How Do Particles Put on Weight?

Some particles are heavier than others, say a trio of theorists, because they are first in line to fill their plate at the source of mass

Why are some things heavier than others? In the case of people, the answer clearly has a lot to do with what gets plunked down on the dinner table. For fundamental particles, however, the answer has never been obvious. In fact, it's so mysterious that the brightest physicists have been scratching their heads for decades trying to figure it out. "The problem of mass," says Lawrence Hall of the University of California, Berkeley, "is the most important outstanding problem of particle physics today." But some recent work may give at least partial relief to these frustrated physicists. And the surprising answer may be that particles, like people, have different appetites! Or, to put it another way, they get treated rather differently at the table: Some can fill their trenchers at the source of all mass, while others must be satisfied with left-overs.

That at least is the conclusion of a trio of physicists whose work has been causing a stir in the small but highly competitive world of theoretical physics. The trio, Savos Dimopoulos of Stanford University, Hall of Berkeley, and Stuart Raby of Ohio State University, has conceived what Hall argues is "the most predictive scheme known" for figuring out the masses of elementary particles. If their model holds up, it could fill a substantial void left by the conceptual framework that currently holds all of theoretical physics together—the Standard Model, for which Sheldon Glashow of Harvard University shared the 1979 Nobel Prize. Glashow himself isn't betting against them: "They're very, very good physicists," he says. And, to top it off, their scheme is testable—no small qualification in the esoteric world of theoretical physics.

Even before the new insights, physicists suspected that elementary particles gained weight by interacting with other, hypothetical particles called Higgs bosons, after the Scotsman who first postulated their existence, Peter Higgs of the University of Edinburgh. "In a manner of speaking," wrote Martinus Veltman of the University of Michigan in *Scientific American*, "particles 'eat' the Higgs boson to gain weight." This picture, now part of the Standard Model, even enabled physicists to explain the weight of two rare particles, the W and Z particles, which are involved in radioactive decay. But that's where the explanatory success ended. Physicists simply couldn't say why some particles—the familiar electron and the quarks that make up protons and neutrons, for example—consume only sparingly, while other kinds of particles tuck in, ending up thousands of times heavier. "It's extremely elusive and obscure," says Michael Chanowitz of the Lawrence Berkeley Laboratory, who was an early worker in the field.

If the new theory, published in a stream of five papers over the past 8 months, does manage to transcend the Standard Model, it would be a feat. Although the Standard Model has reigned since the 1960s, successfully predicting the results of thousands of experiments, it says virtually nothing about the pattern of masses. In fact, it contains 18 "free parameters"—unknowns that must be taken from experiments—and of the 18, 13 have to do with the masses of elementary particles. Hall admits he and his colleagues haven't nailed down all 13, but their theory does predict six of them, which he calls a record.

Three Families, Puzzling Masses

Leptons	Mass (GeV)	Quarks	Mass (GeV)
electron neutrino	$<2 \times 10^{-8}$	up	4×10^{-3}
electron	5.1×10^{-4}	down	7×10^{-3}
muon neutrino	$<3 \times 10^{-4}$	charm	1.5
muon	0.106	strange	0.2
tau neutrino	$<4 \times 10^{-2}$	top (not yet observed)	>91
tau	1.784	bottom	5

Glashow isn't the only physicist who is taking these claims seriously. "The tack that they've taken looks fairly unique," says Harvard's Howard Georgi, who has worked extensively in the field. "I don't think there are any competing theories." Enthusiasm aside, whether the new theory is right will be determined by comparing its predictions to experiments (see box on next page). And though such testability may sound like a minimal claim, in the world of particle theory, where theorists calculate what the world looked like in the fireball 10^{-43} seconds after the Big Bang, at energies beyond any atom-smasher imaginable, it's most unusual.

The trio came up with their apparently unique contribution by focusing on the feeding habits, not just of individuals, but of entire families—the three families of related particles that seem to make up all matter. Borrowing concepts from earlier efforts to go beyond the Standard Model, they tried to put together a picture of the relationships within and between families. In the resulting picture, particles of one kind can briefly assume the identity of another kind, stealing some of the second particle's properties—including its mass. In effect, the first particle "eats" the second particle, gaining mass. What Dimopoulos, Hall, and Raby have done is to arrange these cannabilistic particles in a pecking order in which all the food ultimately comes from Higgs bosons.

To look at the three known families of particles, you wouldn't know where they stand in the pecking order—they're identical except for mass (see table). Each includes two quarks, particles that feel the strong force that binds the atomic nucleus, and two leptons, particles such as the electron. Leptons respond to other forces, such as the weak force involved in radioactivity and the more familiar force of electromagnetism. Because of the differences in mass, only the first, lightest particle family is found in ordinary matter. Particles of the other two families, being far more massive, are unstable. Some make fleeting appearances in cosmic rays or in particle accelerators; others haven't been seen since a small fraction of a second after the Big Bang, 10 billion or 20 billion years ago.

But that's just where the trio aimed their effort to try and make sense of the pattern among the masses. Looking back to the universe's fiery beginning may seem an awfully round-about way to understand the masses seen today. It seems even stranger when you realize that, back then, particles didn't have the same masses as they do now, for obscure quantum-mechanical reasons. But the approach actually has certain advantages. For example, it's thought that just after the Big Bang the strong, weak, and electromagnetic forces were "unified" into one force.

More to the point, the particles affected by these forces—quarks for the strong force, leptons for the other forces—were also related to each other. They were so closely related, according to the "grand unified theories" first postulated by Georgi and Glashow in the 1970s, 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."**
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> **–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

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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.