Great. I will draft a formal English report on Topological Geometrodynamics (TGD), incorporating your corrections and ensuring mathematical rigor. The report will:

- Use the corrected terminology and standardize key terms according to the provided glossary.
- Include a dedicated section on outdated concepts, making it clear what has been superseded.
- Focus on the latest research (2020–2025) while ensuring historical context is properly structured.
- Correct any misrepresentations and misinterpretations, aligning with the most recent theoretical framework of TGD.

I will let you know when the report is ready for your review.

Introduction

Topological Geometrodynamics (TGD) is a proposed unified theory of physics originally developed by Matti Pitkänen in the late 1970s (). The core idea of TGD is that *physical space-time is not a fundamental 4-dimensional manifold on its own*, but rather can be described as a 4-dimensional *sub-manifold* (or "surface") embedded in an 8-dimensional target space. This 8-dimensional *imbedding space* is taken to be the Cartesian product of Minkowski space M^4 (describing macroscopic space-time) and the complex projective space CP^2 (a compact 4-dimensional space that encodes internal degrees of freedom) (Topological Geometrodynamics). In other words, each physical space-time corresponds to a 4-surface $X^4 \subset M^4 \times CP^2$. TGD can be viewed as a *generalization of string theory* in which 1-dimensional strings are replaced by 3-dimensional surfaces (more precisely, *3-dimensional light-like surfaces* bounding 4-volumes) (Topological Geometrodynamics). Equivalently, it can be seen as an attempt to construct a Poincaré-invariant theory of gravitation in which the Poincaré symmetry acts in the fixed 8-dimensional imbedding space (rather than on an abstract space-time manifold as in General Relativity) (Topological Geometrodynamics). This approach yields a rich geometric structure, including the notion of a *many-sheeted space-time* – multiple layered space-time sheets embedded in $M^4 \times CP^2$ – and naturally leads to concepts like **topological field quantization** (where classical field lines or flux tubes are associated with these discrete space-time sheets) (Topological Geometrodynamics).

Over the decades, TGD has evolved into an extensive framework, incorporating elements of quantum theory, general relativity, and number theory. It proposes that known physical forces and particles emerge from the geometry of the 8-dimensional imbedding space and the topological interactions of space-time sheets. For instance, standard model gauge fields are interpreted in TGD as geometrical fields induced from the CP^2 part of the imbedding space, and gravitation is associated with the curvature of these space-time surfaces within $M^4 \times CP^2$. A striking aspect of TGD is the enormous *symmetry structure* it entails: the theory exhibits infinite-dimensional symmetries akin to conformal and super-conformal symmetries, which stem in part from the light-like character of the basic 3-surfaces ("partonic" 2+1 dimensional surfaces) that define the boundaries of space-time sheets (Topological Geometrodynamics). These symmetries play a key role in constraining the theory's dynamics and in the conjectured existence of a unique infinite-dimensional geometry for the "world of classical worlds" (see below).

In recent years (2020–2025), TGD research has focused on solidifying the mathematical foundations and updating several core principles in light of new insights. Emphasis has been placed on a dual number-theoretic and geometric description of space-time (**M^8–H duality**), a novel quantum ontology (**Zero Energy Ontology**, ZEO), and the role of algebraic number fields and **Galois groups** in formulating quantum physics. These new developments mark a shift from some earlier ideas; accordingly, this report will carefully distinguish *current* understanding from *outdated concepts*. In particular, certain early heuristic analogies (such as treating TGD's field equations as an "Einstein–Maxwell" pair of equations in analogy to Einstein's gravity and Maxwell's electrodynamics) and misinterpretations regarding quantization will be corrected in light of the modern formulation. The report is organized as follows:

- **Mathematical Foundations:** We introduce the formal structure of TGD, including the geometry of the imbedding space and space-time surfaces, the action principle and field equations, the concept of the world of classical worlds (WCW), and the quantization scheme.
- **Current Developments (2020–2025):** We highlight the latest theoretical advances – M^8–H duality, refinements in quantum theory via ZEO, the incorporation of p-adic number fields and Galois groups, the twistor lift of TGD, and other cutting-edge ideas – which now form the core of TGD.
- **Outdated Concepts and Historical Perspectives:** We review earlier phases of TGD, pointing out ideas that have since been revised or abandoned. This includes clarifying previous analogies and claims (e.g. the Einstein–Maxwell analogy and assumptions about second quantization) that are now understood to be inaccurate.
- **Comparisons to Other Quantum Gravity Theories:** TGD is contrasted with other approaches to quantum gravity and unification, notably string theory and loop quantum gravity, to underscore differences in assumptions, methodology, and predictions.
- **Applications to Physics and Cosmology:** We discuss how TGD addresses various domains of physics – from particle physics (e.g. hadron spectra, electroweak interactions) to cosmology (early universe, dark matter, cosmic structure) – and even touches upon biologically inspired physics, highlighting where TGD offers novel explanations or predictions.
- **Conclusion and Open Questions:** We summarize the status of TGD as of mid-2020s and outline the open problems and future directions, emphasizing what needs to be resolved for TGD to mature into a fully rigorous theory and how it might be tested or further developed.

Throughout the report, we use standard TGD terminology as defined in Pitkänen's glossary and latest literature. Mathematical rigor is maintained by formulating key ideas with precise definitions and, where appropriate, equations. We will cite sources from the TGD literature to substantiate statements, using the notation 【source†lines】 for references. The aim is to provide a clear, formal, and up-to-date account of Topological Geometrodynamics that reflects its current state (circa 2025) while acknowledging its developmental history.

Mathematical Foundations

Space-Time as an Embedded Manifold in $M^4 \times CP^2$

At the heart of TGD is a radical *geometrization* of physics. Each physical space-time is postulated to be a 4-dimensional *surface* X^4 embedded in the product manifold $M^4 \times CP^2$, where M^4 is four-dimensional Minkowski space and CP^2 (complex projective 2-space) is a 4-real-dimensional compact space with SU(3) symmetry (the isometry group of CP^2 is $SU(3)$, which intriguingly relates to the gauge group of the strong interaction). In technical terms, one considers an embedding $X^4 \hookrightarrow M^4 \times CP^2$ that satisfies certain variational equations (see below). The physical motivation is that this 8-dimensional structure can naturally incorporate both gravitation (through the geometry of the M^4 factor) and standard model interactions (through gauge fields arising from the geometry of CP^2) in a single unified framework (Topological Geometrodynamics) (Topological Geometrodynamics). Space-time, in this picture, is no longer an abstract Einsteinian 4-manifold with *ad hoc* matter fields living on it, but a *concrete surface* in a fixed higher-dimensional space, with all fields interpreted as *induced geometric quantities* on this surface.

Induced Metric and Induced Fields: Given a space-time surface $X^4 \subset M^4 \times CP^2$, one can pull back the metric of $M^4 \times CP^2$ onto X^4. This induced metric $g_{\mu\nu}(x)$ on X^4 plays the role of the space-time metric in TGD. In addition, the standard model fields are envisioned to emerge from the geometry of CP^2. In particular, CP^2 has a Kähler form J (a closed 2-form) and associated Kähler gauge potential A_i (analogous to a U(1) electromagnetic potential). When CP^2 is part of the imbedding space, the pullback of these forms/potentials to X^4 yields field-like quantities on space-time. For example, one gets an induced U(1) field $F_{\mu\nu}(x)$ from the Kähler form, which can be seen as an analog of the electromagnetic field. More generally, the tangent and normal bundles of X^4 in $M^4 \times CP^2$ decompose in ways that give rise to fields corresponding to electroweak and color interactions (Topological Geometrodynamics). (This is a deep connection: the isometries of CP^2 are $SU(3)$, which TGD identifies with the gauge group of strong interactions, and the geometry of CP^2 also yields $U(2)$ subgroups that can be related to electroweak $SU(2) \times U(1)$ symmetry (Topological Geometrodynamics). Thus, the standard model gauge fields are essentially *geometrized* in the CP^2 part of the space.)

Action Principle – The Kähler Action: The dynamics of the space-time surface X^4 is governed by an action principle. The original choice of action in TGD is the *Kähler action*, which is essentially the 4-dimensional volume integral of the induced CP^2 Kähler form's Lagrangian density on X^4. In simple terms, one can write the action (heuristically) as:

$$S = 1gK2 \int X414F\mu\nu F\mu\nu{-}g\, d4x + \Lambda \int X4{-}g\, d4x, S = \frac{1}{g_K^2}\int_{X^4}\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\sqrt{-g}\,d^4x + \Lambda\int_{X^4}\sqrt{-g}\,d^4x,$$

where $F_{\mu\nu}$ is the **induced Kähler field strength** on the surface (coming from CP^2), g_K is a coupling constant (the "Kähler coupling strength"), and the second term with Λ is analogous to a cosmological constant term (in early formulations this was sometimes omitted or considered part of the extremal condition). In practice, the precise form of the TGD action is more specialized – it is often described as the *Kähler action* $S_K = \int_{X^4} L_K, d^4x$ with L_K proportional to the square of the induced Kähler form, possibly plus a volume term. The *preferred extremals* of this action are the allowed physical space-time surfaces. Because CP^2's Kähler form is closed and co-closed, the Euler-Lagrange equations for this action resemble Maxwell's equations in certain limits (hence historically the analogy to an "Einstein–Maxwell" system). However, crucially, TGD imposes a broader condition: the *energy-momentum tensor $T_{\mu\nu}$ of the induced Kähler field is divergence-free* on preferred extremals (What Are the Counterparts of Einstein's Equations in TGD?, viXra.org e-Print archive, viXra:1309.0055). In other words, instead of directly using Einstein's field equations, TGD requires local energy-momentum conservation for the induced fields. This condition reduces to something akin to Einstein's equations with a cosmological constant and a Maxwell field term in special cases, but in general it is a wider condition (What Are the Counterparts of Einstein's Equations in TGD?, viXra.org e-Print archive, viXra:1309.0055). One consequence is that *4-dimensional minimal surfaces* in the imbedding space (which minimize volume) that also satisfy the Kähler field equations are preferred – these can be thought of as analogs of extremal surfaces that satisfy both gravitational (minimal surface) and electromagnetic (Kähler) conditions.

Mathematically, the variational principle leads to a set of *field equations for the embedding*. Early on, Pitkänen conjectured that these field equations imply that the induced metric on X^4 satisfies an *effective Einstein equation* $G_{\mu\nu} = 8\pi G_N T^{(K)}_{\mu\nu} + \Lambda g_{\mu\nu}$, where $T^{(K)}_{\mu\nu}$ is the stress-energy of the induced Kähler field (hence the analogy to an Einstein-Maxwell system) (What Are the Counterparts of Einstein's Equations in TGD?, viXra.org e-Print archive, viXra:1309.0055). It is now understood that this was an overly restrictive interpretation: not all TGD solutions look like solutions to Einstein-Maxwell; the true requirement is the *vanishing of the covariant divergence* $\nabla^\mu T^{(K)}_{\mu\nu} = 0$, which is automatically satisfied if Einstein's equations held but is slightly more general (What Are the Counterparts of Einstein's Equations in TGD?, viXra.org e-Print archive, viXra:1309.0055). This generalization allows, for example, *vacuum extremals* (surfaces with no induced fields) that carry nontrivial geometry without behaving like standard vacuum solutions of Einstein's equations.

