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The Grand Unified Theory

The Quest to Unite All Forces

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Chapter 1: The Discovery of The Grand Unified Theory

Models that do not unify the three interactions using one simple group as the gauge symmetry but do so using semisimple groups can exhibit similar properties and are sometimes referred to as Grand Unified Theories as well. Historically, the first true GUT, which was based on the simple Lie group SU(5), was proposed by Howard Georgi and Sheldon Glashow in 1974.

The Georgi–Glashow model was preceded by the semisimple Lie algebra Pati–Salam model by Abdus Salam and Jogesh Pati also in 1974, who pioneered the idea to unify gauge interactions. The acronym GUT was first coined in 1978 by CERN researchers John Ellis, Andrzej Buras, Mary K. Gaillard, and Dimitri Nanopoulos, however in the final version of their paper they opted for the less anatomical GUM (Grand Unification Mass). Nanopoulos later that year was the first to use the acronym in a paper.

The year 1974 was the moment the idea crystallized. Howard Georgi and Sheldon Glashow at Harvard showed that all the particles of one generation could be seated inside a single mathematical object, the group SU(5), with electric charge falling out as a consequence rather than an input. Independently, Jogesh Pati and Abdus Salam reached for a different structure that braided quarks and leptons together even more intimately. Both proposals shared one radical wager: that the messy proliferation of particles and forces seen at low energy is a mask, and that behind it the universe is startlingly simple.

The fact that the electric charges of electrons and protons seem to cancel each other exactly to extreme precision is essential for the existence of the macroscopic world as we know it, but this important property of elementary particles is not explained in the Standard Model of particle physics.

While the description of strong and weak interactions within the Standard Model is based on gauge symmetries governed by the simple symmetry groups SU(3) and SU(2) which allow only discrete charges, the remaining component, the weak hypercharge interaction is described by an abelian symmetry U(1) which in principle allows for arbitrary charge assignments.

The observed charge quantization, namely the postulation that all known elementary particles carry electric charges which are exact multiples of one-third of the "elementary" charge, has led to the idea that hypercharge interactions and possibly the strong and weak interactions might be embedded in one Grand Unified interaction described by a single, larger simple symmetry group containing the Standard Model. This would automatically predict the quantized nature and values of all elementary particle charges.

Since this also results in a prediction for the relative strengths of the fundamental interactions which we observe, in particular, the weak mixing angle, grand unification ideally reduces the number of independent input parameters but is also constrained

by observations. Grand unification is reminiscent of the unification of electric and magnetic forces by Maxwell's field theory of electromagnetism in the 19th century, but its physical implications and mathematical structure are qualitatively different. SU(5) is the simplest GUT.

The smallest simple Lie group which contains the Standard Model, and upon which the first Grand Unified Theory was based, is $SU(5) \supset SU(3) \times SU(2) \times U(1)$. Such group symmetries allow the reinterpretation of several known particles, including the photon, W and Z bosons, and gluon, as different states of a single particle field. However, it is not obvious that the simplest possible choices for the extended "Grand Unified" symmetry should yield the correct inventory of elementary particles.

The fact that all currently known matter particles fit perfectly into three copies of the smallest group representations of SU(5) and immediately carry the correct observed charges, is one of the first and most important reasons why people believe that a Grand Unified Theory might actually be realized in nature. The two smallest irreducible representations of SU(5) are 5 (the defining representation) and 10.

The elegance of the SU(5) construction was hard to overstate. Every known particle of a generation slotted into two tables — a five-seat table for some quarks and the electron, a ten-seat table for the rest — with electric charges that had to balance across each table for the theory to make mathematical sense. Charges that were mysterious inputs in the Standard Model became mandatory bookkeeping in the unified one. Physicists had spent half a century measuring why charge comes only in whole units; suddenly there was a reason.

This scheme has to be replicated for each of the three known generations of matter. It is notable that the theory is anomaly free with this matter content.

The hypothetical right-handed neutrinos are a singlet of SU(5), which means its mass is not forbidden by any symmetry; it doesn't need a spontaneous electroweak symmetry breaking which explains why its mass would be heavy (see seesaw mechanism).

