Quantum Gravitation and Topological Quantum Computation

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Abstract

In this article the connection of quantum gravitation, as it is understood in the TGD framework, with topological quantum computation (TQC) is considered. I sketched the first TGD based vision about DNA as a TQCer for about 13 years ago. In particular, a model of the system consisting of DNA and nuclear/cell membrane system acting as a TQCer was discussed.

TGD has evolved a lot after this and there are several motivations for seeing what comes out from combining the recent view about quantum TGD and TGD inspired quantum biology with this model.

1. There is a rather detailed view about the role of dark matter as phases of ordinary matter with the effective Planck constant $h_{eff} = nh_0$. Large values of h_{eff} allow to overcome the problems due to the loss of quantum coherence.

   This leads to the notion of the dark DNA (DDNA), whose codons are realized as dark proton triplets and proposed to accompany the ordinary DNA. Also dark photon triplets are predicted and one ends up to a model of communications and control based on dark cyclotron resonance in which codons serve as addresses and modulation of the signal frequency scale codes the signal to a sequence of pulses. Nerve pulses could be one application.

2. Quite recently, also the understanding of the possible role of quantum gravitation in biochemistry, metabolism, bio-catalysis, and in the function of DNA has considerably increased. The gravitational variants of hydrogen bonds and valence bonds between metal ions having very large value of $h_{eff} = h_{gr}$, where $h_{gr} = GMm/v_0$ is the gravitational Planck constant originally introduced by Nottale, are in a key role in the model and explain metabolic energy quantum as gravitational energy liberated when dark protons "drops" from a very long gravitational flux tube in the transition $h_{gr} \rightarrow h$. Also electronic metabolic energy quantum is predicted and there is empirical support for this.

3. A further motivation comes from the number theoretic vision of quantum TGD. Galois groups as symmetry groups represent new physics and the natural questions are whether Galois groups could give rise to number theoretic variants of anyons and what could the TGD counterparts of the condensed matter (effective) Majorana electrons proposed by Kitaev as anyon like states?

   The answer is that quantum superpositions of symmetric hydrogen bonded structures of form X..H-H+X-H...X are excellent candidates for the seats of dark ($h_{eff} > nh_0 > h$) bi-localized electrons defining TGD analogs of condensed matter Majorana electrons.

The Galois groups permute the roots of a polynomial, which determines a space-time region by $M^8 - H$ duality. The roots correspond to mass squared values, in general algebraic numbers, and thus to mass hyperboloids in $M^4_c \subset M^8_c$. The H images correspond to 3-hyperboloids with a constant value $a = a_n$ of light-cone proper time. Therefore the Galois group can permute points with time-like separation. Note however that the real or rational parts of two values of a can be same.

This looks very strange at first but actually confirms with the fact that time-like braidings defining TQC correspond in TGD time-like braidings (involving also reconnections) of string like objects defining string world sheets, which are not now time evolutions of space-like entities as physical state but correspond to time-like entities defining boundary data necessary for fixing holography completely. Their presence is forced by the small failure of the determinism of the action principle involved and is completely analogous to the non-determinism for soap films with frames serving as seats for the failure of determinism.

4. Braidings appear therefore at the level of fundamental TGD and correspond to string world sheets. They are possible only in 4-D space-time but not in string models.

   Also TQC-like processes appear automatically at the level of fundamental physics. In particular, the number theoretical state function reduction cascade for the Galois group following the time evolution induced by braiding can be regarded as a generalization of a decomposition of integers to primes: now primes are replaced by simple groups defining primes for finite groups. Nature is doing number theory!

5. Also zero energy ontology (ZEO) brings in new elements. The change of the arrow of time in "big" state function reductions (BSFRs) implies that dissipation with a reversed arrow of time provides an automatic error correction procedure. Also TQC in which the arrow of time varies for sub-modules, can be considered.

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5. Also zero energy ontology (ZEO) [L8, L22] brings in new elements. The change of the arrow of time in "big" state function reductions (BSFRs) implies that dissipation with a reversed arrow of time provides an automatic error correction procedure. Also TQC in which the arrow of time varies for sub-modules, can be considered.

1.1 Two visions about physics in TGD framework

TGD leads to two visions about physics discussed in [L13, L23]. In the first vision [K3, K2, K6] physics is seen as geometry of space-time identified as 4-surface in $H = M^4 \times CP_2$, and at a more abstract level, geometry of the "world of classical worlds" (WCW) consisting of space of preferred extremals (PEs) of the basic action principle defining analogs of Bohr orbits as minimal surfaces with singularities.

In the second vision [K18] physics is reduced to number theoretic concepts and 4-surfaces in M^8 analogous to momentum space define the basic objects. $M^8 - H$ duality [L9, L10], analogous to momentum-position duality, relates the two visions. The 4-surfaces in M^8_c (complexified M^8), which has interpretation as complexified octonions, are required to be associative in the sense that their normal space is quaternionic.

For given space-time region, they are determined by the roots of polynomial P of real argument continued to polynomials in M^8_c. The roots define a collection of mass shells of $M^4_c \subset M^8_c$ and by holography they define a 4-D surface of H.

The action principle at the level of H is determined by the twistor lift of TGD and is the sum of 4-D Kähler action and volume term (cosmological constant). It is not fully deterministic and space-time surfaces in H as PEs analogous to Bohr orbits can be regarded as analogs of soap films with frames, which correspond to singularities at which determinism fails.

The frames provide additional holographic data besides the hyperbolic 3-surfaces corresponding to light-bone proper times $a = a_n$ which are determined by the roots of P. Frames include light-like orbits of partonic 2-surfaces and string world sheets connecting them. What is new, and consistent with zero energy ontology (ZEO) [K22], is that space-like data are not enough for holography, also time-like data is required and the string world sheets turn out to be absolutely essential for braiding and TQC.

1.1.1 Physics as geometry

The basic elements of physics as geometry are following.

1. Space-time is identified as minimal 4-surface [L24] in $H = M^4 \times CP_2$. Holography follows from general coordinate invariance and implies what might be called Bohr orbitology. It turns out that holography is not quite strict.