Many-Sheeted Space-Time and Topological Field Quantization: Because space-time surfaces are embedded in a higher-dimensional space, multiple surfaces can coexist in the same region of M^4 coordinates, separated only by their different positions in the CP^2 directions. This leads to the concept of *many-sheeted space-time*: physical space-time is composed of a stack or collection of parallel (or more generally, intersecting and touching) sheets, each a separate 4-surface, that together form an effective structure. Particles and fields in TGD are often associated with these sheets. For instance, what we perceive as an electromagnetic field line in space might in TGD correspond to a "wormhole" connecting two space-time sheets – this is referred to as **topological field quantization** (Space-time as 4-surface in

M^4xCP_2.html) (Space-time as 4-surface in M^4xCP_2.html). Every classical field configuration (say a magnetic flux tube) is literally a piece of 3-dimensional topology in the multi-sheeted space-time: a flux tube would be a pair of space-time sheets connected by a small throat (a 3D wormhole) carrying a quantized unit of magnetic flux. In this way, field lines are not continuous lines in a single space but actually *tubes of 4-surface* carrying the field. The "many-sheeted" structure allows the superposition principle to be replaced by a *set-theoretic union of surfaces*: rather than summing fields from different sources, TGD conceptually puts each source on its own space-time sheet, and the combined effect on a test particle arises from that particle touching multiple sheets (TGD and GRT.html. Indeed, an *effective space-time metric* experienced by an observer can be defined as a sum of the Minkowski metric plus small perturbations from each sheet; in regions where many sheets overlap, the effective metric approximately satisfies Einstein's equations (TGD and GRT.html. This is how standard General Relativity is recovered as a low-energy limit: the many-sheeted structure "packs" into an effective single-sheet description where the deviations from flat Minkowski metric on different sheets sum to produce the usual curved metric of Einstein (TGD and GRT.html. In such a limit, TGD predicts that Einstein's field equations hold for this effective metric (thus satisfying the equivalence principle in an approximate sense) (TGD and GRT.html), and the usual Newtonian gravity, black hole solutions, etc., emerge in the approximation where the sheets are not resolved separately.

Another outcome of the many-sheeted space-time concept is the introduction of the idea of a **magnetic body** or **field body** for particles (Topological Geometrodynamics). Each particle is not just a point; it has a body in terms of field lines or flux sheets in TGD. This has found use in TGD's approach to biological systems, where it is proposed that organisms have hierarchical magnetic bodies controlling them – though that lies beyond our current focus on fundamental physics.

World of Classical Worlds (WCW) and Quantum TGD

While the classical theory of preferred space-time surfaces is rich, TGD is fundamentally a *quantum theory*. However, its approach to quantization differs from standard quantum field theory (QFT). In QFT, one usually starts with fields in space-time and then *second quantizes* them (promoting fields to operators, or path-integrating over field configurations). In TGD, the starting point is not fields on a fixed space-time, but the space-time surfaces themselves. The set of all possible space-time surfaces (satisfying appropriate conditions) can be seen as an infinite-dimensional "configuration space." Pitkänen calls this the **World of Classical Worlds (WCW)** – essentially the space of all 3-dimensional spatial surfaces (or 4-surfaces, depending on context) that are permissible in the theory. Quantization in TGD means defining a quantum theory on this space of surfaces. This is an enormous generalization of the Wheeler–DeWitt concept in canonical quantum gravity: instead of a wave functional on the metric of the entire universe, we have wave functionals on the **3-surfaces** that define space-time via embedding.

WCW Geometry and Spinor Fields: A remarkable hypothesis of TGD is that the WCW – the space of all possible 3-surfaces (think of specifying a 3-dimensional "initial" surface in $M^4 \times CP^2$ which then dynamically evolves within a causal region) – has a rich geometrical structure: it is endowed with a *Kähler metric* and even *spin structure*. In fact, Pitkänen conjectures that the WCW is a union of infinite-dimensional symmetric spaces, and it admits a unique (up to scalar) Kähler metric fixed by the huge symmetry requirements of the theory (including general coordinate invariance, superconformal symmetries, etc.). On this WCW, one can then define analogs of *spinor fields*, which represent quantum states. In other words, a *quantum state in TGD* is a kind of spinor-valued functional $\Psi[\text{surface}]$ on the space of 3-surfaces. This is analogous to how in quantum field theory one might have a wave functional $\Psi[\phi(x)]$ depending on a field configuration $\phi(x)$; here the "field" is the embedding of the 3-surface.

Because of this, **quantum TGD can be seen as a kind of third-quantized theory**, or equivalently a "second quantization of geometry itself." Standard QFT already involves second quantization (field operators create particles); TGD replaces ordinary quantum fields with these WCW spinor fields – effectively *second quantized fields living on an infinite-dimensional space* (How quantum TGD differs from standard quantum [physics.html](). In practical terms, the fermionic degrees of freedom of matter are incorporated by considering spinor fields on the space-time surface (these are induced spinors from the $M^4 \times CP^2$ Dirac bundle, often called *induced spinor fields*). The modes of these induced spinors, when quantized, give rise to creation and annihilation operators that act on the WCW spinor field, endowing it with a Fock space structure. Indeed, it has been shown that the Kähler geometry of WCW is directly related to what one would get by second quantizing the *induced spinor fields* on the space-time surface () (). For instance, the infinite-dimensional gamma matrices of the WCW (needed to define the Dirac operator on the WCW) can be identified with quadratic fermionic oscillator operators coming from the space-time spinors (). Thus, the mathematical formalism of TGD's quantum state space resembles a giant *Fock space*, where each "mode" corresponds to an entire 3-surface and is built from fundamental fermionic components.

One convenient way to think of this is: **Replace pointlike particles by 3-dimensional surfaces, and replace ordinary quantum fields by a quantum wave functional on the space of those 3-surfaces** ([How quantum TGD differs from standard quantum physics.html]()). This encapsulates how TGD departs from quantum field theory. There is no fundamental point-particle or even string-like excitation; the fundamental objects are 3D surfaces (and their 4D evolutions), and the "quantum field" is a functional of those. This paradigm eliminates the traditional distinction between "first quantization" (wavefunctions for particles) and "second quantization" (field of many particles). A single WCW spinor field in TGD describes *all* possible many-particle configurations, since a given 3-surface can contain topological features corresponding to multiple particles. The Fock space of the induced spinors essentially encodes the different numbers of particles on a given 3-surface. In short, **TGD realizes quantum physics as geometry**: classical physics corresponds to the geometry of individual space-time surfaces, while quantum physics corresponds to the geometry of the infinite-dimensional space of all such surfaces ([Topological Geometrodynamics]()).

Symmetries and Constraints: The consistency of this enormous quantization scheme relies on several key symmetry principles. TGD requires *General Coordinate Invariance* (GCI) – invariance under diffeomorphisms of the space-time surface – which is inherited from the diffeomorphism invariance of the imbedding space (with an important caveat: $M^4 \times CP^2$ has a huge isometry group $Poincare \times SU(3)$, but space-time surfaces break some of these symmetries, leaving a smaller group that is effectively the analog of general coordinate invariance on X^4). Additionally, there are infinite-dimensional *superconformal* or *symplectic* symmetries: for example, the light-like 3-surfaces (the "partonic" surfaces at the boundaries of space-time regions or at joint boundaries between Minkowskian and Euclidean regions on the surface) support conformal field theory-like degrees of freedom. These symmetries yield constraints analogous to Virasoro conditions in string theory, which TGD uses as quantum conditions to select physical states (the "vanishing of super-conformal charges" acts as gauge conditions picking out the physical subspace of the WCW) (). There is also the so-called **maximal conformal algebra** (actually an algebra related to the group of area-preserving diffeomorphisms on a 2-sphere) which becomes the basic symmetry of WCW in the latest formulation. The presence of these symmetries ensures that the WCW metric and spinor structure can be defined and, remarkably, that the resulting theory avoids the usual UV infinities of quantum field theory – essentially because the infinite-dimensional geometry acts like a natural regulator.

Classical–Quantum Correspondence: TGD insists on a strong form of *classical–quantum correspondence*, meaning every quantum state (a WCW spinor) should correspond to some features of classical geometry of space-time surfaces, and vice versa. This is embodied in the concept that "*classical physics is an exact part of quantum physics*" in TGD. More concretely, the field equations (the extremal conditions of the Kähler action) are not just mean-field equations, but have a direct role in selecting the quantum states: one expects that the quantum average of the induced fields in a given quantum state should correspond to a particular classical space-time surface in the ensemble. This philosophy guides how one identifies observables in quantum TGD and how one connects to the classical world: the geometry of X^4 is to be reflected in the quantum state and vice versa.

In summary, the mathematical foundations of TGD consist of **(1)** a new space-time ontology – space-time as a 4-surface in $M^4 \times CP^2$ with an associated action principle (Kähler action) and conservation laws, leading to many-sheeted space-time and topologically quantized fields; **(2)** an accompanying quantum formulation – physics as an infinite-dimensional geometry of the world of classical worlds (space of 3-

surfaces), in which quantum states are described as spinor fields on this configuration space. These foundations already incorporate a unification of gravitation and standard model interactions at the classical level (via geometry of the imbedding space) and a unification of principles of quantum theory and geometry at the quantum level (quantum states as geometric objects in WCW). With these foundations set, we now turn to the recent developments that refine and extend this framework.

Current Developments (2020–2025)

In the last few years, considerable progress has been made in Topological Geometrodynamics, leading to refinements of its core ideas and resolution of some long-standing issues. Here we outline the major current developments (circa 2020–2025) in TGD, highlighting how they modify or enhance the foundational picture.

M8–H Duality and Number-Theoretic Physics

One of the most significant advances is the concept of **M^8–H duality**, which bridges *two complementary descriptions of space-time surfaces*: one in terms of geometry and one in terms of number theory. "H" denotes the standard *imbedding space* $M^4 \times CP^2$ (sometimes called H), and "M^8" denotes an 8-dimensional Minkowski space (or more precisely, an 8D space with octonionic structure) used for a number-theoretic description. The duality states that physics can be described either in the *H-picture* (four-dimensional dynamics of 3-surfaces in $M^4 \times CP^2$) or in the M^*8-picture*, where space-time surfaces are seen as 8-dimensional algebraic surfaces defined by polynomial equations in an 8D algebraic extension of octonions ([Progress in TGD: M8-H Duality & Zero Energy Ontology | Pitkänen | Prespacetime Journal]). In the M^8-picture, a space-time surface is represented by a condition like $P(x^1, \ldots, x^8) = 0$ for some octonionic polynomial P; the *roots* of these polynomial equations correspond to 4D surfaces when projected to H.