This is already the largest simple group that achieves the unification of matter in a scheme involving only the already known matter particles (apart from the Higgs sector).

Since different Standard Model fermions are grouped together in larger representations, GUTs specifically predict relations among the fermion masses, such as between the electron and the down quark, the muon and the strange quark, and the tau lepton and the bottom quark for SU(5) and SO(10). Some of these mass relations hold approximately, but most don't (see Georgi-Jarlskog mass relation).

While GUTs might be expected to offer simplicity over the complications present in the Standard Model, realistic models remain complicated because they need to introduce additional fields and interactions, or even additional dimensions of space, in order to reproduce observed fermion masses and mixing angles. This difficulty, in turn, may be related to the existence of family symmetries beyond the conventional GUT models.

Due to this and the lack of any observed effect of grand unification so far, there is no generally accepted GUT model.

The collapse of minimal SU(5) taught a method as much as a lesson. Theorists responded not by abandoning unification but by enlarging the group: SO(10) absorbed the right-handed neutrino, supersymmetry re-tuned the running of the couplings, flipped models rearranged the assignments. Each escape hatch preserved the core idea while changing its predictions — a normal day in science, though the accounting is brutal: half a century later, every surviving version remains unconfirmed.

The initial enthusiasm met a hard experimental wall. The simplest version of the theory predicted that protons — the supposedly eternal building blocks of every atom — should occasionally decay, and physicists calculated roughly how often. Huge underground detectors filled with water and patience waited years for a telltale flash that never came. The proton refused to disappear, and the simplest SU(5) model, so beautiful on paper, was ruled out. The lesson was double-edged: grand unification had produced a testable, falsifiable prediction, which is exactly what good physics is supposed to do — and the experiment had said no.

Chapter 2: Understanding The Grand Unified Theory

The boson matrix for SO(10) is found by taking the 15 × 15 matrix from the 10 + 5 representation of SU(5) and adding an extra row and column for the right-handed neutrino. The bosons are found by adding a partner to each of the 20 charged bosons (2 right-handed W bosons, 6 massive charged gluons and 12 X/Y type bosons) and adding an extra heavy neutral Z-boson to make 5 neutral bosons in total.

Chapter by chapter, the same three characters keep reappearing: the coupling constants. In the Standard Model each force has its own strength, its own dial set by experiment and explained by nothing. In a grand unified theory the three dials are required, at high enough energy, to read the same number — one interaction admits only one strength. Whether the measured dials actually converge is therefore the theory's central quantitative test, the one part of the dream that can be checked against data rather than admired as architecture.

Strip the mathematics to its story and a GUT is an argument about symmetry. Gauge groups are the rulebooks by which forces operate; the Standard Model stitches three rulebooks together and reads them side by side. A grand unified theory replaces the shelf with one volume: a single compact Lie group, one connection, one coupling constant. Everything the Standard Model achieves separately must then be derived — the particle families, the charges, even the fact that quarks come in three colors. The group does the bookkeeping, and the physicist checks whether the ledger balances.

The boson matrix will have a boson or its new partner in each row and column. These pairs combine to create the familiar 16D Dirac spinor matrices of SO(10). In some forms of string theory, including E8 × E8 heterotic string theory, the resultant four-dimensional theory after spontaneous compactification on a six-dimensional Calabi–Yau manifold resembles a GUT based on the group E6.

Notably E6 is the only exceptional simple Lie group to have any complex representations, a requirement for a theory to contain chiral fermions (namely all weakly-interacting fermions). Hence the other four (G2, F4, E7, and E8) can't be the gauge group of a GUT.

Non-chiral extensions of the Standard Model with vectorlike split-multiplet particle spectra which naturally appear in the higher SU(N) GUTs considerably modify the desert physics and lead to the realistic (string-scale) grand unification for conventional three quark-lepton families even without using supersymmetry (see below). On the other hand, due to a new missing VEV mechanism emerging in the supersymmetric SU(8) GUT the simultaneous solution to the gauge hierarchy (doublet-triplet splitting) problem and problem of unification of flavor can be argued.