2. Twistor lift of TGD [K16] [L25, L26] replaces space-time surface with what can be regarded as a counterpart of its twistor space having X^4 as a base space and sphere CP_1 as a fiber. The twistor structure is induced from the product of $T(M^4) \times T(CP_2)$ of twistor spaces $T(M^4)$ $TC(P_2)$, which are the only twistor spaces allowing Kähler structure. The induced twistor structure and determined by an action principle with is 6-D Kähler action existing only for M^4 and CP_2. Twistor structure requires dimensional reduction so that one bundle structure and the action reduces to a sum of a volume term having interpretation in terms of cosmological constant and of 4-D Kähler action as analog of Maxwell action.

   PEs realizing the holography are identified as minimal surfaces [L24], which, apart for lower-dimensional singularities, are also locally extremals of the 4-D Kähler action and possess a holomorphic structure reducing the field equations to algebraic conditions analogous to Cauchy-Riemann conditions. One can regard the space-time surface as an analog of soap film spanned by frames assignable to the singularities at which minimal surface property fails but extremal property for the entire action remains true so that conservation laws are not lost. As in the case of ordinary soap films, frames are seats of finite non-determinism interpreted as space-time correlates of quantum non-determinism.

3. The concrete study of the extremals of the action principle leads to the identification of the basic candidates for the basic PEs. From the point of view of TQC, magnetic flux tubes are the most interesting objects and define counterparts of the braid strands. The notion of magnetic body (MB) is central. Its detailed identification is still far from complete: for the latest view about gravitational MB see [L27].

1.1.2 Physics as a generalized number theory and $M^8 - H$ duality

Physics as (a generalized) number theory is the dual vision of TGD.

1. p-Adic physics emerged originally from a model for the particle massivation based on p-adic thermodynamics for the mass squared of the particle [K4, K1]. From the beginning it was clear that various p-adic physics had to be fused with the real number based physics to a larger framework, which could be called adelic physics. For mathematical reasons, the natural interpretation of various p-adic physics would be in terms of physical and mathematical correlates of cognition. Number theoretical universality stating that the basic equations of TGD are number-theoretically universal and make sense in all number fields is a natural constraint on the theory.

2. $M^8 - H$ duality [L9, L10] realizes the number theoretical vision about TGD and also holography. M^8_c identified as complexified M^8 and interpreted as complexified octonions, is analogous to momentum space and 4-surfaces define the basic objects at the level of M^8.

   The 4-surfaces in M^8_c (complexified M^8), which have an interpretation as complexified octonions, are required to be associative in the sense that their normal space is quaternionic. These 4-surfaces are determined by the roots of polynomials of real argument continued to polynomials in M^8_c. The roots define a collection of 3-D mass shells of $M^4_c \subset M^8_c$ and by holography they define a 4-D surface of M^8_c. Physical states correspond to 4-momenta at these mass shells analogous to Fermi balls.

   $M^8 - H$ duality, analogous to momentum-position duality, relates the two visions by mapping the 4-surfaces in M^8 to those in H. $M^8 - H$ duality generalizes to the level of twistor space [L9, L10, L23, L25, L26].

3. One can assign to a given polynomial an algebraic extension of rationals. The collection of points of the 4-surface of M^8_c defines a cognitive representation. The mass shells as sources of holographic data are however number theoretically exceptional in that the number of points with algebraic M^8_c coordinates is infinite: cognitive explosion takes place both at the level of M^8 and H: these values of the light-one proper time a correspond to very special moments in the life of self, kind of moments of enlightenment.

   In M^8 the points of mass shells are identifiable as quark momenta assumed to be algebraic integers just as ordinary momenta for particles in a box are integers with suitable choice of momentum unit. These momenta can also be interpreted as points in extension of p-adic numbers so that number theoretical universality follows. The p-adic prime in question is identified as the largest ramified prime of the extension considered.

   This gives rise to a hierarchy of algebraic extensions and cognitive representations as unique discretizations of the 4-surface in M^8 and space-time surface and suggests a generalization of computationalism replacing integers with the hierarchy of algebraic integers for extensions of rationals.

4. The dimension n of algebraic extension is identified as an effective Planck constant $h_{eff} = nh_0$ where $h_0 < h$ is true. The identification of the value of n_0 in $h = n_0h_0$ has been proposed [L21]. The phases of ordinary matter labelled by the value of n behave in many respects as dark matter and the identification as dark matter has been proposed. A particularly important class of phases corresponds to $h_{eff} = nh_0$. These phases would play a central role in living matter. The relationship with galactic dark matter is however somewhat unclear.

   What makes these phases so important is the scale of quantum coherence is expected to scale like h_{eff}. Dark phases are also expected to have very weak interaction with ordinary matter and the proposal is that living matter is controlled by this kind of phases located at MB and approaching only slowly thermal equilibrium with it: this would have interpretation as aging [L29]. The small value of h and thermal fluctuations spoiling quantum coherence and entanglement belong to the key problems of QC and dark matter could solve these problems.

5. Galois confinement [L16] states that physical states have total momenta, whose components are ordinary integers. Galois confinement provides a universal mechanism for the formation of bound states. Galois confinement also applies in spin degrees of freedom and provides spin representations for the covering of the Galois group. The number theoretic degrees of freedom are of special interest in QC and suggest that number theoretic quantum computation (NQC) as a counterpart of TQC, which would involve what might be called Galois anyons. The Galois group could allow identification as a subgroup of the braid group. This would mean strong restrictions on TQC.

6. $M^8 - H$ duality leads to a view about the construction of the counterpart of S-matrix in the TGD framework [L25, L26]. S-matrix would be replaced by the analog of Kähler metric in fermionic degrees of freedom [L15], which by the infinite dimension of Fock space is expected to be highly unique as also the Kähler metric of WCW [K3, K2, K6].

   Incoming and outgoing states of particle scattering would be Galois singlets constructed from lower level states which need not be Galois singlets. Quarks, whose momenta at mass shells are algebraic integers are free and the scattering would be mere reorganization of Galois singlets to new ones.

   Scattering could be also seen as analog of QC and computation in an extension of rationals: both the input and output would consist of a set of rational integer valued momenta and scattering would map them to each other.

   This applies in the twistor picture also to spins having a representation as points of the twistor sphere S^2 known as Bloch sphere. In this case number theoretic constraints suggest that the set of quantization axes corresponds to a finite discrete subgroup of $SO3)$ assignable to regular polygons and Platonic solids.