M^8–H duality has led to a deeper understanding of several issues:

- **Causal Diamonds (CDs):** A *causal diamond* is the intersection of a future light-cone and a past light-cone (a diamond-shaped region of space-time with finite time extension). In TGD's H-picture, it was posited that all physical processes occur within a hierarchy of CDs of various sizes – this is part of the **Zero Energy Ontology** to be discussed shortly. Recent work showed that *causal diamonds emerge naturally from the M^8 picture*: in the M^8 description, a space-time region is bounded not by explicit time-like surfaces, but by conditions like two nested light-cones (mass shells). Under M^8–H duality, what corresponds to a region between two mass-shells in M^8 (an "annular" region in momentum space defined by $P = 0$ and bounded by two light-like surfaces in M^8) is mapped to a causal diamond region in H ([TGD diary: TGD as it is towards end of 2021]). In other words, the requirement that a space-time surface in M^8 has a finite temporal extent translates into the statement that the corresponding $X^4 \subset M^4 \times CP^2$ fits inside a CD in H. This result provided a first-principles justification for introducing causal diamonds, which were originally a heuristic part of ZEO – now they appear as a prediction of the octonionic (M^8) formulation ([TGD diary: TGD as it is towards end of 2021]).

- **Algebraic Holography:** M^8–H duality also supports a form of *holography*: data defined on a lower-dimensional set in the M^8 picture (say, the polynomial's structure on roots of unity, etc.) can determine the 4D surface in the H picture. In particular, it has been found advantageous to think in terms of *complexified octonions* and *quaternionic subspaces*: a preferred *quaternionic 4-space* in the 8D space is selected (related to the notion of associative subalgebras of octonions), and this corresponds to the physical space-time surface. The duality and the requirement of "quaternionicity" or "holomorphicity" of the surface in the appropriate sense impose powerful constraints on what kind of 4-surfaces are allowed. This has led to the concept of **number theoretic holography**, wherein the space-time surface is partly characterized by algebraic data (like values of coordinates that are algebraic numbers) at special points (e.g., partonic 2-surfaces or their M^8 counterparts). Solving field equations in TGD may thus reduce to solving algebraic conditions (polynomial equations), a dramatic simplification due to the underlying octonionic structure () ().

- **Galois Groups and Confinement:** Closely related to the M^8 picture is the introduction of *Galois groups* (groups of field symmetry of algebraic number extensions) into physics. Pitkänen's recent work suggests that each space-time surface – characterized by a particular polynomial in the octonionic M^8 – comes with an associated algebraic number field (the splitting field of that polynomial, for instance). The Galois group of this field can be seen as a *fundamental symmetry or "horizontal" symmetry* relating different sheets of the many-sheeted space-time. An exciting application of this idea is **Galois confinement**. The proposal is that the momenta of fundamental fermions (like quarks) are quantized such that, in appropriate units, their components are *algebraic integers* in some number field; however, when these fermions form bound states (e.g., three quarks forming a proton), the combined state corresponds to a Galois singlet for which the sum momenta are ordinary integers (TGD diary: TGD as it is towards end of 2021). In essence, free quark states would require algebraic (non-integer) momenta which are not observed – nature only realizes Galois-singlet states as asymptotic states, thereby explaining confinement in number-theoretic terms. The momenta of a bound state like a hadron would lie in the base field (e.g., rationals) while the internal constituents' momenta live in an extension field (e.g., a cyclotomic field). The condition that the total momentum is in the base field forces the allowed combinations of constituents. As Pitkänen puts it, *quark momenta in suitable units are algebraic integers, but for a Galois-singlet bound state (like a physical hadron) those momenta sum up to an ordinary integer* (TGD diary: TGD as it is towards end of 2021). This is a novel approach to confinement, not via a potential or a flux tube in the usual sense, but through an arithmetic "bookkeeping" that disallows isolated non-integer states.

- **Hierarchy of Planck Constants:** The M^8–H duality and number-theoretic approach also yield insight into the so-called hierarchy of effective Planck constants. In earlier TGD, a crucial hypothesis was that Planck's constant h (or rather $\hbar$) can have effective values that are integer multiples of the standard $\hbar_0$: $\hbar_{\rm eff} = n, \hbar_0$. These large effective $\hbar$ phases were associated with what TGD calls "dark matter" (not dark matter in the usual cosmological sense, but in the sense of matter that behaves quantum coherently on macroscopic scales by virtue of having an enlarged $\hbar$). Recent work links n – the integer defining $\hbar_{\rm eff}$ – to the *dimension of the Galois group or number field extension associated with the space-time surface* (). Specifically, n can be identified with the degree of the polynomial defining the surface in M^8, which is also the size of the Galois group of that polynomial. This means that the effective Planck constant is larger for systems whose description requires a larger algebraic extension of rationals. Physical intuition suggests that more complex systems (with more particles entangled, or with more layers of space-time sheets) correspond to larger extensions, and hence can behave as if $\hbar$ is larger. This formalizes the earlier heuristic that nature has a *generalized coupling constant hierarchy* in which macroscopic quantum phases (like those in living matter or in certain astrophysical objects) have large $\hbar_{\rm eff}$ (Topological Geometrodynamics) (). The *"book-like" structure of the imbedding space* – the idea that there are multiple sheets of $M^4 \times CP^2$ stacked like pages, each page corresponding to a different value of $\hbar_{\rm eff}$ – is now grounded in algebraic geometry: each page corresponds to choosing a different extension of the rationals for defining the space-time surface (Topological Geometrodynamics).

In summary, M^8–H duality has infused TGD with *number theoretic content*: physics laws might be seen as statements about algebraic surfaces and their symmetries. This duality has tightened the connection between TGD and fields like algebraic geometry, while also providing new ways to understand physical phenomena such as confinement and dark matter as consequences of deep arithmetic properties (TGD diary: TGD as it is towards end of 2021) ().

Zero Energy Ontology (ZEO) and Quantum Measurement Theory

Another pillar of modern TGD is the **Zero Energy Ontology (ZEO)**, which represents a fundamental shift in the understanding of quantum states and processes. In ZEO, *all physical states have net zero conserved quantum numbers*. Rather than thinking in terms of an initial state evolving unitarily to a final state (as in conventional quantum mechanics), ZEO posits that any physical state can be viewed as a *pair of "bra" and "ket" states – one at the future boundary of a finite space-time region and one at the past boundary*. These two boundaries (usually taken as the two light-like boundaries of a causal diamond, as introduced earlier) carry opposite quantum numbers, so the overall state is a zero energy state. Essentially, a single physical event or object is like a "matrix element" between an initial and final state, and the only allowed overall states are those closed in this sense.

Under ZEO, a quantum "measurement" or "state function reduction" has a very different interpretation. In ordinary quantum theory, a measurement randomly collapses a state to an eigenstate and resets the system's state. In TGD's ZEO, a distinction is made between two types of state function reductions:

- **Small State Function Reductions (SSFRs):** These are analogous to weak measurements or mere increments in information without changing the overall ZEO state. Under an SSFR, the *"arrow of time"* – which boundary of the CD has the unaffected (fixed) state and which has the evolving state – remains the same. One can have a sequence of SSFRs which, roughly speaking, corresponds to a sequence of observational events that *do not change the net quantum numbers* and do not collapse the entire structure.
- **Big State Function Reduction (BSFR):** This is the TGD counterpart of a "quantum jump" that resets the state in a major way. In a BSFR, the roles of the past and future boundaries swap: what was the fixed bra becomes the new initial state and vice versa. This can be thought of as the *arrow of time reversing for the subsystem involved*. After a BSFR, subsequent SSFRs would occur with the opposite arrow of time (until another BSFR happens).

This rather surprising idea leads to the notion that the *flow of time and quantum measurements are intimately connected*: normally, systems have a definite arrow of time (from past to future) because they are in a specific ZEO state with, say, the past-end of the CD being "prepared" and the future-end "open." A BSFR flips this, which TGD associates with the concept of "death" of a conscious entity and rebirth with opposite time arrow, in its speculative consciousness theory. But even at a more pedestrian level, ZEO offers a solution to the infamous measurement paradox of quantum mechanics. In ZEO, *quantum states are not absolute states at a time, but rather whole histories between two times* (). Thus a "state" is already akin to a quantum transition or process. The collapse (BSFR) does not mysteriously choose one state out of infinitely many; it rather changes the boundary conditions of the history. This way, **ZEO "solves the basic paradox of quantum measurement theory" by reconceptualizing quantum states as time-symmetric entities** ().

To be more concrete, in ZEO the counterpart of the usual S-matrix (which evolves initial to final state) is something called the **M-matrix**, which is effectively the "half" of a unitary S-matrix – conceptually like a square root of a density matrix. The M-matrix is defined as the collection of *"entanglement coefficients between the positive-energy part and the negative-energy part of a zero energy state"* (Topological Geometrodynamics). These coefficients play the role of probabilities (technically, they are related to the concept of *Connes tensor product* in von Neumann algebra theory, ensuring a mathematically sound definition). The M-matrix is "almost unique" given the symmetries, and it unifies quantum theory with thermodynamics by providing a built-in thermal interpretation (the negative energy part can be seen as akin to a "heat bath" or past state) (Topological Geometrodynamics). In fact, Pitkänen describes this as *quantum theory as a square root of thermodynamics* (Topological Geometrodynamics) – a poetic way of saying that the Born rule probabilities (squares of amplitudes) emerge as *entanglement probabilities* in a two-state system and thus have a form reminiscent of thermal weights.

ZEO has also led to new insights in particular areas:

- **Quantum Measurement and Consciousness:** (While not the focus of this report section, it's worth noting as current research) Pitkänen has integrated ZEO with a theory of consciousness, where the sequence of SSFRs is identified with the "flow of thought" or the life of a conscious entity, and a BSFR corresponds to a "large" shift such as the death of a conscious entity and the creation of a new one with opposite time orientation (). This provides a novel angle on why we experience a definite arrow of time and why we never see violations of causality: any subprocess that might have reversed arrow is segregated into a different CD context that doesn't interfere with ours, or happens at scales we don't directly perceive (some TGD-inspired explanations for anomalous effects in neuroscience and quantum biology invoke this idea).

- **Consistency with Macroscopic Causality:** ZEO might seem to allow strange effects (like future influencing the past) due to its time-symmetric setup. However, in TGD this is controlled. The "generalized causality" is such that one *cannot* send signals to one's own past in the ordinary sense, because once a BSFR occurs and flips the time arrow, the system that did so is effectively now propagating in the opposite time direction in its own CD, and from our point of view, it looks like an anti-system moving forward in time. This is closely related to the idea that antiparticles in QFT are particles moving backward in time. In TGD, an object and its time-reversed counterpart are literally the same object seen in two different ZEO phases. This is actually elegant in explaining certain CP and time-reversal asymmetries: TGD suggests that whenever a "big" quantum jump occurs, it might induce an effective T violation that could even relate to matter–antimatter differences.

In practical terms, ZEO means that when we compute amplitudes in TGD, we do so between an initial and final state which are both specified (the state is like a *bra-ket pair* $\langle \mathrm{bra}|\mathrm{ket}\rangle$). But we only have access to one end (the one corresponding to the past, normally). The other end behaves like a "boundary condition at infinity". The outcome is that one can build a theory of scattering where the usual notion of time-evolution is replaced by these ZEO-based transitions. Indeed, understanding how to compute scattering amplitudes in ZEO has been a major goal and recent progress indicates that the WCW Kähler metric itself might contain the key to constructing a unitary S-matrix or its generalization ().

To summarize ZEO: It is a radical re-interpretation of quantum ontology wherein *every physical object or event is described as a zero energy state – essentially a finite space-time story with a beginning and end*. This addresses the measurement problem by making collapse a natural "end of story" (a big jump that closes a CD and opens a new one) rather than a mysterious non-unitary process. Over 2020–2025, ZEO has been a cornerstone of TGD's narrative, and much effort has gone into elaborating its implications for quantum measurement, thermodynamics, and even the arrow of time in cosmology () ().

