that quarks and leptons could readily turn into each other, something that rarely happens today. As a result, their masses had to be similar, and related in a fairly simple way. In the first, lightest family, says Dimopoulos, the mass of the electron was just one-third of the mass of the "down" quark. In the second family, the strange quark mass was one-third that of the muon. And finally, in the third family, the mass of the bottom quark was simply equal to the mass of the tau lepton.

> **"I have no idea if the theory is right, but I can tell you it's testable."**
>
> **–Lawrence Hall**

But while grand unified theories said something about how particles within a given family had once been related, they said nothing about relations between families. For that part of their family portrait, Dimopoulos, Hall, and Raby borrowed another idea called family symmetry, invented as an adjunct to grand unification by Georgi and Cecilia Jarlskog of the University of Stockholm in 1979. This theory, explains Dimopoulos, says that during the early epoch of grand unification, members of the first family could turn into members of the second family, and members of the second family could turn into those of the third. But there were no shortcuts: The first family couldn't leap directly to the third.

Together, these theories from the 1970s gave Dimopoulos and his colleagues a whole slew of mass relationships—a particle physics food chain, in which the interconversion rates describe the particles' "appetites" for each other—relevant to a time long past. The particles that make up ordinary matter (those in the first family) gained their relatively scrawny mass by nibbling on the second family. The second family in turn gnawed on particles of the third family, which took their ample mass directly from the Higgs.

All of this cannibalism could still be taking place today, even though some of the second and third family particles haven't been around for billions of years. Although they are officially extinct, Heisenberg's uncertainty principle allows them to flicker briefly into and out of existence as "virtual" particles. That way they could still be taking part in the cannibalistic interplay that generates mass. To find out whether that picture really could explain the observed particle masses, though, the trio had to convert the mass ratios predicted for just after the Big Bang into ratios for today's world—no small task.

And there was a deeper problem: The theory underlying many of these predictions, grand unification, had been declared dead by the vast majority of physicists back in the 1980s. For good reason: The simplest grand unified theory predicted that protons—considered to be immortal in the Standard Model—could decay into other particles. But after a decade of patient watching, experimental physicists have seen no clear sign of the proton's mortality. In the early 1980s, however, Dimopoulos, Raby, and Frank Wilczek of the Institute for Advanced Study in Princeton saw a ray of hope for grand unification: mating it with another theory called supersymmetry, which holds that every particle has a hypothetical "superpartner." The shadowy presence of these superpartners would, among other things, put a damper on proton decay.

Supersymmetric grand unification got a boost 2 years ago, when researchers at CERN measured something called the weak-mixing angle, a number—left open in the Standard Model—that is related to the relative strengths of the electromagnetic and weak forces. The result agreed to one part in a few hundred with the theory's prediction, as first calculated by Dimopoulos and Georgi. "It's just one number," says Berkeley's Chanowitz, "but it's making supersymmetry's stock rise." And now supersymmetry is performing another feat of theoretical first aid: It enables Dimopoulos, Hall, and Raby to get sensible results when they extrapolate from the grand unification masses to those seen today.

Rather than affecting the food chain or the particles' appetites, says Dimopoulos, supersymmetry "comes in the back door." The back door is, once again, the uncertainty principle, which implies the existence of a cloud of virtual particles that affect the energy and hence the mass of real particles. By including supersymmetric superpartners in this virtual cloud, the group found, they were able to bring their predictions into agreement with the observed masses. Even today, it seems, the third family heads the dinner table while, as Dimopoulos puts it, "the others get the breadcrumbs" as they are passed down the table.

While this banquet scene doesn't explain all the particle masses, it at least explains some trends. And for physicists, that could be a giant stride, holding out the possibility of a complete theory that might finally make sense of the maddeningly random pattern of particle masses. For the rest of us, of course, it only bears out what intuition tells us: It's a dog-eat-dog, particle-eat-particle world out there.

–Paul Selvin

Paul Selvin is a postdoctoral researcher in biophysics at the University of California, Berkeley.

A Gauntlet of Tests for the Theory

When it comes to the new ideas he and two of his colleagues have come up with to explain the bewildering array of masses of elementary particles, Lawrence Hall isn't making grandiose claims: "I have no idea if the theory is right," says the University of California, Berkeley, theoretical physicist. But the theory has another virtue that's almost as important in his field—and quite rare: "It's testable." Indeed, Hall and his colleagues Savas Dimopoulos of Stanford and Stuart Raby of Ohio State can list a series of ongoing or planned experiments that should provide a check on parts of their theory.

What test of a theory of mass could be more direct that its ability to predict the mass of an undiscovered particle? There's only one missing piece in the current picture of matter, the top quark, and experimenters at Fermilab and CERN are vying to find it and determine its mass. Hall and his colleagues predict that the top quark will weigh in at between 160 and 190 billion electron volts, approximately 200 times more than the proton. Unfortunately, says Dimopoulos, that mass would put the top quark out of reach of the accelerators at both CERN and Fermilab as presently configured, and so the test could well be delayed until the Superconducting Super Collider comes on line—at least 6 years in the future.

Even when the top quark finally makes its entrance, it will provide just one point of reference. A far more rigorous test will come when physicists get a chance to check the theory's predictions about particle decays—specifically, the decay rates and products of the two-quark composites called B-mesons. Such experiments could be done at the proposed "B-factories," specialized accelerators that physicists hope to build in the near future (*Science*, 22 March 1991, p. 1416).

But the most immediate test of the scheme may come from a different decay—of the apparently immortal proton. Proton decay has provided an excellent test of earlier theories: The so-called grand unified theories of the 1970s predicted relatively rapid proton decay, and when it didn't happen, the theories were set aside. The new theory, though, incorporates a modified grand unified theory that predicts slower proton decay, following a different route. If it's right, two proton-decay experiments—Icarus, in the Gran Sasso tunnel in Italy, and Super-Kamiokande in Japan—could see a proton decay "in the next 5 years," says Hall.

–P.S.