   The quark momenta belonging to the extensions of rationals are invisible, which implies invisible algebraic complexity of cognition and brings in mind unconscious information processing. Quantum physics and psychoanalysis would meet!

1.2 Zero energy ontology (ZEO) and QC

The first basic motivation for the introduction of ZEO was that by the general coordinate invariance space-time surface as a preferred extremal is a more natural notion than 3-surface. For exact holography, these notions are equivalent but the identification of space-time surface as minimal surface predicts a small violation of the strict holography identifiable as a correlate for quantum non-determinism associated with the physics of cognition or possibly quite generally. This non-determinism would be essential for the possibility of TQC in TGD.

Second motivation was the basic problem of quantum measurement theory to which ZEO provides an elegant solution if one assumes that the arrow of time changes in "big" state functions reductions (BSFRs) as analogs of ordinary SFRs. In "small" SFRs, which are analogs of "weak" measurements introduced in quantum optics, the arrow is not changed [K22] [L8, L22].

In the TGD framework, quantum measurement theory generalizes to a quantum theory of conscious experience in which SSFR defines the basic element of conscious experience. BSFR has an interpretation as a counterpart of death/sleep. The change of the arrow of time in BSFRs has profound implications in quantum biology. Since the dissipation with a reversed arrow of time for a subsystem looks like self-organization from the point of view of a system with an opposite arrow of time [L7]. The arrow of time can change for macroscopic time periods at the MBs with large h_{eff} and since MB controls the ordinary matter, it induces not only effective quantum coherence but also an effective reversal of time also at this level.

The basic ideas of ZEO [L8, L22] are following.

1. In zero energy ontology (ZEO) [L8, L22], the pair of incoming and outgoing states of particle scattering are replaced with zero energy state and zero energy states define scattering amplitudes as entanglement coefficients.

2. At the level of H, positive and negative energy parts of zero energy states are located at boundaries of causal diamonds (CD), which form a fractal hierarchy. At the level of M^8, they reside at the boundaries of mass shells, which corresponds to the roots of the polynomial defining the space-time region. $M^8 - H$ duality maps these points to the boundary of CD. One can also consider an alternative for which mass shells as hyperbolic spaces $H^3 \subset M^8$ are mapped to their counterparts in H by a map which is essentially inversion (Uncertainty Principle).

3. Scattering events [L25, L26] are QC like events. Input (output) data correspond to incoming (outgoing) quark momenta identified as algebraic integers in an extension of rationals and to spins. Since fermionic Fock state basis defines a Boolean algebra, the fermionic states define quantum analog of Boolean algebra, and the scattering amplitudes could be also seen as a quantum generalization of Boolean maps and realizing statements which are true that is consistent with laws of physics. These transitions could be interpreted in terms of Boolean cognition.

   The replacement of the S-matrix with Kähler metric in fermionic Hilbert space degrees of freedom represents a new element. The analog of unitary transformation is assigned with CD and from the point of view of QC, CD could be interpreted as an embedding space analog of gate. Since gates allow control bits not affected by the unitary transformation, also the Boolean functions, which are not 1-1, can be realized as unitaries. Same is expected to be true also now.

4. The scattering amplitudes correspond a tensor net-like structure. Physical states are Galois singlets consisting basically of free quarks. At the number theoretical level, scattering can be seen as a recombination of Galois singlets to new ones.

ZEO could have a profound impact on QC.

1. Negentropy Maximization Principle (NMP) [K5] [L20] is the variational principle of TGD inspired theory of consciousness. Negentropy can correspond to the sum of p-adic negentropies or to the sum or p-adic and real negentropies, which can be possible and tends to be so by NMP. For both options, NMP guarantees that the p-adic entanglement negentropy increases

and is positive. It however also forces the real entanglement entropy to grow. NMP therefore implies cognitive evolution but also second law.

From the point of view of QC, this picture is very promising since the laws of physics would take care that the entanglement negentropy grows and also that negentropic entanglement tends to be stable. This is quite contrary to what standard physics predicts. This leads to evolution [L4, L5] in the sense that the dimension $n = h_{eff}/h_0$ of the extension of rationals as a measure of algebraic complexity tends to increase since this provides larger negentropic resources. This evolution takes place at MB in human length and time scales and the challenge is to learn to manipulate dark matter.

2. BSFR could take care of error correction automatically since for the reversed arrow of time dissipation looks like error correction by self-organization. This error correction is a key feature of living matter but has remained poorly understood. One can also ask whether BSFRs could make possible QCs involving sub-QCs in both time directions. Could the use of sub-programs with opposite time direction allow a faster QC.

1.3 Finite field approximation and QC

Number theoretic vision about QC leads to new ideas about QC itself.

1. The momenta in the extension of rationals as algebraic integers can be interpreted as p-adic integers in the induced extension of p-adic numbers. The p-adic number field corresponds to prime p, which is the maximal ramified prime for the polynomial in quesetion.

   In the approximation $O(p) = 0$ they define a finite field $F(p,n)$ having dimension is is not larger than the dimension of extension but can be smaller. The number of elements is p^n and the situation corresponds to n pinary digits, qupits, instead of qubits. TQC using elements of $F(p,n)$ is an attractive possibility. Besides this one has also spin degrees of freedom.

2. The elements of $F(p,n)$ can be regarded as roots of some, in general non-unique, polynomial with degree p^n. This polynomial is in general not the polynomial inducing the extension of p-adic numbers.

3. The Galois group for the finite field should transform to each other the roots of the originalpolynomial interpreted as a polynomial in $F(p,n)$ and is a subgroup of the Galois group for the polynomial having all points of $F(p,n)$ as its roots.

The automorphism group of quaternions is analogous to Galois group and in the TGD framework with discretization it looks like a natural notion.

1. In the continuous case, the automorphism group of quaternions is the rotation group $SO(3)$ having $SU(2)$ as covering group. In the discrete situation, one expects it to be a finite group and would correspond to symmetries of Platonic solid in non-abelian case and to the symmetries of a regular polygon in abelian ase. Icosahedron, tetrahedron, and octahedron have triangles as faces and the proposal is that genetic code realized in terms of bioharmony [K9] [L12] corresponds to so called icosa-tetrahedral tessellation of H^3 [L19].