Towards a Twistor Lift of TGD

A more technical but crucial development is the incorporation of **twistor methods** into TGD. Inspired by Roger Penrose's twistor theory and its successful adaptation in string theory (e.g., Witten's twistor string for $\mathcal{N} = 4$ SYM), Pitkänen has sought a "twistor lift" for TGD. The basic idea is to associate to the ordinary imbedding space $M^4 \times CP^2$ a 12-dimensional *twistor space* (for example, the twistor space of M^4 is $M^4 \times S^2$, and the twistor space of CP^2 is obtained by adding a fiber $\approx S^2$ as well). The twistor lift of TGD involves introducing a new part to the action: a term that depends on the self-dual (or anti-self-dual) part of the curvature, which effectively acts like a cosmological constant term. Indeed, one outcome of the twistor lift is a natural explanation for the presence of a small **cosmological constant**: the twistor lift predicts that in addition to the Kähler action, the action contains a volume term with a fixed coefficient, giving rise to a tiny cosmological term in the four-dimensional effective theory ().

Concretely, the twistor lift can be thought of as extending each point of the space-time surface into a fiber (like a small sphere S^2 representing the twistor sphere of possible light-like directions at that point). The *twistor space of* $M^4 \times CP^2$ has dimension $4 + 2 + 4 + 2 = 12$. In this 12D space, one can impose a requirement that a physical space-time surface lifts to a *6-dimensional holomorphic surface* in the twistor space of CP^2 and similarly an associate in the twistor space of M^4. Solving these conditions yields that the space-time surface is not just an extremal of the Kähler action but also a *minimal surface* (extremal of volume) in $M^4 \times CP^2$ (). This means that a specific ratio of the Kähler action and volume action is fixed. The presence of both terms is like having both the Maxwell (Kähler) and Einstein-Hilbert (volume/cosmological) terms. By tuning these via the twistor principle (holomorphicity in twistor space), one gets field equations that are *algebraic (holomorphic) conditions rather than differential equations* (). This dramatically simplifies the problem of solving the theory: the field equations in the twistor-lifted theory reduce to stating that the space-time surface is a certain type of complex submanifold (a *"Kähler calibrated" surface*).

Some highlights from twistor-lift research:

- The twistor lift leads to an explanation of why preferred extremals of the action are not only solutions to a "unified field equation" but actually *minimal surfaces* (i.e., they satisfy something like $K_{\mu\nu} = \Lambda g_{\mu\nu}$, a sort of mean curvature condition). This combined with the Kähler condition implies *quantization conditions* on coupling constants so that no explicit coupling parameters appear in the field equations ().

- It provides a more rigorous way to handle **massless degrees of freedom** (like the graviton) and **scattering amplitudes**. Twistor methods have excelled in simplifying scattering amplitude calculations in ordinary quantum field theory. In TGD, the hope (partially realized) is that formulating the theory in twistor space clarifies how to build scattering amplitudes that respect all TGD symmetries. Indeed, some recent work examines the relationship between twistors, permutations and braidings of partonic 2-surfaces, and how these might encode the analog of Feynman diagrams in TGD () (). There is a conjecture that scattering amplitudes can be written as *sums over collections of wormhole contacts (string world sheets) such that each corresponds to a "multi-twistor" configuration*, effectively yielding an *"effective reduction of string theory"* within TGD's twistor lift (). This means that although TGD is fundamentally not string theory, in the twistor formulation and in perturbative expansion, each term behaves like a string theory diagram (with string world sheets living on the 4-surface and connecting partonic 2-surfaces).

- The twistor lift also ties into the concept of **three dualities** of field equations that Pitkänen notes: much like the AdS/CFT or S-duality in string theory, TGD with twistor lift exhibits dual descriptions (M^8 vs H, strong vs weak form of holography, and the duality between Kähler action and volume action). Understanding these can help in proving consistency and possibly equivalence of various ways of calculating observables ().

In the big picture, the twistor lift adds credibility to TGD by embedding it in a methodology that has had success in conventional theoretical physics. It shows that TGD's exotic ideas (like huge configuration spaces and number theoretic physics) can still be made to output concrete calculations, e.g., of scattering amplitudes, via twistor techniques. It also makes TGD more palatable by showing it yields an effective low-energy action containing general relativity with a small cosmological constant – something empirically true (we do observe a tiny cosmological constant). In fact, Pitkänen argues that in the twistor-lifted TGD, *dark energy and dark matter find a natural geometric explanation*: the original primordial objects in TGD cosmology are lightlike 2D surfaces (cosmic strings) which, through twistor lift and cosmic evolution, "thicken" into 4D flux tubes whose energy is split between ordinary matter and dark energy (). The cosmological constant in TGD is not put by hand but emerges from this twistor structure, and its extremely small value is related to the huge size of cosmological space-time sheets (i.e., the volume term is almost negligible for small sheets but cumulative for largest sheets).

Other Ongoing Developments

Finally, we list a few additional research frontiers in TGD (2020–2025) that complement the above major themes:

- **Relationship to Standard Model Physics:** There have been updates on how standard model fermions and bosons are realized in TGD. A concept called **bosonic emergence** is hypothesized, where all elementary bosons (W, Z, gluons, photon, graviton) are actually bound states of fundamental fermions and antifermions on the space-time surface (this is somewhat analogous to gauge bosons as bilinear combinations of fermionic operators in some grand unified models) (Topological Geometrodynamics). TGD provides a topological explanation for family replication: fermions come in three generations because of the topology of their 2-dimensional partonic surfaces (handles on genus-0 surface, etc.), related to the three separate complex structures of CP^2. Over 2020–2025, detailed work has been done to match observed particle masses and mixing angles with TGD's p-adic mass calculations and topological considerations, refining earlier successes in this domain.

- **SUSY and TGD:** TGD does not have conventional supersymmetry (no superpartners at the TeV scale in the usual sense), but it has an alternative: supersymmetry is associated with the right-handed neutrino and is badly broken for other particles. This means only right-handed neutrino and left-handed antineutrino modes can be seen as generating a modest supersymmetry. This idea was revisited with the number theoretic perspective, suggesting that "supersymmetry" in TGD might correspond to mixing of different p-adic length scales or something to do with algebraic extensions ().

- **p-Adic and Adelic Physics:** TGD's use of p-adic numbers has been deepened. The concept of **adelic physics** (simultaneous consideration of all completions of the rationals: real and various p-adics) aligns perfectly with TGD's number theory approach. In 2020s, Pitkänen has articulated how physical observables could be adelic invariants – yielding predictions that normally hold in the real sector but are rooted in p-adic analyticity. For example, p-adic mass calculations for hadrons and leptons have been updated, and new anomalies (like a possible M_{89} hadron physics, indicating a copy of QCD at a vastly higher mass scale around $10^{(-89)}$ times some scale) were investigated ().

- **Quantum Biology Connections:** Although at the periphery of fundamental physics, one cannot ignore that a lot of TGD's latest attention (especially by Pitkänen himself) goes into explaining biological and neurophysical phenomena. Using the hierarchy of Planck constants and ZEO, TGD proposes mechanisms for things like quantum coherence in biosystems, the functioning of sensory perceptions, and even collective consciousness. For instance, the idea of "DNA as topological quantum computer" with braidings, or "membrane proteins and EEG frequencies via Josephson junctions" are being developed. These ideas remain speculative but serve as potential tests of TGD at the intersection of physics and life – something no other theory of quantum gravity attempts.

Each of these developments reinforce TGD's identity as a comprehensive, if unconventional, framework: it is not just about quantum gravity in isolation, but about unifying physics and even integrating physics with other domains like cognition. The period 2020–2025 has been about *refining the theory to correct past misconceptions and integrate new mathematical tools*, making TGD more robust and ready for critical comparison with other theories, as we shall do next.

Outdated Concepts and Historical Perspectives

Topological Geometrodynamics has undergone a long evolution since its inception in the late 1970s. Understandably, some early ideas and conjectures were later found to be incomplete or incorrect, and the modern version of TGD has moved past them. In this section, we highlight several key concepts from TGD's historical development that are now considered *outdated*, and clarify how the current understanding differs. This will also serve to correct misinterpretations that might persist from older literature.

Early Einstein–Maxwell Analogy and its Correction

What was the old idea? In the early stages of TGD, it was noted that if one decomposes the geometry of $M^4 \times CP^2$, the 4-dimensional part (M^4) could be associated with gravitation and the CP^2 part with gauge fields. Pitkänen speculated that the classical field equations of TGD might effectively reduce to *Einstein's field equations for gravitation coupled with Maxwell's equations for an electromagnetic field*. The "electromagnetic" field in this analogy is the induced Kähler field from CP^2. For a while, he conjectured that preferred extremal surfaces of the Kähler action correspond to 4D space-time geometries that satisfy something like $G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T^{(K)}_{\mu\nu}$ (an Einstein equation with a cosmological constant term and stress-energy from the Kähler field). Indeed, he found that in many explicit solutions ("vacuum extremals"), the induced fields behave like a classical electromagnetic field with energy-momentum tensor that could serve as the source in an Einstein equation (What Are the Counterparts of Einstein's Equations in TGD?, viXra.org e-Print archive, viXra:1309.0055). This led to the impression that *TGD = Einstein gravity + Maxwell field in disguise*.

What is the current view? This analogy turned out to be too simplistic and, in places, incorrect. The modern understanding is that *TGD's field equations are more general than Einstein-Maxwell and do not strictly imply Einstein's equations except in an approximate or special-case sense*. The true fundamental condition is the vanishing divergence of the energy-momentum tensor of the induced Kähler field: $\nabla^\mu T^{(K)}_{\mu\nu} = 0$ (What Are the Counterparts of Einstein's Equations in TGD?, viXra.org e-Print archive, viXra:1309.0055). In a general relativistic context, $\nabla^\mu T_{\mu\nu} = 0$ is a consequence of Einstein's equations (thanks to Bianchi identity), but here it is postulated without requiring $G_{\mu\nu} = \kappa T_{\mu\nu}$. In fact, Pitkänen demonstrated that the *space of allowed solutions is much larger than the space of solutions to any Einstein-Maxwell system*. For example, there exist "vacuum extremals" of the Kähler action in TGD which carry no induced fields ($T^{(K)}_{\mu\nu} = 0$) but are not trivial geometries – some of these embed standard cosmological solutions (like de Sitter or Robertson–Walker spaces) into $M^4 \times CP^2$ in a way that Einstein's equations would not allow except with a special cosmological term. This showed that **the original hypothesis (TGD extremals = solutions of Einstein-Maxwell with Λ) was *too restrictive*** (What Are the Counterparts of Einstein's Equations in TGD?, viXra.org e-Print archive, viXra:1309.0055). It had to be abandoned because it fails for perfectly good TGD solutions.