GUTs with four families / generations, SU(8): Assuming 4 generations of fermions instead of 3 makes a total of 64 types of particles. These can be put into 64 = 8 + 56 representations of SU(8). This can be divided into SU(5) × SU(3)F × U(1) which is the SU(5) theory together with some heavy bosons which act on the generation number.

GUTs with four families / generations, O(16): Again assuming 4 generations of fermions, the 128 particles and anti-particles can be put into a single spinor representation of O(16). Symplectic gauge groups could also be considered. For example, Sp(8) (which is called Sp(4) in the article symplectic group) has a representation in terms of 4 × 4 quaternion unitary matrices which has a 16 dimensional real representation and so might be considered as a candidate for a gauge group.

Sp(8) has 32 charged bosons and 4 neutral bosons. Its subgroups include SU(4) so can at least contain the gluons and photon of SU(3) × U(1). Although it's probably not possible to have weak bosons acting on chiral fermions in this representation.

A quaternion representation of the fermions might be: e i j v k r d g b L A further complication with quaternion representations of fermions is that there are two types of multiplication: left multiplication and right multiplication which must be taken into account.

It turns out that including left and right-handed 4 × 4 quaternion matrices is equivalent to including a single right-multiplication by a unit quaternion which adds an extra SU(2) and so has an extra neutral boson and two more charged bosons. Thus the resulting quaternionic group is Sp(8) × SU(2), which does include the Standard Model bosons.

If the 3 generations are then put in a 3x3 hermitian matrix with certain additions for the diagonal elements then these matrices form an exceptional (Grassmann) Jordan algebra, which has the symmetry group of one of the exceptional Lie groups (F4, E6, E7, or E8) depending on the details.

Because they are fermions the anti-commutators of the Jordan algebra become commutators. It is known that E6 has subgroup O(10) and so is big enough to include the Standard Model.

Chapter 3: Key Characteristics of The Grand Unified Theory

An E8 gauge group, for example, would have 8 neutral bosons, 120 charged bosons and 120 charged anti-bosons. To account for the 248 fermions in the lowest multiplet of E8, these would either have to include anti-particles (and so have baryogenesis), have new undiscovered particles, or have gravity-like (spin connection) bosons affecting elements of the particles spin direction. Each of these possesses theoretical problems. Other structures have been suggested including Lie 3-algebras and Lie superalgebras. Neither of these fit with Yang–Mills theory.

In particular Lie superalgebras would introduce bosons with incorrect statistics. Supersymmetry, however, does fit with Yang–Mills. The unification of forces is possible due to the energy scale dependence of force coupling parameters in quantum field theory called renormalization group "running", which allows parameters with vastly different values at usual energies to converge to a single value at a much higher energy scale.

The renormalization group running of the three gauge couplings in the Standard Model has been found to nearly, but not quite, meet at the same point if the hypercharge is normalized so that it is consistent with SU(5) or SO(10) GUTs, which are precisely the GUT groups which lead to a simple fermion unification. This is a significant result, as other Lie groups lead to different normalizations.

However, if the supersymmetric extension MSSM is used instead of the Standard Model, the match becomes much more accurate. In this case, the coupling constants of the strong and electroweak interactions meet at the grand unification energy, also known as the GUT scale: GUT GeV

It is commonly believed that this matching is unlikely to be a coincidence, and is often quoted as one of the main motivations to further investigate supersymmetric theories despite the fact that no supersymmetric partner particles have been experimentally observed. Also, most model builders simply assume supersymmetry because it solves the hierarchy problem—i.e., it stabilizes the electroweak Higgs mass against radiative corrections.

One of the theory's strangest predictions is an empty stretch of physics. Between the energies any collider can reach and the energies where grand unification is expected to kick in, most models predict a desert: no new particles, no new forces, nothing but the familiar ones running their coupling constants up the slope. Crossing that emptiness is why the theory is so hard to test — the interesting territory begins roughly a trillion times beyond where the Large Hadron Collider stops.

Since Majorana masses of the right-handed neutrino are forbidden by SO(10) symmetry, SO(10) GUTs predict the Majorana masses of right-handed neutrinos to be close to the GUT scale where the symmetry is spontaneously broken in those models. In supersymmetric GUTs, this scale tends to be larger than would be desirable to

obtain realistic masses of the light, mostly left-handed neutrinos (see neutrino oscillation) via the seesaw mechanism.