2. Therefore genetic code and bioharmony could closely relate to the quaternionic aspects of number theoretic physics and perhaps also to TQC for quantum variant $SU(2)_q$ of quaternionic automorphisms acting in the normal space of the space-time surface. A natural proposal is that the points of the icosahedron and tetrahedron correspond to points for the discretized unit sphere known as Bloch sphere defining possible directions of the quantization axis of spin in TQC.

3. The finite subgroups of $SU(2)$ are associated with the hierarchy of inclusions of hyperfinite factors of type II_1 and the proposal is that the inclusion of these factors define finite measurement resolution such that the included factor defines the resolution [K21, K12].

1.4 TQC and the new view about space-time

The new view about space-time is highly relevant for the TGD view of TQC.

1.4.1 Galois anyons

The basic problem of the TGD inspired model of TQC is the identification of the topological qubit identified as an anyon-like state in standard TQC. One could say that topological qubit or its analog does not correspond to quantum state but representation of braid group or quantum group assignable to Chern-Simons action. Topological qubits also satisfy a nice algebra defined by the decomposition rules of the representations of the braid group.

The motivation for this identification is that topological qubits are expected to be highly stable since the change of the representation is not expected to be probable unlike the change of spin direction. The non-local character is also an important aspect. The braids defining TQC program as unitary representation of the braid group allows to identify the gates, which are universal in the sense that they have finite computational accuracy.

The increase of the order of the covering group as a finite covering of the permutation group S_N for N braid strands allows to improve the accuracy. Kitaev [B2, B1] has proposed [D1] that anyon-like bi-localized states of condensed matter Majorana fermions could define stable qubits. Majorana electrons would be superpositions of electron states localized at the ends of a superconducting wire and would have parity $+/-1$ under permutations of ends of the wire.

In TGD framework the electrons defining analogs could be bi-localized states with localization to the ends of a monopole flux tube or pair of them. Galois degrees of freedom are a new element and anyons could correspond to multi-localized states defining representations of Galois group at its orbits consisting of points of the cognitive representation at mass shell H^3. Also spin degrees of freedom would define Galois representation. If the braidings correspond to lifts of number theoretic symmetries, Galois group corresponds to a subgroup of the braid group.

In the standard picture of TQC, a computationally interesting situations corresponds to non-Abelian anyons to guarantee that the states defining topological qubits form a higher-D space. This means that the swap $ab \leftrightarrow ba$ is not a commutative operation inducing a mere phase anymore. Since the status of Majoran fermions is unclear, it is still unclear whether any anyonic system satisfies this constraint. Galois groups are in general non-commutative so that this problem disappears.

Physical states would be Galois singlets and anyon-like states would be their building bricks just as quarks would define building bricks of general Galois singlets including also leptons and various bosons. Since Galois non-singlet cannot appear as a free particle, one could also understand topological entropy associated with anyons as relating to the entanglement with environment forced by Galois singletness in spin degrees of freedom.

1.4.2 Braidings and reconnections as basic elements of TQC

TQC in the TGD Universe involves also other new elements besides Galois groups.

1. The flux tubes connecting the nodes of a tensor net-like structure define natural candidates for braid strands. Both space-like and time-like braiding are possible.

   Time-like braiding defining TQC of the moving nodes connected by flux tubes induces a space-like braiding so that the TQC is recorded to memory as a kind of log file. Dance metaphor expresses this neatly: dancers at the parquette are connected by threads, which get braided and form a memory representation about the dance. This mechanism could define quite a general representation of memories based on space-time topology.

2. The fusion defined by the tensor product for the representation of the braid group or associated quantum groups is a key operation in standard quantum computation. The decomposition of the tensor products gives a superposition of topological qubits or more general qubit-like entities An interesting question is whether the fusion could have a more concrete topological meaning. Could the fusion of flux tubes correspond to a formation of a bound state of flux tubes inside a flux tube?

3. TQC as a braid generalizes to tensor-net (for tensor nets in TGD sense see [K13] [L3]). The nodes can have M incoming qubits and N outgoing qubits. The node corresponds to a quantum computation defined as a map between the incoming and outgoing qubits. In the framework, the nodes would correspond to CDs For $M \neq N$ is not a unitary transformation 1-1 transformation but can be an injection so that it is still an isometry at the level of the state space.

4. Besides swap as the basic braiding operation, also reconnection, having the same effect as far as initial and final states are considered, appears as a basic operation. When the incoming and outgoing qubits cannot move, reconnection could take the same role as swap and make TQC possible.

5. One can wonder whether this more general view about TQC could be realized in quantum biology. Could biochemical reactions correspond to fusions of braids of a tensor net, could reconnections and braidings make it possible to have a larger repertoire of TQCs. Could ZEO-based error correction requiring only time reversal play a key role in TQC.

1.4.3 Different TGD based views of TQC

TGD suggests several different perspectives of TQC.

1. In the flux tube picture, the basic elements are braiding, reconnections and fusions in which flux tubes could even form a bound state inside a larger flux tube so that the fusion could have a geometric meaning. At the level of H, fusion could correspond to a process in which the incoming particles arriving into the CD form a tensor product. Inside CD fusion occurs and gives rise to a decomposition of irreps. Measurement selects one irrep first and outgoing states are obtained by an SFR cascade reducing the total Galois group to the factors defined by relative Galois groups by a cascade of SSFRs defining cognitive measurements.

   Dance metaphor implies a mechanism of memory with spatial braidings representing spatial braidings. This mechanism would be realized in all scales and define kinds of topological Akashic records. If reconnection is equivalent with swap operation, then TQC is also possible without braiding induced by the motions of braid ends.

2. CDs are counterparts of gates at the level of H and define a fractal hierarchy of gates with sub-CDs defining sub-modules.

   Space-time surface in H can be also seen as a 4-D soap film with frames as seats of non-determinism and one could assign mental images with this non-determinism. This suggests that the gates at space-time level correspond to the frames whereas CDs would correspond to entire TQCs at the level of H. This also suggests that TQC in the TGD sense must allow intermediate SSFRs at the frames. The situation is far from obvious since fractality is also present and involves a hierarchy of CDs.