The resolution was to realize that Einstein's equations in TGD are only *effective*, describing how an observer who cannot resolve the many-sheeted structure sees gravity. At the fundamental level, TGD's classical equations are not those of 4D General Relativity. Instead, the condition $\nabla \cdot T^{(K)} = 0$ serves as a master equation. In particular, Minkowskian regions of the space-time surface with nonzero Kähler field can mimic a stress-energy that would satisfy Einstein-Maxwell equations in an *effective metric* (the sum of the Minkowski metric and small deviations from various sheets) ([TGD and GRT.html] (https://www.tgdtheory.fi/webCMAPs/TGD and GRT.html#::text=ti,variance%20could%20have)). One can show that if you define $g^{\rm eff}_{\mu\nu} = \eta_{\mu\nu} + \sum_i h^{(i)}_{\mu\nu}$ as the sum of the induced metric contributions from various space-time sheets labeled by i, then under some conditions $g^{\rm eff}_{\mu\nu}$ will satisfy $G_{\mu\nu}(g^{\rm eff}) = T^{\rm eff}_{\mu\nu}$ where $T^{\rm eff}_{\mu\nu}$ includes contributions from the Kähler fields on all sheets (TGD and GRT.html). In that sense, Einstein's equations hold *in the emergent sense*, but not for the fundamental metric (which is flat M^4 metric on each sheet) – they hold for a meta-metric describing the stack of sheets.

In summary, the early *Einstein–Maxwell analogy*, while pedagogically useful, is **not exact**. TGD does not simply reduplicate Einstein's General Relativity plus electromagnetism; it generalizes the concept in a way where local conservation laws (and a kind of "effective variational principle" with projector decompositions (What Are the Counterparts of Einstein's Equations in TGD?, viXra.org e-Print archive, viXra:1309.0055)) replace the simple Einstein equations. Modern TGD texts explicitly caution that assuming an Einstein-Maxwell form was a too narrow ansatz and that the theory actually *forces a generalization of Einstein's equations beyond what General Relativity allows* (What Are the Counterparts of Einstein's Equations in TGD?, viXra.org e-Print archive, viXra:1309.0055) (What Are the Counterparts of Einstein's Equations in TGD?, viXra.org e-Print archive, viXra:1309.0055). This correction is important to avoid misinterpreting TGD as something already covered by known physics – it is a distinct theory with its own equations.

Misconceptions about Quantization and "Second Quantization"

What was the old idea? In the early development of quantum TGD, there was some ambiguity in how to describe the relationship between TGD and standard quantum field theory. Because TGD seemed to imply a quantum theory of 3-surfaces (the WCW picture) which encompassed many-particle states automatically, Pitkänen often emphasized that *TGD does not need second quantization in the usual sense*. Sometimes he phrased this as "in TGD, everything is classical, but in an infinite-dimensional sense" or conversely "quantum TGD is achieved by second quantizing induced spinors, not by second quantizing the 4D fields." These statements led to confusion. Some readers took it to mean that TGD was a kind of *deterministic classical theory* (which is false – it is a quantum theory, but formulated geometrically), or that TGD denied the existence of quantum field quanta, or that it was only a theory of single particles, etc. Another source of confusion was the term "third quantization" occasionally used to describe the WCW spinor field concept – it made it sound as if an infinite tower of quantizations was needed.

What is the current view? The contemporary understanding clarifies that **TGD fully accepts the principles of quantum mechanics and quantum field theory, but implements them in a novel way**. The phrase "no second quantization needed" was an overstatement. It is more accurate to say: *in TGD, the analog of second quantization already happens at the level of WCW and induced spinors.* We saw in the Mathematical Foundations that the configuration space spinor field is indeed constructed using creation and annihilation operators corresponding to the modes of induced fermion fields () (). So, TGD does have a Fock space and particle excitations, just like ordinary QFT – they are encoded in the structure of the WCW wave functional. The difference lies in what is being quantized:

- In ordinary QFT, one starts with a classical field $\phi(x)$ and then one promotes ϕ to an operator (or path integrates over ϕ). The quanta are particles located at points of space(-time).
- In TGD, one starts with a classical *3-surface* (carrying classical induced fields), and one promotes the *modes of the induced spinor field on that 3-surface* to operators. The quanta are contributions to the WCW spinor – effectively, adding a particle to a state corresponds to acting with a creation operator that inserts a fermionic mode on the 3-surface.

From the point of view of an observer in space-time, TGD's "quantum" does appear as a particle: for instance, an electron is a certain topological feature (a handle or vortex or genus on the 3-surface) accompanied by a specific induced spinor mode. The creation operator for that mode increases the eigenvalue of certain charges by one unit, etc., just like an electron creation operator in QFT would. Thus, **TGD does not do away with field quanta or particle excitations at all; it simply merges the concept of particle into the geometry of space-time and the algebra of spinor modes** ([How quantum TGD differs from standard quantum physics.html](https://www.tgdtheory.fi/webCMAPs/How quantum TGD differs from standard quantum physics.html#:~:text=STANDARD%20QUANTUM%20FIELD%20THEORY%3F%202,state%20function%20reduction%2C%20Zero

The phrase "repeated second quantization" appears in TGD literature in a different context: Pitkänen has drawn analogies between the structure of WCW and *iterated second quantization of arithmetic QFTs* () (). This means if one had a hierarchy of fields of fields of fields (e.g., fields whose arguments are themselves field configurations, etc.), one would get something like TGD's WCW. But in practical terms, we do *not* perform an infinite regress of quantizations in TGD. One quantization – to get the WCW spinor field – suffices, because that step already includes all multi-particle states.

So the misconception to correct is: **TGD is a quantum theory that contains quantum field theory as a limiting case; it is not a purely classical theory, nor does it avoid the concept of creation and annihilation operators.** It does, however, avoid the traditional functional integral over 4D fields. Instead, it involves an integral/sum over 3-surfaces (the "world of classical worlds"). The result is that UV infinities and some other issues of QFT are tamed, but the physical content (existence of photons, gluons, etc., as quanta) remains intact. In short, any statement implying "TGD does not use second quantization" should be understood as "TGD implements second quantization differently, via the geometry of WCW." Modern expositions emphasize that *quantum TGD can be seen as second quantization of the induced spinor modes of the embedding space* () (). The upshot is that the quantum dynamics of TGD is very much like a quantum field theory (one can derive Feynman diagram analogs, S-matrix elements, etc., albeit with new twists due to ZEO and topology), and earlier fears that it might be non-quantum or contradictory to quantum principles have been allayed.

Other Historical Shifts

- **Role of p-Adic Numbers:** Initially, p-adic numbers entered TGD as a strange add-on hypothesis in the 1990s to explain mass spectra. It might have seemed optional or speculative. Now, however, p-adic number fields are integral to TGD's identity – they are part of the number theoretic vision. The *p-adic length scale hypothesis* (that each particle is characterized by a p-adic prime and that masses follow from p-adic thermodynamics) was empirically successful early on. Over time, it became *derived* from deeper principles (M^8–H duality and extension of rationals). So what was once a heuristic rule is now a theorem candidate. The historical shift is from *"p-adic hypothesis"* to *"p-adic and adelic physics as a pillar of TGD"*.

- **Dark Matter Hierarchy:** The concept of an entire hierarchy of Planck constants was introduced around 2006 to explain various anomalies (like quantal effects in living systems and astrophysics). This was originally a phenomenological layer on TGD, but in the current view, as discussed, it is explained by the mathematics of large algebraic extensions (and thus not just an ad hoc addition). So the idea remains but its foundation is sturdier.

- **Classical Conservation Laws:** In earlier versions of TGD, there was worry about whether energy and momentum are conserved in the many-sheeted context (since gravity in a finite region might seem not to have global energy conservation). Now, with ZEO, classical conservation laws are seen in a new light and are respected in a more nuanced way. For example, classical four-momentum is conserved in every "zero energy state" by construction (the outgoing and incoming momenta sum to zero). Angular momentum conservation led to the notion of a *cosmic spin glass* of CDs, which was not present initially.

- **Strong Form of Holography (SH):** More recently, Pitkänen has introduced what he calls SH: the idea that data on 2-dimensional partonic surfaces and 1-dimensional strings at their boundaries uniquely determine the space-time surface (a strong form of the holographic principle). This was not part of original TGD but is a later addition influenced by black hole holography and AdS/CFT. SH is now a guiding principle in solving the theory, but obviously was absent in 1980s TGD. This indicates how TGD has absorbed lessons from mainstream theoretical physics over time.

In conclusion, the trajectory of TGD shows a pattern of bold conjectures being refined into solid theory. The **outdated concepts** – such as the literal Einstein-Maxwell equivalence and misconceptions about quantization – have been replaced with a more accurate and generalized understanding. The theory has moved closer to standard physics formalisms in some ways (embracing things like twistor methods, better understanding of how GR emerges, etc.) while also becoming more radical in others (zero energy ontology, number-theoretic physics). By drawing these distinctions between past and present, we ensure clarity going forward and avoid conflating earlier speculative ideas with the polished framework TGD is today.

Comparisons to Other Quantum Gravity Theories

Topological Geometrodynamics is one among several approaches aiming to unify gravity with quantum physics. It is illuminating to compare and contrast TGD with other prominent theories of quantum gravity and unification, notably **superstring/M-theory** and **loop quantum gravity (LQG)**. We also briefly note comparisons with a few other approaches (such as twistor theory and holographic duality) when relevant. Below, we outline key similarities and differences:

TGD vs. String Theory

- **Fundamental Degrees of Freedom:** String theory posits that the fundamental objects are one-dimensional strings (with vibrational modes corresponding to particles). TGD, by contrast, posits 3-dimensional surfaces (extended objects of spatial dimension 3, or space-time dimension 4 when including time) as fundamental ([Topological Geometrodynamics](#)). In a sense, TGD can be thought of as a higher-dimensional extended object theory – *3-branes instead of strings*. However, TGD's 3-surfaces propagate in an 8-D target ($M^4 \times CP^2$), whereas superstrings propagate in a 10-D target (often $M^{9,1}$ or with compactified extra dimensions like Calabi–Yau manifolds). A string has a 2D world-sheet; a TGD surface has a 4D world-volume.

- **Embedding Space and Background:** Both string theory and TGD use a fixed *embedding space (background spacetime)* as part of their formulation. This is in contrast to loop quantum gravity (see below) which is background independent. In string theory, one usually assumes a fixed 10D background (which might be flat or a fixed curved geometry like $AdS_5 \times S^5$, etc., depending on context). TGD explicitly assumes the background $M^4 \times CP^2$ with a flat Minkowski metric and the standard Fubini-Study metric on CP^2. Thus, neither theory is *manifestly background-free* in the sense of General Relativity; they both start with a chosen geometry for the universe (though string theory in principle allows different backgrounds, they are chosen and then strings quantized on them). A difference is that string theory's extra dimensions can be *generic* (any Calabi–Yau or orbifold consistent with supersymmetry), whereas TGD's extra dimensions are uniquely fixed as CP^2 by a priori theoretical arguments (like the existence of a spinor structure and the standard model group embedability) ([Topological Geometrodynamics](#)).

- **Supersymmetry:** Superstring theory heavily relies on supersymmetry (either in 10D or 11D M-theory, and typically requires supersymmetry breaking to match the real world). TGD as it stands does not incorporate conventional SUSY – instead it has an unconventional view where only an N=1 SUSY generated by right-handed neutrinos might exist, which would be badly broken for other particles. Thus TGD in its current form does not predict superpartners for, say, electrons or quarks at accessible energies, unlike many string-inspired models. In this sense, TGD is *less supersymmetric* but more symmetric in other ways (infinite-dimensional conformal symmetries, etc.).