Grand unification also came with an unexpected dividend: neutrino mass. In the SO(10) version of the theory, a right-handed neutrino is forced into the roster, and its mass is allowed to be enormous — close to the unification scale. Through the seesaw mechanism, that enormous hidden mass squeezes the ordinary neutrinos down to almost nothing, explaining in one stroke why neutrinos are so fantastically lighter than the electron. The ghostly particles streaming through the Earth by the trillions are, on this reading, a faint echo of physics at the grand unified scale.

These predictions are independent of the Georgi–Jarlskog mass relations, wherein some GUTs predict other fermion mass ratios.

Several theories have been proposed, but none is currently universally accepted. An even more ambitious theory that includes all fundamental forces, including gravitation, is termed a theory of everything.

The most promising candidate is SO(10). A number of other GUT models are based upon subgroups of SO(10). They are the minimal left-right model, SU(5), flipped SU(5) and the Pati–Salam model. The GUT group E6 contains SO(10), but models based upon it are significantly more complicated.

The primary reason for studying E6 models comes from E8 × E8 heterotic string theory. GUT models generically predict the existence of topological defects such as monopoles, cosmic strings, domain walls, and others. But none have been observed. Their absence is known as the monopole problem in cosmology. Many GUT models also predict proton decay, although not the Pati–Salam model. As of now, proton decay has never been experimentally observed.

At the heart of the unified force sit the X and Y bosons, unlike any particle anyone has seen. Each carries both color charge and electric charge, letting them convert quarks into leptons and back — the very conversions that would allow a proton to decay. In effect, the distinction between nuclear matter and everyday particles becomes a question of which seat a particle occupies in the unified table. They must be trillions of times heavier than a proton, which is why they have never been seen and why their effects, if any, surface only as vanishingly rare processes.

The minimal experimental limit on the proton's lifetime pretty much rules out minimal SU(5) and heavily constrains the other models. The lack of detected supersymmetry to date also constrains many models. Some GUT theories like SU(5) and SO(10) suffer from what is called the doublet-triplet problem. These theories predict that for each electroweak Higgs doublet, there is a corresponding colored Higgs triplet field with a very small mass (many orders of magnitude smaller than the GUT scale here).

The search for proton decay is a study in patience. Detectors like Super-Kamiokande in Japan — a tank holding fifty thousand tons of ultra-pure water, watched by thousands of light-amplifying tubes — sit deep underground, waiting for a proton inside the water to betray itself. Decades of watching have pushed the proton's

lifetime past ten trillion trillion trillion years, a lower limit that grows more forbidding every year. Each year without a signal narrows the field of allowed models a little further.

In theory, unifying quarks with leptons, the Higgs doublet would also be unified with a Higgs triplet. Such triplets have not been observed. They would also cause extremely rapid proton decay (far below current experimental limits) and prevent the gauge coupling strengths from running together in the renormalization group.

Most GUT models require a threefold replication of the matter fields. As such, they do not explain why there are three generations of fermions. Most GUT models also fail to explain the little hierarchy between the fermion masses for different generations.

A GUT model consists of a gauge group which is a compact Lie group, a connection form for that Lie group, a Yang–Mills action for that connection given by an invariant symmetric bilinear form over its Lie algebra (which is specified by a coupling constant for each factor), a Higgs sector consisting of a number of scalar fields taking on values within real/complex representations of the Lie group and chiral Weyl fermions taking on values within a complex rep of the Lie group.

Symmetry breaking supplies the stage machinery. A unified theory at full strength is a perfectly symmetric hot state in which no interaction can be distinguished from another; as the universe cools, the symmetry is hidden the way a magnet hides rotational symmetry by choosing a direction, and the familiar forces crystallize out one after another. The Higgs mechanism, discovered for the electroweak force, plays the same role at the unified scale — and grand-unified versions of the Higgs, if they exist, would be among the heaviest particles ever hypothesized.