   The $M^8 - H$-duality provides a further view about TQC. A highly attractive idea is that TQC programs can be constructed as functional composites of polynomials giving rise to extensions of extensions of .... and inclusion hierarchies of corresponding Galois groups, each defining a normal subgroup of its sup-group.

   The normal subgroup hierarchy makes it possible to understand cognitive measurements as SSFR cascades reducing the representation of the Galois group to a product of representations for the subgroup and normal subgroup associated with it. This decomposition could generalize the decomposition of the anyonic representations. This would also suggest a deep connection with the paradigm in which computations are functions.

2 What could the replacement of the braid group with the Galois group mean?

The replacement of the braid group acting on anyons with the Galois group looks a rather innocent proposal first but has profound implications. The reason is that the Galois group permutes the roots of the polynomial P, which correspond to different mass shells in M^8 and therefore different values of light-cone proper time in H.

2.1 Functional composition of the polynomials and many-particle states

Functional composition of the polynomials is proposed to give rise to many-particle states.

1. The roots of P correspond to mass shells. Quarks have momenta at these complex mass shells. Roots and corresponding momenta are in general complex algebraic numbers and total momenta and mass squared values are real by Galois confinement.

2. Functional composite $P = P_n \circ ... \circ P_1$ of polynomials defines the interactions of particles in the number-theoretical picture. Functional composites are proposed to define particles as many-quark states and further functional compositions make it possible to engineer many particle states formed from these.

3. One can also consider iterates of a polynomial as analogs of many particle states involving only a single kind of particle. Functional decomposition gives as roots inverse iterates of the roots of the polynomial Q in $P = Q \circ Q... \circ Q$ [L11, L25, L26]. Asymptotically they give rise to an analog of the true Julia set (`https://mathworld.wolfram.com/JuliaSet.html`) as a boundary of the filled Julia set. The inverse iterates near the boundary of the Julia set would correspond to very nearly the same mass squared values and thus proper time constant hyperboloids.

4. One can regard the roots of P_i as roots with respect to the variable $y = P_{i-1} \circ ...P_1(x)$ if $y = P_{i-1} \circ ...P_1(x)$ defines the ground state coordinate. $h_{eff} = n_0 h_0$ would define a natural ground state for which $h_{eff} = nh$ would hold true.

5. If the polynomials appearing in the composite satisfy $P_i(0) = 0$, one has "inheritance of roots". The roots y_i of P_i are mapped to their inverse images $(P_{i-1} \circ ...P_1)^{-1}(y_i) = P_1^{-1} \circ P_2^{-1} ... \circ P_{i-1}^{-1}(x)$. This inheritance brings in mind conserved genes. A weaker form of "inheritance" would be that some polynomials, say $P_1, P_2, ..., P_k$ at the lowest level have $P_k(0) \neq 0$. For $P = Q \circ P_F$, where $P_F = x^2 - x - 1$ is "Fibonacci polynomial", the roots would be of form $(-1 \pm \sqrt{5 + 4y_n})/2$, where y_n is a root of Q. Note that one has $P_1(0) \neq 0$. If one has $P_k(0) \neq 0$ for $k > 1$, the roots of P_1 are roots of any P and therefore universal. This suggests the possibility that the ground state polynomial corresponding to $h_{eff} = h = n_0 h_0$ is non-vanishing at origin.

2.1.1 Ground state polynomial

The ground state polynomial P_g corresponding to $h_{eff} = h = nh_0$ is of special interest physically.

1. The arguments allowing to deduce the value of n_0 in $h = nh_0$ lead to a conclusion that the ground state polynomial P_g [L21] corresponding to $h_{eff} = h = n_0 h_0$ corresponds to a Galois group with $7!^2$ elements.

2. This allows several options. For instance, the semidirect product $S_7 \rtimes S_7$ could act as a Galois group. S^7 decomposes to a semidirect product of the simple alternating group A_7 and Z_2 acting as a normal group. S_7 can appear as a maximal Galois group for a polynomial of order 7. In this case S_7 could correspond to $Q_a = P_7 \circ P_2$ or $Q_b = P_2 \circ P_7$ and one would have four options $P = Q_i \circ Q_j$. Also $P_7 \circ P_7 \circ P_{2,a} \circ P_{2,b}$ $P_{2,a} \circ P_{2,b} \circ P_7 \circ P_7$ are possible.

3. Second roots appear in all basic formulas of quantum mechanics. Therefore one can argue that P_2 should appear at the bottom of the composite polynomial defining the ground state. Fibonacci quantum computation involves Golden Mean and the roots $x_\pm = (-1 \pm \sqrt{5})/2$ of Fibonacci polynomial $P_F(x) = x^2 - x - 1$. All roots would appear as pairs with members related by the Galois group of P_F. For $P_1 = P_F$ and $P_k(0) = 0$ for $k > 1$ (inheritance), the roots of P_F are roots of any P and Golden Mean would play a key role in fundamental physics.

2.1.2 Mass squared formula and inheritance hypothesis

For Galois singlets, the total momentum has components, which are ordinary integers. Also mass squared is integer.

1. If the stringy mass formula $m^2 = n$ holds true for the quark mass squared values as roots of a polynomial, one must have $m^2 = \sum m_i^2 = n$. This requires that the sum of the inner products

of quark momenta vanishes. The interpretation would be as an additivity of conformal weights. If every root is realized as quark momentum, $m^2 = \sum m_i^2$ equals the constant coefficient of the total polynomial P giving $m^2 = P(0)$.

2. If the strong form of inheritance holds true, one has $\sum m_i^2 = 0$ so that the total conformal weight vanishes. Could the interpretation be in terms of conformal invariance? Could one say that the tachyonic total mass squared assignable to the space-like states defined by braid strands compensates for the non-tachyonic total mass squared?

   Total momentum would be light-like and the $M^8 - H$ duality should be defined as the map $p^k \rightarrow m^k = \hbar_{eff} p^k/(p^0)^2$ where m^k belongs to the light-like boundary of CD containing the CDs assignable to the mass squared values as sub-CDs.