- **Dimension of "World" vs "Target":** In string theory, the fundamental world-sheet is 2D and the target space is 10D (or 11D in M-theory if you include branes). In TGD, the fundamental "world-sheet" is actually a 3-surface (3D at a given time, 4D as it evolves) and the target is 8D. This difference means that string theory's mathematics is based on 2D conformal field theory (which is extremely powerful due to holomorphic factorization and the infinite-dimensional Virasoro symmetry). TGD, dealing with 3-surfaces, does not have the luxury of 2D CFT techniques on the whole 3-surface (however, TGD *does* have 2D surfaces – the partonic boundaries – which behave like 2D CFT and give it an infinite-dimensional symmetry algebra analogous to conformal/Virasoro algebra) ([How quantum TGD differs from standard quantum physics.html](https://www.tgdtheory.fi/webCMAPs/How quantum TGD differs from standard quantum physics.html#:~:text=STANDARD%20QUANTUM%20FIELD%20THEORY%3F%202,state%20function%20reduction%2C%2 String theory needed 10D for anomaly cancellation and to incorporate gravity; TGD's 8D choice is made to incorporate the standard model symmetries and gravity in a different way, and TGD achieves anomaly cancellation via its unique infinite-dimensional symmetries.

- **Quantum Formulation:** In string theory, one quantizes the string by promoting the coordinates $X^\mu(\sigma, \tau)$ to operators or by path integrating over them. The result is a particle Fock space (excited modes of the string correspond to particles like graviton, etc.). In TGD, one does not quantize the 4D surface in the same way; instead one quantizes via the WCW approach (a functional integral or, more properly, a functional quantum wave equation on the space of surfaces). Despite this difference, both approaches ultimately yield a *state-space that is a Fock space of particle-like excitations*. String Fock space has creation operators $a_n^\dagger$ for string modes; TGD's state space has creation operators for induced spinor modes on 3-surfaces (). Both theories naturally include a massless spin-2 particle in their spectrum: string theory has the graviton in the closed string sector; TGD has the massless graviton emerging from the 4-dimensional general coordinate invariance and induced spin-2 excitations (in the weak-field limit, TGD's many-sheeted graviton imitates GR's graviton).

- **Role of Number Theory:** Traditional string theory is not number-theoretic (though there are corners like AdS/CFT and amplituhedron developments that hint at number theoretic and combinatorial structures). TGD is *explicitly number theoretic*, making significant use of p-adic numbers, extension of rationals, etc., as described. This is a philosophical and methodological difference: string theory is a continuum theory with real manifolds and requires extra conditions (modular forms, etc.) for consistency, whereas TGD boldly incorporates algebraic discretization (rationals, algebraics) at a foundational level (e.g., the idea that physics should not depend on the choice of big algebraic extension – a concept of *adelic physics*). In that sense, TGD is closer to approaches like *arithmetical physics* or certain ideas in *quantum logic*, none of which are mainstream.

- **Testability and Development Stage:** String theory has a huge community, a well-established (though not rigorously proven) mathematical framework, and has generated concrete calculations (e.g., scattering amplitudes at tree and loop level, myriad compactification scenarios connecting to particle physics). However, it still lacks experimental support and has the issue of the "landscape" of solutions. TGD is a more solitary endeavor with a single main proponent; it is less developed in terms of mainstream recognition. It claims a more unique solution (no landscape: $M^4 \times CP^2$ is fixed) but as a consequence it must match the real world exactly or fail. TGD has made various sharp predictions (particle mass calculations, exotic particle states, cosmological models), some of which are interesting, but it also does not have mainstream experimental confirmation. In terms of maturity, string theory has established ways to do calculations in low-energy effective field theories (like computing supersymmetry breaking effects, etc.), whereas TGD's calculational machinery (e.g., constructing the M-matrix or scattering amplitudes using strong form of holography and WCW geometry) is still under development and mostly at the conceptual stage.

- **Holography and Dualities:** In the era of AdS/CFT, string/M-theory has embraced holographic duality – e.g., a 4D gauge theory can be equivalent to a 5D string theory. TGD also exhibits a kind of holography: data on 2D partonic surfaces and 4D tangent space of CP^2 can determine the 4D space-time interior (strong holography). However, TGD's holography is of a *different flavour* – it is tied to the deterministic dynamics of surfaces via octonionic analyticity (SH, "strong form of holography"), rather than being a duality between two physical theories. In TGD, one might say there is a duality between the description in terms of space-time surfaces (physical spacetime) and in terms of algebraic surfaces in M^8 (a number-theoretic "momentum space" description), i.e., M^8–H duality is analogous to a duality between two formulations of the theory ([Progress in TGD: M8-H Duality & Zero Energy Ontology | Pitkänen | Prespacetime Journal]). String theory has various dualities (S, T, U-dualities, mirror symmetry, etc.) exchanging strong/weak coupling, electric/magnetic charges, etc. TGD's analog would be symmetries like the exchange of space-time and causal domains in ZEO (like P, CP, time reversal symmetries at deeper level) and the translational symmetry of the cosmic time (i.e., an entire fractal hierarchy of CDs). These are not as well studied as string dualities.

In broad strokes, **TGD and string theory share the vision of a unifying framework with extended objects in higher-dimensional space, but they diverge in the choice of dimensionality, the role of supersymmetry, the approach to quantization, and the integration of number theory.** String theory is more established and conventional (in method if not in content), whereas TGD is more radical by reconstructing physics from geometry and arithmetic with less reliance on existing paradigms like QFT Lagrangians or SUSY. They also target slightly different domains: string theory naturally includes quantum gravity and is often studied in near-supersymmetric regimes or high-energy limits, whereas TGD insists on covering everything from quantum gravity to low-energy hadronic physics and even biological phenomena under one roof.

TGD vs. Loop Quantum Gravity

- **Background Independence:** A key selling point of loop quantum gravity is that it quantizes spacetime geometry *without assuming a background metric*. LQG works with equivalence classes of connections on a manifold (no fixed metric background). TGD, on the other hand, explicitly uses the fixed background $M^4 \times CP^2$. Therefore, TGD is *background-dependent*. The metric of $M^4 \times CP^2$ is absolute, and the physical gravitation comes from the shape of the 4-surface, not from a dynamic space-time metric in the usual sense. Critics from the LQG side might view this as a step backward (like an "embedding" approach). However, TGD would counter that $M^4 \times CP^2$ provides needed structure (like Poincaré symmetry, standard model gauge group in isometries) which one risks losing in a background-independent approach. In short, LQG quantizes the *metric* (the gravitational field) itself; TGD quantizes the *embedding* of space-time into a higher space.

- **Fundamental Variables:** LQG uses Ashtekar variables – essentially an $SU(2)$ gauge connection (or spin network edges carrying $SU(2)$ representations). Spacetime is made discrete by spin networks/spin foams. In TGD, the fundamental variables are the coordinates of points on 3-surfaces (embedding maps $X^M(x^\mu)$) along with induced spinor fields on them. There is no *a priori* discretization of spacetime in TGD; however, number theory considerations introduce a kind of *discreteness in the values of the fields* (algebraic points, etc.), and p-adic length scale hypothesis introduces *discreteness in length scales*. But space-time itself remains a continuum (a differentiable manifold embedded in continuum $M^4 \times CP^2$). TGD's 3-surfaces are smooth objects (though perhaps with finite genus etc.), whereas LQG's spin network states are often depicted as combinatorial graphs. This is a stark difference: **LQG is combinatorial and algebraic in spacetime quantization, TGD is geometric and analytic**.

- **Dimensionality:** LQG strictly speaking deals with 4D spacetime (no extra dimensions, unless one tries to unify other forces by adding them later in a separate way). TGD has 8D imbedding space to account for forces. Thus, LQG aims to quantize pure gravity (and perhaps incorporate standard model via additional fields on spin networks eventually), whereas TGD is from the start a unified theory including the standard model. This means TGD has *more structure but also more baggage*: for instance, CP^2 provides a built-in quantum number structure (like color charges, etc.), which LQG by itself doesn't have to worry about.

- **Quantum States:** LQG states are described by spin network graphs labeled by spins. These correspond to quantized 3-geometry in some sense (areas and volumes are quantized in discrete spectra). TGD states, as discussed, are described by functional spinors on the space of 3-surfaces. It is a continuum (albeit infinite-dimensional) description. So in LQG, space at small scale is discrete (no smooth space-time, it's polymer-like); in TGD, space-time is always a smooth manifold, but the *collection of all possible* such manifolds has a very rich structure.

- **Gravity and Gravitons:** Loop quantum gravity's graviton is an emergent concept from collective excitations of spin networks (still an unresolved aspect: deriving the continuum graviton from LQG states is highly nontrivial and not fully solved). In TGD, the graviton is more conventional: small perturbations of the 4-surface around a flat M^4 slice can be decomposed into massless spin-2 modes, etc. Essentially, TGD's linearized theory gives something like linearized GR but in a fixed background – akin to perturbations of a membrane. Because TGD's gravitational field is just the deviation of the induced metric from the flat Minkowski, it automatically gives a graviton with two polarizations similar to the usual one. In LQG, showing that the continuum limit yields Einstein's gravity with correct degrees of freedom is part of ongoing research (the "semiclassical limit" problem).

- **Matter Coupling:** In LQG, adding matter (like the standard model fields) is conceptually possible (one can add gauge field links on spin networks, etc.), but it's not as developed as pure gravity. TGD integrates matter directly by its geometry of CP^2. TGD also provides a specific integration of quantum physics of fermions: induced spinor fields on the surface yield matter, whereas LQG might have to separately quantize matter fields on the spin network (making it a bit cumbersome). In TGD, matter and geometry are more unified – fermions propagate on the same 3-surfaces whose shape encodes gravity.

- **Experimental Prospects:** Both LQG and TGD face the issue that quantum gravitational effects are tiny. LQG might produce potential observable consequences like discreteness of area possibly affecting black hole entropy or primordial gravitational waves, but nothing clear and unique yet. TGD, by claiming unification, has more potential points of contact: it claims to predict standard model parameters, particle spectra, cosmological signatures (like FRW cosmology deviations, cosmic strings as seeds of structures), and even the existence of macroscopic quantum phases (with large $\hbar$) that could be tested in laboratory (e.g., anomalies in condensed matter or bio systems). However, these are at this stage qualitative or match known anomalies rather than definite predictions. LQG has fewer predictions beyond quantum gravity domain, since it hasn't been fleshed out to a full standard model.

- **Philosophy:** LQG is conservative in that it keeps spacetime 4D and tries to quantize GR as is, using new variables. It doesn't add extra dimensions, doesn't unify forces (in its core formulation), and emphasises rigorous quantization and background independence (closer to mathematical physics style). TGD is more ambitious and radical: it reformulates the entire ontology of physics (surfaces in higher space, new quantum principles like ZEO, etc.). It sacrifices background independence for a chance at a richer structure mimicking standard model. It's more speculative (in the eyes of the mainstream) than LQG.

To put it succinctly, **TGD is to some extent an alternative to string theory's way of unification, whereas loop quantum gravity is an alternative to string theory's method of quantizing gravity**. TGD's goals overlap with string theory (unify all interactions in one geometric framework) but its methods differ, whereas LQG's methods (non-perturbative quantization, no background) contrast with string's but its scope is narrower (just quantum gravity).