The Lie group contains the Standard Model group and the Higgs fields acquire VEVs leading to a spontaneous symmetry breaking to the Standard Model. The Weyl fermions represent matter. The discovery of neutrino oscillations indicates that the Standard Model is incomplete, but there is currently no clear evidence that nature is described by any Grand Unified Theory. Neutrino oscillations have led to renewed interest toward certain GUT such as SO(10).

Some of the few possible experimental tests of certain GUT are proton decay and fermion masses. There are a few more special tests for supersymmetric GUT. However, minimum proton lifetimes from research (at or exceeding the 1034~1035 year range) have ruled out simpler GUTs and most non-SUSY models. The maximum upper limit on proton lifetime (if unstable), is calculated at 6×1039 years for SUSY models and 1.4×1036 years for minimal non-SUSY GUTs.

The gauge coupling strengths of QCD, the weak interaction and hypercharge seem to meet at a common length scale called the GUT scale and equal approximately to 1016 GeV (slightly less than the Planck energy of 1019 GeV), which is somewhat suggestive. This interesting numerical observation is called the gauge coupling unification, and it works particularly well if one assumes the existence of superpartners of the Standard Model particles.

Still, it is possible to achieve the same by postulating, for instance, that ordinary (non supersymmetric) SO(10) models break with an intermediate gauge scale, such as the one of Pati–Salam group. Unification of theories in physics

Different fields in physics include vector fields such as the electromagnetic field, spinor fields whose quanta are fermionic particles such as electrons, and tensor fields such as the metric tensor field that describes the shape of spacetime and gives rise to gravitation in general relativity. Unified field theories attempt to organize these fields into a single mathematical structure. For over a century, the unified field theory has remained an open line of research.

The term was coined by Albert Einstein, who attempted to unify his general theory of relativity with electromagnetism since the 1920s. Einstein attempted to create a classical unified field theory. Among other difficulties, this required a new explanation of particles as singularities or solitons instead of field quanta. Later attempts to unify general relativity with other forces incorporate quantum mechanics. The concept of a "Theory of Everything" or Grand Unified Theory are closely related to unified field theory.

A theory of everything attempts to create a complete picture of all events in nature. Grand Unified Theories do not attempt to include the gravitational force and can therefore operate entirely within quantum field theory. The goal of a unified field theory has led to significant progress in theoretical physics. Unified field theory attempts to give a single elegant description of the following fields: All four of the known fundamental forces are mediated by fields.

In the Standard Model of particle physics, three of these result from the exchange of gauge bosons. These are: Strong interaction: the interaction responsible for holding quarks together to form hadrons, and holding neutrons and also protons together to form atomic nuclei. The exchange particle that mediates this force is the gluon. Electromagnetic interaction: the familiar interaction that acts on electrically charged particles. The photon is the exchange particle for this force.

Weak interaction: a short-range interaction responsible for some forms of radioactivity, that acts on electrons, neutrinos, and quarks. It is mediated by the W and Z bosons. General relativity likewise describes gravitation as the result of the metric tensor field, which describes the shape of spacetime: Gravitational interaction: a long-range attractive interaction that acts on all particles. In hypothetical quantum versions of GR, the postulated exchange particle has been named the graviton.

Gauge boson fields also have quanta, such as photons for the electromagnetic field. The Standard Model has a unique fundamental scalar field, the Higgs field, the quanta of which are called Higgs bosons. The first successful classical unified field theory was developed by James Clerk Maxwell.

In 1820, Hans Christian Ørsted discovered that electric currents exerted forces on magnets, while in 1831, Michael Faraday made the observation that time-varying magnetic fields could induce electric currents. Until then, electricity and magnetism had been thought of as unrelated phenomena. In 1864, Maxwell published his famous

paper on a dynamical theory of the electromagnetic field.

This was the first example of a theory that was able to encompass previously separate field theories (namely electricity and magnetism) to provide a unifying theory of electromagnetism.

By 1905, Albert Einstein had used the constancy of the speed-of-light in Maxwell's theory to unify our notions of space and time into an entity we now call spacetime. In 1915, he expanded this theory of special relativity to a description of gravity, general relativity, using a field to describe the curving geometry of four-dimensional (4D) spacetime.

In the years following the creation of the general theory, a large number of physicists and mathematicians enthusiastically participated in the attempt to unify the then-known fundamental interactions.