3. In p-adic mass calculations the total conformal weights are however non-vanishing and real. What could this mean?

   (a) The thermal excitations should be excitations of the $m^2 = 0$ state due to interaction with the environment, which extends the system. The thermal excitations would be described by polynomials $Q_{ex} = P_{ex} \circ P$. The roots of Q_{ex} would include, besides roots of P (inheritance), also the roots y_n of P_{ex} and these correspond to non-vanishing values of $P(y_n)$. $y_n \neq 0$ would give non-vanishing mass for the thermalized subsystem defined by P.

   (b) If one gives up the "inheritance" hypothesis and allows $P_i \neq 0$, one has $m^2 = \sum m_i^2 = P_n(0)$. Monic polynomials $P(x) = x^n + a_{n-1}x^{n-1} + ... + a_0$ are good candidates for the allowed polynomials. The coefficients a_k are integers so that the mass squared as a conformal weight $\sum m_i^2 = a_0$ is an integer.

2.1.3 Decomposition of Galois group to a product of relative Galois groups

The Galois group Gal for an extension of extension.... decomposes to a product of the relative Galois groups Gal_k/Gal_{k-1}.

1. One can speak of the ground state characterized by some Galois group Gal_0. Ordinary Planck constant h would correspond to Gal_0 and in [L21] it was proposed to be a product of permutation groups S_7 giving $n_0 = (7!)^2$. This allows to interpret CP_2 length scale squared as $n_0 l_P 2$, l_P Planck length. Galois group can be identified as a relative Galois group: as Galois group for extension of the extension defining the ground state.

2. The structure of the Galois group reflects the functional composition involving a large number of identical polynomials with the same mass spectrum as free particles. In the functional composite $P \circ Q$ the mass spectrum S of P is mapped to $Q^{-1}(S)$. Large number of iterations of P produces Julia set as a fractal. One can speak of an asymptotic mass spectrum.

3. The orbit of Galois group consists of mass shells and its cognitive representation can contain momenta at these mass shells.

   Galois symmetry would be a discrete symmetry connecting quarks with different mass values (which are counterparts of virtual masses rather than real masses). Galois symmetry would be analogous to a dynamical symmetry and would not commute with Poincare and Lorentz symmetries.

   Physical states are Galois singlets and have well defined real mass squared. Galois singlet property of physical states would imply that these symmetries would be respected. Physical states correspond to a CD containing sub-CDs... and at the lowest level there would be quarks. Essentially 4-D objects would be in question.

2.2 $M^8 - H$ duality at the level of M^4

$M^8 - H$ duality maps the algebraic physics at the level of M^8 formulated using polynomials to the geometric physics at the level of $H = M^4 \times CP_2$ formulated using variational principle and partial differential equations. The preferred extremal property required by general coordinate invariance reduces the number of solutions of field equations so that they can correspond to a much smaller set of solutions of algebraic equations. The holographic aspects of M^8-H duality have been already considered and in the following only the map $M^8 \supset M^4 \rightarrow H \supset M^4$ is discussed.

1. M^8-H duality maps the surfaces of M^8 to minimal surfaces in H having singularities at which only the field equations for the full action containing also Kähler action besides the volume term hold true. M^8-H realizes holography: the mass shells determined by the roots of P can be continued to 4-surfaces containing them.

2. The precise form of M^8-H duality is not quite clear. The first question is whether one should allow complexification of M^4 as at the H side. One could define the H image as $M^k = \hbar_{eff} Re[p^k/m^2]$, where p^k is the quark momentum and at mass shell m^2. M^k would define some geometric objects in H. For physical states m^2 is integer and corresponds to a finite value of $a = \hbar_{eff}/m$. If the stringy mass formula $m^2 = \sum m_i^2 = 0$ is true, the image belongs to the light-cone boundary.

   The image could be a geodesic line of H parallel to m^k, which could start from the origin from the common center of CDs forming a fractal Russian doll hierarchy or from the tip of a given sub-CD.

   The image could also be identified as a point or a set of points. The point could be identified as the intersection of these lines with the boundary of the sub-CD defined by the mass value or its real part. Also the intersections with boundaries of all sub-CDs involved can be considered. Also the map of mass shells to M^8 to hyperboloids $a = a_n$, where a is light-cone proper time and a_n is inversely proportional to mass to realize Uncertainty Principle, makes sense.

3. The image of the orbit of the Galois group would correspond to a geodesic line starting at the centers or tips of various CDs defined by the mass shells. If the CDs are inside each other like a Russian doll, the geodesics intersect the $a = a_n$ hyperboloids and the boundaries of corresponding sub-CDs corresponding to different values of the light-cone proper time a and are time ordered. What is highly non-trivial is that the points at the orbit have time- like distances.

2.3 The orbits of the Galois group in H transform hyperboloids to each other

Mass squared values correspond to the roots a_n of a polynomial and are in general complex algebraic numbers. Their real projections can be negative and therefore tachyonic. The big surprise during writing of this article was the trivial observation that the Galois group permutes the mass shells defined by the roots of P.

If the real projections of mass shells to M^4 are mapped to H, Galois group can connect points with different values of complex "cosmic time" $a = a_n$. This does not conform with the idea that the particles of the physical state always have space-like distance but could conform with ZEO and non-determinism inspiring the view that time-like braiding is a physical state rather than its time evolution.

Note however that the spatial distance $(M_1 - M_2)^2$ in H is space-like for $(E_1 \geq m_1^2 + m_2^2)/m_2$ in the coordinate system in which M_2 and p_2 have a vanishing spatial part. This holds true also for the M^4 images.

2.3.1 Orbits of the Galois group as braidings?

Could the orbits of the Galois group for off-mass shell states be identified as braidings?

1. If the braiding is time-like, the value of the real part of the proper time parameter corresponding to the mass shells or CD sizes increases along the orbit.

   This would conform with the idea that the orbit of the Galois group consists of images of mass shells at the quark level. It also conforms with the breaking of Lorentz and Poincare symmetries at the level of the Galois group. This finding also justifies the Galois confinement: physical states correspond to a single value of a.

2. What about number theoretic anyons? These anyons must have non-trivial Galois quantum numbers and algebraic momenta. Here the relative Galois group is a convenient concept. Galois non-singlet property is with respect to the relative Galois group and one can forget the huge complexity of the Galois singlet ground state altogether.