It should be noted that TGD has sometimes been likened to a *"hybrid"* of string-like thinking and geometric unification: like string theory, it introduces an extended object in a higher-dimensional space to get gravity; like Kaluza-Klein, it uses extra compact dimensions (CP^2) to get gauge forces; like loop quantum gravity, it respects (in principle) all the diffeomorphism symmetries of 4D surfaces (hence the huge symmetries of WCW). Yet it stands apart by its number theoretic and cosmological ontology choices (ZEO and multiple sheets).

In conclusion, TGD differentiates itself by offering a comprehensive vision that ties together aspects of particle physics, gravitation, and even consciousness, whereas theories like string theory and LQG typically focus on certain aspects (unification or quantization) in isolation. The price TGD pays is complexity and non-conventional mathematics, which have hindered its wider acceptance. But the potential pay-off is a theory that, if correct, explains an unparalleled breadth of phenomena from a single set of principles.

Applications to Physics and Cosmology

One measure of a theory's success is its ability to explain known phenomena and predict new ones across different domains. Topological Geometrodynamics, being a candidate for a "Theory of Everything" (or at least a theory of all fundamental interactions), has been applied to a wide range of topics in physics and even beyond. Here we summarize how TGD addresses various fields:

Elementary Particle Physics and the Standard Model

TGD was designed to reproduce and refine the standard model of particle physics. The embedding space $M^4 \times CP^2$ was chosen such that its isometry and symmetries contain the gauge group of the standard model. The CP^2 factor in particular has isometry group $SU(3)$ (which TGD associates with color charge of quarks and gluons) and supports a $U(1)$ Kähler form (associated in TGD with electromagnetic/hypercharge interactions). Meanwhile, the spinors on CP^2 decompose in a way that yields the correct chiral couplings for electroweak interactions when combined with four-dimensional spinors.

Masses and P-Adic Physics: A notable achievement claimed by TGD is the explanation of the spectrum of particle masses using p-adic thermodynamics. By treating particle mass squared as analogous to thermal energy in a fictitious p-adic temperature $T = 1/2$, Pitkänen was able to calculate masses for hadrons and leptons that match experimental values within a few percent ([hep-ph/9510361] About the construction of p-adic QFT limit of TGD) ([hep-ph/9510361] About the construction of p-adic QFT limit of TGD). For example, the electron's mass, various meson masses, etc., were produced by this approach. The idea is that each particle is characterized by a p-adic prime p, and its mass is given by a formula $m \propto \sqrt{p^{-K}}$ times some fundamental scale, with K determined by a p-adic "thermal" sum. This p-adic mass calculation is not something standard model itself could do (the SM treats masses as free parameters), so if valid, it's a win for TGD. Over time, these ideas have been refined; for instance, superconformal invariance and number-theoretic consistency have been used to pin down which primes correspond to which particles (often primes near powers of 2 appear, like $2^{127} - 1$ for electron). The latest view ties the p-adic prime to the structure of the polynomial in M^8 (for instance, the prime might divide the discriminant of the polynomial, etc.). Regardless of interpretation, **TGD can in principle calculate particle masses from first principles**, a major success claim ([hep-ph/9510361] About the construction of p-adic QFT limit of TGD).

Hadrons and Exotic States: TGD offers an alternative picture of QCD. Quarks in TGD are not pointlike but little 3-dimensional wormhole throats carrying quantum numbers. In normal hadrons (protons, neutrons, mesons), three quark throats are connected by flux tubes (color flux sheets which are actual 3D surfaces connecting the quarks – these are the TGD avatars of QCD strings or flux tubes). Confinement in TGD is topological: quarks can't be pulled apart because they're literally connected by these colored wormhole contacts. TGD also allowed speculation of exotic states like **leptoquarks** or **leptohadrons** – bound states where, say, a quark and a antiquark form something that looks like a lepton or vice versa (Topological Geometrodynamics). Historically, Pitkänen predicted a meson-like state of size ~ hadronic that behaves like an electron (one reason was to explain anomalous production of electron-positron pairs in certain experiments). Such ideas are unorthodox, but if any evidence of leptoquark resonances or anomalous baryon number violation is found, TGD might accommodate it naturally via topology (wormhole contacts connecting standard model fermions in different ways). Recently, LHC anomalies (like R_K in B-meson decays or anomalies in heavy ion collisions) have motivated mainstream proposals of leptoquarks; TGD's version is quite different but shows it has room for new physics if needed.

Family Replication and CP2 Geometry: TGD explains why there are three (and only three) generations of fermions by topology of the partonic 2-surfaces. Essentially, a fermion is associated with a homology class in CP^2 (or equivalently, boundary components of the 3-surface). The simplest topology yields the first generation, and the higher-genus surfaces yield higher generations, up to three before things become unstable (Topological Geometrodynamics). This gives a reason for three families – something the standard model does not explain. Similarly, the differing masses of generations come from the fact that higher-genus partonic 2-surfaces correspond to larger p-adic primes (hence smaller thermal masses). This ties into why the top quark is heavy and the up quark is light, etc., by giving them different p-adic prime characteristics.

Absence of Higgs Field: In TGD, there isn't a fundamental Higgs scalar field per se. Instead, what we perceive as the Higgs effect (fermions having mass and weak bosons being massive) comes from the geometry of the space-time surface. Essentially, couplings in TGD that break chiral symmetry do the job of the Higgs. That said, Pitkänen has an improved view where a "Higgs like" scalar emerges as a composite or as part of the fermionic 0-modes in CP^2. He has even considered identification of certain CP^2 excitations as the Higgs. But broadly, TGD predicts Higgs properties consistent with the standard model, since it must match those successes (like the 125 GeV boson as found at LHC would be something TGD has to allow for, and it does through a small vacuum expectation of certain configuration space coordinates).

Solitonic Aspects: TGD also yields classical solitons that mimic various particles. For example, the space-time surface corresponding to a spinning topologically quantized vortex line in the primordial plasma could behave like a classical gravitating string (giving cosmic strings), or a pair of wormhole throats connected by a flux tube with opposite chiralities could mimic a neutrino. TGD tends to blur the line between particles and space-time topology: e.g., an electron might be essentially a *Kähler magnetic monopole* in the CP^2 projection of the space-time surface, giving it the mysterious feature of a magnetic charge in hidden form (this relates to the fact that $U(1)_{em}$ in TGD comes from a mix of M^4 and CP^2 components, allowing for Kähler magnetic monopole flux which could explain why we have charge quantization and hint at why monopoles aren't seen – they are confined by flux tubes). These kinds of models show TGD actively engages with particle physics puzzles like charge quantization, family structure, etc.

Gravitation and Cosmology

TGD yields a very distinctive cosmological scenario, though one that can overlap with standard cosmology in appropriate limits:

Big Bang and Evolution: Instead of a single big bang, TGD suggests a cosmology with a fractal decomposition into sub-cosmologies. The notion of *causal diamonds (CDs)* allows one to think of each CD as a mini-universe with a birth and death (in line with ZEO). The global universe might not have a beginning in TGD; instead, there was an infinite nested structure of CDs. However, one can still have an "overall" big bang type moment if one considers the largest CD that contains our visible universe. TGD can reproduce standard Big Bang cosmology solutions by suitable choice of initial 3-surface: for instance, an exponentially expanding 3-surface in $M^4 \times CP^2$ can mimic inflation. Pitkänen has constructed models of **inflation** using the idea of a *phase transition increasing* $\hbar_{\mathrm{eff}}$, meaning the early universe might have been in a smaller-$\hbar$ phase that caused a fast expansion when $\hbar$ jumped to a larger value (this ties inflation to the hierarchy of Planck constants idea). Alternatively, cosmic strings (described next) play a major role.

Cosmic Strings and Large-Scale Structure: TGD's primordial entities are *massless extremals* (MEs) and *cosmic strings*. A cosmic string in TGD is a 2-dimensional singular surface in M^4 (topologically R^2) times a very small CP^2 geodesic sub-manifold. Initially, the universe is a gas of these cosmic strings (very high string tension, essentially one-dimensional structures with huge energy density). As the universe evolves, these cosmic strings *thicken* – they sprout 4D volume around them, becoming like flux tubes (this is driven by the Kähler action and twistor lift requiring 4-volume). When a cosmic string thickens, it sheds energy from its Kähler field into standard radiation/matter. This provides a candidate for **dark energy and matter**: the unthickened portion is dark (trapped in the form of the string's Kähler field or magnetic energy), the emitted part becomes visible matter () (). The thickened cosmic strings then appear as gravitationally like cosmic strings of GUT scale but now with finite thickness, which in standard cosmology could seed the formation of galaxies along filaments. Indeed, TGD predicts a "cosmic web" of long stringlike objects – which is observationally something we do see (filamentary galaxy supercluster networks). The difference is these are not just gravitational but have magnetic and monopole fluxes playing a role. TGD nicely explains the existence of *a primordial magnetic field and its preservation*: cosmic strings carry monopole flux that cannot dissipate (since it's conserved topologically), so even when they thicken into flux tubes, they maintain enormous magnetic fields – possibly the origin of pervasive cosmological magnetic fields that are observed (which standard LCDM struggles to explain).

Dark Matter as Phases with Large Planck Constant: TGD's approach to dark matter is not the WIMP paradigm; instead, dark matter is identified with ordinary particles (say photons, electrons) in a state with large $\hbar_{\mathrm{eff}}$ – which means they have macroscopic quantum coherence and do not readily interact via absorption/emission with normal matter because their interactions (which conserve action quanta) are suppressed or quantized in large lumps (). Such dark matter is not "missing mass" in TGD – it resides on specific space-time sheets (for example, a planet might have dark matter on a large n sheet making a halo around it, but gravitationally it still contributes). TGD has been used to model for instance the anomalous phenomena in rotating magnetic systems, where large $\hbar$ phases could explain findings like superconductor large-scale quantum effects or plasma anomalies. In cosmology, dark matter being in these large n phases means it clumps differently – likely forming the long tubes along with the cosmic strings rather than local small clumps. TGD also provides a neat resolution to why we don't see dark matter in particle detectors: it's not a new particle, it's an altered state of known particles, which we don't create in those experiments (or if we did, they'd escape detection by not interacting normally).

Quantum Gravity Phenomena: At the level of classical predictions, TGD must reproduce all of GR's successes: gravitational lensing, Mercury's perihelion, gravitational waves, etc., and in normal conditions (planetary systems, binary pulsars) it does, because it essentially reduces to GR with an effective metric at long length scales ([TGD and GRT.html](https://www.tgdtheory.fi/webCMAPs/TGD and GRT.html#::text=ti,variance%20could%20have)) ([TGD and GRT.html](https://www.tgdtheory.fi/webCMAPs/TGD and GRT.html#::text=ive%20metric%20as%20sum%20of,equations%20hold%20true%20for%20the)). For example, TGD's many-sheeted space-time suggests that what we call "gravitational force" is really an accumulation of small gradients on many tiny space-time sheets: effectively, one can package it as a single curvature in the approximation. So TGD doesn't conflict with observed GR tests. Where it might differ is in more extreme or subtle regimes. For example, TGD's view on black holes is different: a TGD "black hole" might not have a singularity or an event horizon in the same sense, because the space-time surface can extend through what would be the horizon to a Euclidian region or join another sheet. There is speculation that in TGD black holes could avoid singularity by shifting topology (removing mass via wormholes to other space-time sheets). Also, TGD naturally has the Hawking-Bekenstein formula for entropy because the horizon area would correspond to a 2-surface whose area is proportional to number of degrees of freedom (and TGD's gravitation has an interpretation in terms of 2D partonic surfaces too). But these are yet to be fleshed out.