Given later developments in this domain, of particular interest are the theories of Hermann Weyl of 1919, who introduced the concept of an (electromagnetic) gauge field in a classical field theory and, two years later, that of Theodor Kaluza, who extended General Relativity to five dimensions. Continuing in this latter direction, Oscar Klein proposed in 1926 that the fourth spatial dimension be curled up into a small, unobserved circle.

In Kaluza–Klein theory, the gravitational curvature of the extra spatial direction behaves as an additional force similar to electromagnetism. These and other models of electromagnetism and gravity were pursued by Albert Einstein in his attempts at a classical unified field theory. By 1930 Einstein had already considered the Einstein-Maxwell–Dirac System [Dongen]. This system is (heuristically) the super-classical [Varadarajan] limit of (the not mathematically well-defined) quantum electrodynamics.

One can extend this system to include the weak and strong nuclear forces to get the Einstein–Yang-Mills–Dirac System.

The French physicist Marie-Antoinette Tonnelat published a paper in the early 1940s on the standard commutation relations for the quantized spin-2 field, in an attempt to unify general relativity with quantum mechanics. She continued this work in collaboration with Erwin Schrödinger after World War II. In the 1960s Mendel Sachs proposed a generally covariant field theory that did not require recourse to renormalization or perturbation theory. In 1965, Tonnelat published a book on the state of research on unified field theories.

In 1963, American physicist Sheldon Glashow proposed that the weak nuclear force, electricity, and magnetism could arise from a partially unified electroweak theory. In 1967, Pakistani Abdus Salam and American Steven Weinberg independently revised Glashow's theory by having the masses for the W particle and Z particle arise through spontaneous symmetry breaking with the Higgs mechanism.

This unified theory modelled the electroweak interaction as a force mediated by four particles: the photon for the electromagnetic aspect, a neutral Z particle, and two

charged W particles for the weak aspect. As a result of the spontaneous symmetry breaking, the weak force becomes short-range and the W and Z bosons acquire masses of 80.4 and 91.2 GeV/c2, respectively. Their theory was first given experimental support by the discovery of weak neutral currents in 1973.

In 1983, the Z and W bosons were first produced at CERN by Carlo Rubbia's team. For their insights, Glashow, Salam, and Weinberg shared the 1979 Nobel Prize in Physics. Carlo Rubbia and Simon van der Meer received the Prize in 1984. After Gerardus 't Hooft showed the Glashow–Weinberg–Salam electroweak interactions to be mathematically consistent, the electroweak theory became a template for further attempts at unifying forces.

In 1974, Sheldon Glashow and Howard Georgi proposed unifying the strong and electroweak interactions into the Georgi–Glashow model, the first Grand Unified Theory, which would have observable effects for energies much above 100 GeV. Since then there have been numerous proposals for Grand Unified Theories involving larger and larger unifying groups. While these theories are self-consistent, no proposal produced a solution to outstanding issues in cosmology, like the baryon asymmetry problem or the missing mass now attributed to dark matter.

Experimental tests of such theories requires an energy scale well beyond the reach of current accelerators so no empirical evidence outside of cosmology can guide theory. Grand Unified Theories make predictions for the relative strengths of the strong, weak, and electromagnetic forces, and in 1991 LEP determined that supersymmetric theories have the correct ratio of couplings for a Georgi–Glashow Grand Unified Theory.

Many Grand Unified Theories (but not Pati–Salam) predict that the proton can decay, and if this were to be seen, details of the decay products could give hints at more aspects of the Grand Unified Theory. It is at present unknown if the proton can decay, although experiments have determined a lower bound of 1035 years for its lifetime. Theoretical physicists have not yet formulated a widely accepted, consistent theory that combines general relativity and quantum mechanics to form a theory of everything.

Some common mainstream GUT models are:

Georgi–Glashow model – SU(5); and Flipped SU(5) – SU(5) × U(1)

SO(10) model; and Flipped SO(10) – SO(10) × U(1)

331 model – SU(3)C × SU(3)L × U(1)X

Note: These models refer to Lie algebras not to Lie groups.

The most promising candidate is SO(10).

Chapter 4: Important Features of The Grand Unified Theory

ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.