2.3.2 Do Galois anyons require tachyonic states?

The momenta of quarks define the basic representation of the Galois group. One can also imagine representations in spin degrees of freedom. If only the spin degrees of freedom carry Galois quantum numbers, the space-time action of the Galois group is trivial. This does not look attractive and does not conform with time-like braiding. Anyon property therefore suggests the presence of tachyonic momenta.

1. I have played with the idea that quarks and also weak bosons appear in the scale of cells in living matter as dark quarks or even scaled variants with very small mass. How could the dark quarks manifest themselves?

   I have proposed that the protons of dark nucleon triplets representing codons are connected by meson-like bonds, which could be colored and confine codons to genes. This could the case also for the bonds connecting nucleons in the ordinary nuclei. Strong interaction would also make it possible to have dark neutrons.

   I have assigned the Z_3 Galois group with the dark nucleon triplets defining dark codons: this is required by the correct statistics in the model of the genetic code. Could Galois group Z_3 correspond to the center Z^3 of the color group $SU(3)$?

2. In the original proposal for DNA TQC [K7], quark triplets were indeed considered instead of dark nucleon triplets. Dark tachyonic electrons assignable to symmetric hydrogen bonded structures looks like a more realistic option. One can also consider mesons with quark and antiquark ends associated with the ends of the space-like braid strands. Dark tachyonic electrons could be associated with the ends of string world sheets for which the time dimension corresponds to a space-like normal dimension.

   Could one assign a colored quark pair to anyon-like electron? Leptohadrons [K19] are a basic prediction of TGD and there is empirical evidence for them. The predicted mass of the lepto-electron is very nearly the same as electron mass and evidence for its existence was found already in the seventies. Lepto-electron would be a color octet: this is allowed in the TGD framework.

   Lepto-hadron is associated with the breaking of parity symmetry in nuclear collisions involving strong electric and magnetic fields not orthogonal to each other. Its description involves Chern-Simons Kähler action associated also with anyons. The notion of induced gauge field allows its interpretation as SU(3) Chern-Simons action. A possible identification of lepto-electron would be as an anyon for which electron would be accompanied by a color octet quark pair formed by the quarks at the ends of the flux tube.

3. Polynomials can also have roots corresponding to space-like mass squared values. Could dark quarks be tachyonic in the sense that they have a negative real part of mass squared so that time direction as a normal direction for this object would be naturally space-like?

4. Could one see time-like braids structures as genuinely 4-D objects predicted by ZEO and the failure of the strict determinism of the action principle? Singularities as frames span 4-D soap films serve as a source of non-determinism.

2.3.3 How could dark DNA correspond to time-like braids strands for dark DNA?

The following represents a long list of cautious proposals represented as questions.

1. Can one Galois symmetries acting in time direction have projections acting effectively as 3-D symmetries of ordinary matter at time=constant surface.

   The Galois group at the level of (presumably gravitational) MB does not act at the level of ordinary matter. Could the time-like braids at the level of the dark DNA correspond to the ordinary DNA strands in the sense that the temporal sequences would be mapped to spatial sequences by some simple rules?

2. Could genes have a representation as time-like braids? Could one imagine a pile of or ordinary DNA strands and their dark counterparts at different values of $a = a_n$ such that time like braid strands would have the same DNA content as the DNA in $a = constant$ or $t = constant$ plane. For instance, could the intersections of the points of cognitive representation at $a = a_n$ hyperboloids with $t = constant$ hyperplane define the DNA strand.

   The codons of dark DNA as a temporal sequence would correspond to codons of the ordinary DNA unless one assumes that only identical codons correspond to the orbits of the Galois group. This looks like a more reasonable option. Codons themselves would correspond to orbits of the discrete and finite subgroups of automorphisms of quaternions acting as symmetries of Platonic solids and regular polygons. Therefore two kinds of Galois groups would be involved.

3. Could the physical DNA correspond to the space-like braidings assignable to the time-like braidings of dark DNA? Could one realize the representations of the Galois group by using these projections at the level of ordinary DNA.

4. Could identical codons of a gene correspond to projections of points related by the Galois group? If so, the collections of identical codons (64 of them) would correspond to 64 orbits and the anyons would be realized at these collections as wave functions. Different representations would correspond to different anyons serving as number theoretical qupits.

2.3.4 String world sheet interpretation of time-like braidings at the level of H

$M^8 - H$ duality implies time-like braids correspond to physical states rather than time evolutions of an ordinary physical state localizable to time= constant hyperplane. The time-like character of states conforms with ZEO and is implied by the predicted non-determinism in which the singularities of the minimal surface correspond to loci for the failure of strict determinism. These singularities define analogs of frames for the space-time surface as an analog of a 4-D soap film. They are a necessary part of the data allowing to realize holography.

$M^8 - H$ duality [L9, L10] predicts candidates for the singularities as loci of non-determinism. The following argument suggests that the 2-D orbits of braid strands defined by string world sheets as fundamental objects of the TGD Universe giving rise to braidings could characterize the non-determinism.

1. 3-D light-like surfaces defining orbits of partonic 2-surfaces starting at the boundaries of CD and 2-D string world sheets connecting two light-like 3-surfaces. Strong form of holography, whose status is uncertain, states that only the partonic 2-surfaces at the boundaries of CD are needed.

2. String world sheets would provide additional data to fix the preferred extremal and the failure of 4-D determinism manifested as the failure of the minimal surface property would be localizable to the string world sheets. According to the dance metaphor, the ends of the strings would represent dancers and strings would represent the threads connecting their feet.

   String world sheets would be necessary for fixing the space-time surface. This is a profound deviation from string models, where data at time=constant section would fix the time evolution.

   In fully deterministic physics, the direction of time coordinate is normal to $t = constant$ slice. The normal directions of the string world sheet are analogous to time direction: that they are space-like conforms with tachyonicity. String world sheet would represent a tachyonic virtual particle exchange between particles with time-like momenta.

3. Also strings are minimal surfaces apart from singularities. Reconnection is a singularity at which the string world sheets intersect at a single point and involves failure of determinism. The effect of reconnection is the same as that of braiding (SWAP). Reconnection therefore corresponds to the SWAP gate in TQC.

4. The 4-D character of the space-time surface implies that the strings develop spatial braiding during the dance and can also reconnect. This does not happen in super string models with 10-D embedding space for strings.