Expanding Earth and Astro Anomalies: On a more exotic note, TGD has been applied to certain anomalistic geophysical or astrophysical ideas. For instance, Pitkänen entertained the old hypothesis of an Expanding Earth (to explain certain geological data) and offered a TGD mechanism: if matter is fed into Earth from spacetime sheets or if $\hbar_{\text{eff}}$ changes, the size of gravitational bound orbits could change, etc. While mainstream science does not endorse expanding Earth, it shows how TGD is flexible in addressing out-of-the-box questions. Similarly, TGD has considered whether changing $\hbar_{\text{eff}}$ in Jupiter's magnetic body could explain the mysterious periodic climate patterns. These are speculative, but demonstrate TGD's scope.

Quantum Biology and Consciousness (Briefly)

Though not explicitly requested in the section title, it's worth one paragraph to note that **TGD extends to quantum biology and consciousness** in ways unique among quantum gravity theories. Pitkänen has proposed explanations for the EEG spectrum, the functioning of the brain, and even aspects of sensory perception using TGD concepts like magnetic flux tube networks (the brain as a four-dimensional computational hologram, with nerve pulse clusters corresponding to topological quantum computations via braiding of flux tubes). The concept of **"magnetic body"** in TGD – an invisible field structure carrying dark matter with large $\hbar$ that envelops living systems – is used to explain how living organisms maintain coherence and receive signals (for example, how a cell could sense EM fields: via resonance with its magnetic body). The TGD-based model of consciousness identifies quantum jumps (state function reductions) as moments of consciousness, and the hierarchy of selves with the hierarchy of nested space-time sheets or CDs (Topological Geometrodynamics). These ideas are speculative, but notably, TGD was used to predict biological effects (like non-local coordination of DNA by magnetic flux loops) which some experimental results (e.g., strange ability of small EM fields to induce changes in genes) might hint at.

No other theory that unifies physics attempts to also unify biology and consciousness, which makes TGD quite singular. This breadth is both an asset (if these ideas pan out, it's revolutionary) and a liability (it departs far from empirically grounded science).

Summary of Applications

In a nutshell, TGD aims to *not just* unify interactions but to explain *why* the standard model has the features it does (charges, families, mass ratios), to offer a new picture of the early universe and cosmology that naturally solves some puzzles (magnetic fields, dark matter, matter-antimatter asymmetry via CP2 partial waves perhaps, etc.), and even to give a framework for life and mind. Some of these applications align with known data (p-adic mass calculations, cosmic filament structure, etc. have some successful points), while others remain qualitative.

The next steps for TGD in terms of application would be to produce more concrete, testable predictions: for example, a precise particle physics prediction like a mass of an unknown resonance, or a cosmological prediction like a subtle signature in the CMB from cosmic string networks, or a laboratory test of large $\hbar$ (some experiment showing macroscopic quantum effects that can't be explained by conventional physics). Work is ongoing in these directions, and there are intriguing hints (like the reported 10 Hz ELF radiation associated with human cognition which TGD ties to electron's Compton time (Topological Geometrodynamics)).

At this point, TGD provides a rich *explanatory* tapestry for diverse phenomena, tying them to a common foundation. The task ahead is to strengthen the *quantitative* predictive power in these areas, something the theory's developer and collaborators are actively working on.

Conclusion and Open Questions

Topological Geometrodynamics, after four decades of development, stands as an expansive and ambitious theoretical framework. It achieves a remarkable synthesis of ideas from geometry, quantum physics, and even number theory, offering a novel perspective on how space-time and matter are unified. In this report, we have presented TGD in a modern, rigorous fashion: introducing its foundations in terms of space-time as a 4-surface in $M^4 \times CP^2$, detailing its updated principles like M^8–H duality and Zero Energy Ontology, distinguishing old conjectures from current understanding, and comparing it with other leading approaches. We have also seen how TGD addresses concrete physics domains from particle spectra to cosmology. It is fitting now to conclude by assessing the status of TGD and highlighting the key open questions and challenges that remain.

Summary of Achievements: TGD's strengths include its broad unifying power and its introduction of genuinely new concepts. It provides a single conceptual home for gravity and standard model forces via geometry of an 8D space (Topological Geometrodynamics). It solves the correspondence problem between quantum and classical by elevating quantum states to geometric objects in an infinite-dimensional space (WCW). It resolves the quantum measurement paradox with Zero Energy Ontology by making every physical state a time-symmetrized entity (). It offers plausible explanations for otherwise unexplained features: the three-generation structure of fermions, quantization of electric charge, the origin of dark matter and dark energy as phases of matter on different space-time sheets (), and even the values of particle masses ([hep-ph/9510361] About the construction of p-adic QFT limit of TGD). In domains where the standard paradigm has little to say (such as consciousness), TGD ventures well-founded hypotheses grounded in its physical principles (Topological Geometrodynamics). The mathematical backbone of TGD – especially the vision of WCW as a Kähler geometry and the use of algebraic topology and number theory in physics – is innovative and could have implications even if TGD itself were to evolve or be subsumed by a future theory.

Open Questions and Challenges:

1. **Mathematical Rigor of WCW:** The "World of Classical Worlds" is assumed to have a unique Kähler

metric and spinor structure, but proving the existence and uniqueness of such a structure is a deep open problem. It essentially requires solving an infinite-dimensional Einstein-type equation. While symmetry arguments have been given, a full construction is lacking. Additionally, functional integral techniques in an infinite-dimensional context are formal. Progress in rigorous definition of the WCW functional integral or the M-matrix (perhaps in a discretized or toy model setting) would bolster TGD's foundations.

2. **Dynamics and Calculations:** TGD currently provides a compelling *framework*, but explicit calculations of physical processes (scattering amplitudes, cross sections) are still at an early stage. One needs to formulate, for example, a Feynman diagram expansion or an alternative within TGD. Ideas like strong form of holography (SH) suggest that scattering could be calculated from 2+1 and 1+1-dimensional data on partonic surfaces and strings, but demonstrating this to at least reproduce known perturbative results of QED or QCD is crucial. Essentially, can TGD **do the math** and get the right answers for, say, the electron's g-2, the scattering of two gluons, or the blackbody spectrum of Hawking radiation? These are tests TGD must ultimately pass.

3. **Connection to Experiment:** While TGD has explanatory value, it needs clear-cut predictions that distinguish it from other theories. Some potential signatures:

   - The existence of long-lived exotic bound states (like leptohadrons or colored hemispheres) that standard model doesn't allow.
   - Evidence of p-adic length scales in data (for instance, mass differences following p-adic scaling by $\sqrt{p}$).
   - Anomalies in quantum measurements hinting at retrocausality or ZEO effects, perhaps in the context of quantum computing or brain physics.
   - Astrophysical phenomena explicable by varying effective $\hbar$ (like quantized redshifts, periodicities in pulsar emissions, etc.). As of now, these ideas await either discovery or the identification of existing data that TGD can uniquely fit. A falsifiable prediction (e.g., a specific new particle mass or a deviation in a cosmological parameter) would elevate TGD significantly.

4. **Relationship with Other Theories:** TGD exists somewhat in isolation from mainstream efforts, but it would enrich both sides to build bridges. For instance, can TGD be formulated in a way that makes contact with string theory techniques (could there be a limit in which the TGD 3-surface behaves like a string worldsheet, making some computations easier)? Or could LQG's spin networks be embedded in TGD's many-sheeted space-time (perhaps each spin network edge corresponds to a small wormhole contact)? If connections are found, TGD might be seen not as a competing paradigm but as a complementary viewpoint that can borrow and contribute. Another intriguing question: is there a limit in which TGD's M^8–H duality reduces to something like *Penrose's twistor theory or Witten's twistor strings*? Given that twistors are now a part of TGD, exploring this could help tap into known mathematical results.

5. **Computational Tools and Simulations:** Due to its complexity, TGD might benefit from computational experimentation. For example, one could simulate minimal surfaces in $M^4 \times CP^2$ with certain boundary conditions to see what shapes result, or numerically minimize the Kähler action in symmetric cases. This might reveal whether, say, the analog of a hydrogen atom (electron's 3-surface around a proton's 3-surface) in TGD yields the correct energy levels – a direct check on how quantum mechanics emerges. These are challenging tasks, but increasing computing power and better algorithms for geometric PDEs could make them feasible.

6. **Conceptual Clarifications:** Some conceptual aspects of TGD remain subtle. For instance, the precise physical meaning of *momentum in M^8 picture* vs. *momentum in H picture* needs further elucidation (especially how conservation laws work across the duality). Also, the idea of *finite measurement resolution* is often mentioned in TGD (using inclusions of hyperfinite factors of type II_1 to model the idea that real measurements have limited resolution). Working out the implications of this for practical measurements (like how exactly does it regularize infinities or fuzz out certain degrees of

freedom) is an open conceptual program. If successfully understood, it might provide a quantum theory with built-in decoherence mechanisms for "unobserved" degrees, something highly valuable.

Outlook: The path ahead for TGD is twofold. On one hand, *integrate and validate* – integrate TGD with the body of existing theoretical results (so it doesn't reinvent every wheel) and validate it by deriving known physics (reducing to the standard model, Einstein's gravity, etc., in all appropriate limits) with the same or better precision. On the other hand, *innovate and inspire* – continue using TGD's unique elements (like number theory and ZEO) to crack problems that are currently out of reach of conventional theories, thereby attracting interest. If TGD can successfully solve even one major open problem (for example, a first-principles calculation of the masses of all elementary particles that matches experiment – something often touted ([hep-ph/9510361] About the construction of p-adic QFT limit of TGD)), it would command serious attention.

In conclusion, Topological Geometrodynamics is a richly structured theory that has matured significantly by 2025, correcting many earlier issues and incorporating modern insights. It stands at the fringe of established science, yet it addresses profoundly central questions. The coming years will be critical: with further development and interaction with empirical science, TGD will either demonstrate its superiority and carve a place in mainstream physics, or it will need to yield or transform in the face of new data. The open questions enumerated are not just challenges for TGD, but also opportunities – by solving them, TGD could potentially fulfill its promise as a "Grand Geometrical Symphony" of reality, where physics, mathematics, and even consciousness are different movements of the same overarching composition (Topological Geometrodynamics) (Topological Geometrodynamics).

Ultimately, the judgment of TGD will rest on its *fruitfulness*: can it predict and explain the world better than its rivals? As of 2025, it remains an enticing theoretical laboratory. The next chapters – to be written in both theoretical derivations and experimental discoveries – will determine how this bold venture in topological geometry plays out on the stage of physics. The work is ongoing, and as Pitkänen himself often remarks, the theory has evolved continuously and sometimes unpredictably; one can expect further surprises as the exploration of TGD's ideas continues.

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