, tail, or nervous system, says Randall Moon of the University of Washington School of Medicine in Seattle. Blocking β-catenin produces similar results. But no one knew how the microtubule-driven rotation and the protein cascade were connected.

To find out, Moon, postdoctoral fellow Jeffrey Miller, and their colleagues attached the gene for green fluorescent protein (gfp)—a small glowing protein originally found in jellyfish—to the gene for Dishevelled, a cytoplasmic protein in the β-catenin cascade. Developmental biologists Carolyn Larabell and Brian Rowning of Lawrence Berkeley National Laboratory in Berkeley, California, then inserted the RNA message for the composite protein, a fluorescent version of Dishevelled, into frog eggs, so that the eggs made the new protein. The researchers then pricked the cells with a needle, tricking the eggs into thinking that they had been fertilized and prompting them to start dividing.

As the eggs prepared for their first cell division, the team took microscope images of them every few seconds. They combined those images into an embryo home movie,* showing that as the cytoplasm rotates, gfp—and therefore its Dishevelled partner—also "zips over at high velocity to the dorsal side," says Moon.

The Dishevelled particles move at about the same speed—28 micrometers per minute—and in the same direction as vesicles moved along the microtubules in previous studies. So the authors propose that vesicles rolling along the microtubule tracks carry Dishevelled and perhaps other proteins to one side of the egg. There, Dishevelled stabilizes β-catenin so that it can turn on the other key genes, creating a back side. It's "the nearest thing yet to the 'missing link' " between the egg's rearrangement and the β-catenin cascade, says Jonathan Slack of the University of Bath in the United Kingdom.

Rowning notes that the same kind of intracellular railway might govern development in other large eggs known to have microtubules, such as those of zebrafish. The implications might extend to adults as well, for Dishevelled is part of the Wnt signaling pathway, which is also involved in cancer and hair growth (*Science*, 4 September 1998, pp. 1438 and 1509; 27 November 1998, p. 1617), Larabell notes. Understanding the protein's mode of travel may help researchers unravel those events, too.



Making connections. Long cell extensions stretch toward signaling centers in a developing fly wing.

CREDIT: KORNBERG AND RAMÍREZ-WEBER

Cells reach out

Well after front and back, head and tail have been determined, the now many-celled embryo still relies on protein messengers to trigger distinct developmental steps. Another gfp study now presents a bold new alternative explanation for how these signals get around. In the 28 May issue of *Cell*, developmental geneticists Felipe-Andrés Ramírez-Weber and Kornberg of UCSF reported never-before-seen cell extensions they call cytonemes, for their threadlike appearance (*neme* means thread in Latin). Only about 0.2 micrometer wide, the cytonemes they saw extended from cells in the outer regions of a developing fly wing toward a region in the center known to produce key developmental signals called Hedgehog and Decantaplegic (DPP), which regulate growth and cell fate. Because the cytonemes carry vesicles, the researchers suspect that they reach out and pick up signals from other cells.

The team has yet to prove that cytonemes play this role, but even so, these skinny cellular extensions are "really something amazing," says developmental biologist Edward De Robertis of the University of California, Los Angeles. "It's going to change all the thinking" about how signals might be transported to distant cells.

Kornberg describes the find as "pure luck," saying, "We didn't know what we were looking for." Ramírez-Weber had randomly inserted a copy of the *gfp* gene into the genomes of various fly strains, hoping that it might light up a gene of interest to wing development. In one genetically altered strain, the anterior and posterior regions of the embryonic wing lit up bright green, but the middle stayed dark. Upon closer inspection, Ramírez-Weber spotted long green threads stretching from the outer cells toward the center region. The delicate threads, several times the cells' length, disappeared when the researchers applied any fixative or even when they moved the microscope objective to try to follow the threads to their ends.

But the researchers found they could culture cytonemes on demand: They grew small pieces of tissue from the outer wing next to tissue from the center, and within about an hour the outer cells sprouted cytonemes stretching toward the center cells. In a few of these cultured cytonemes, the scientists spotted a vesicle moving away from the cell body—implying that the extensions can transport proteins. Similar methods also yielded cytonemes in cultured mouse limb bud cells and chick embryo cells, and several researchers, including De Robertis, have now spotted them in their own labs.

The researchers theorize that the vesicles in these cellular threads cart Hedgehog and DPP back to the outer cells. Such a system would transport these powerful signals efficiently and also limit their spread, fitting their observed effects, says Kornberg. But it's a challenge to current thinking. "When we draw cells, we draw them as little round spheres," says McMahon. The idea that cells stretch several cell lengths away "changes the whole equation of how signaling interactions may occur," he says.

Of course, as Kornberg readily admits, he and his colleagues have a long way to go before they prove that the signaling proteins really are on or within the cytonemes. If this and other early findings hold up, however, cytonemes, intracellular railways, and other active transport systems could explain the long-standing mystery of how signaling molecules orchestrate development so precisely. "There's a lot more organization than we know about," Kornberg says. "Almost nothing is left to chance."

—GRETCHEN VOGEL

* www.lbl.gov/LBL-Programs/Larabell