   The braiding and reconnection patterns would represent the time evolution of string-like entries in 4-D space-time so that TQC would reduce to a string model-like theory with one important exception: braiding and reconnections are not possible in string models.

   Gravitational flux tubes would be one particular case of flux tubes. They seem to be key players in biology and provide a quantum gravitational view about metabolism, biocatalysis, and DNA [L27]. TQC involves braiding and flux tubes with strings attached with them: TQC would have a direct connection with string model type description of quantum gravitation and other interactions.

Tachyonicity of the time-like braids as physical states could be therefore understood. One can look at the situation also from the point of M^8-H duality to gain additional perspective.

1. Virtual particles of QFT picture would in TGD framework have a discrete mass squared spectrum give by the roots of a polynomial and thus algebraic, in general complex, numbers [L25, L26]. Their finite number in zero energy state would resolve the divergence problem of QFTs.

   Only quarks appear as fundamental fermions. Mass squared values and momenta of many quark states constructed are in an extension of rationals without the condition of Galois confinement implying stringy mass squared spectrum and integer valued momentum components using the scale of CD as unit.

2. Quarks at mass shells of $M^4 \subset M^8$ are mapped to geodesic lines of H by M^8-H duality. They can be also space-like unless one assumes that the real parts of the roots of P are non-negative. For negative real parts, the momenta would be space-like and define points outside the sub-CD but a larger CD could contain them.

   Could the total momentum of say 3-quark state possibly associated with codon (3N quark state associated with a gene) be tachyonic? Could the tachyonic quark triplets be located along the time-like braid strand associated with the codon and define a tachyonic many-quark states?

3. For anyons as tachyons Galois confinement must fail and they should correspond to virtual states made from quarks. Could the strands of a space-like braid as a string with quark and antiquark at its ends define an entity analogous to a virtual meson? Could this meson-like entity have non-trivial color quantum numbers?

   How do Galois confinement and color confinement relate? At the level of "world of classical worlds" (WCW) quark color corresponds to partial waves in CP_2 for cm degrees of freedom for the partonic 2-surfaces associated with quark. At the level of the space-time surface there are no color partial waves since fermions do not have color as a spin-like quantum number. I have proposed a Z_3 subgroup of the Galois group as a counterpart for $Z_3 \subset SU(3)$. Correct statistics requires antisymmetry with respect to Galois Z_3.

   One must take this with caution: maybe the braid statistics of anyons could solve the statistics problem. Note however that braid statistics is analogous to Fermi statistics in that two particles are not possible in the same state.

The original proposal for DNA as a TQCer, was that DNA and nuclear membrane are connected by flux tubes having quark and antiquark at their ends. Also DNA strands would be connected by this kind of strands. The proposal was motivated by the observations and the classical counterpart of color gauge field is proportional to the induced Kähler form, and can define a coherent field in arbitrarily long scales.

I gave up this proposal a long time ago but it seems that this proposal had some seed of truth in it. Anyonic electrons replace quarks and antiquarks.

1. What comes in mind first is that the DNA strand and its conjugate involve, besides dark nucleon triplets, also dark quark/antiquark triplets forced by the time-likeness of the braiding

regarded as a physical state in ZEO. This however leads to problems since dark nucleons are strongly favored. Doubling of the genetic code without need for it looks ugly. The mere quantum gravitational modification of the standard chemistry should be enough.

Most importantly, tachyonicity does not require single quark states. Also the dark anyonic electrons could be virtual particles carrying tachyonic momenta. The 3+3 dark electrons assignable to the asymmetric HBs of form O..H-N would provide electronic realization of the genetic code. The dark codons would serve as names, addresses in the symbolic dynamics of TQC involving the resonance mechanism of communications requiring addresses.

The dark anyonic electrons assignable with G-C bonds would carry tachyonic momenta and make the braiding possible. The tachyonic electronic momenta assignable to bonds symmetric O...H-O type bonds connecting water molecules and phosphates would be realized in the same way.

2. It is good to bring in mind the possible weak points of the scenario once again. Dark protons are strongly suggested by the Pollack effect and the proposed picture about dark gravitational HBs with delocalized dark protons [L27]. In the original view, dark protons screened the negative charge of phosphates. In the new picture the negative charge of phosphate is assignable with bi-localized (anyonic/dark/virtual) electrons of O...H-O +O-H...H: at the level of ordinary matter, DNA is not negatively charged. In QFT language, one might perhaps say that a dark electron is exchanged between the ends of the flux tube associated with the dark HB.

2.3.5 Connection with time-like character of music experience and cognition

A connection with the model of DNA based on bioharmony is suggestive.

1. DNA and RNA codons are identified as points at the orbits of icosahedral and tetrahedral subgroups of quaternion automorphisms. Amino acids (AAs) have been identified as orbits of the icosahedral and tetrahedral groups, which are discrete subgroups of quaternionic automorphisms, which is completely analogous to Galois groups.

2. Harmony is the basic element of music and music involves time in an essential way. Same is true of cognition. Perhaps the time-like braid strands could give a concrete content to the proposal. Codons would correspond to 3-chords and gene would correspond to a piece of music in a much more concrete way than originally proposed. Genes would also represent primitive cognitions.

2.4 Cognitive measurement cascades as counterparts of measurements of anyon charges

The measurements of topological charges reduce the tensor products for the representations of the braid group to irreducible representations. What would the counterpart for this process be at the level of the NQC?

1. I have discussed cognitive measurements [L1, L14] as a cascade of "small" state function reductions (SSFRs) for the irreducible representations of the Galois group of extensions of extensions of.... . The full Galois group has a representation as a product of relative Galois groups $R_n = Gal_n/Gal_{n-1}$. The SSFR cascade means a reduction of the representation to a product of representations of the relative Galois groups R_n.

2. This measurement cascade would be the opposite for the measurement of anyonic topological charges involving an analogous decomposition of the tensor product of representations to irreducible representations of the full braid group.

   In ZEO, the counterpart for the measurement of topological charges would correspond to the time reversal of this process starting with BSFR, which creates a completely entangled state as the representation of the full Galois group, and is followed by SSFR cascade proceeding in an opposite time direction. The formation and decomposition of tensor products would occur in different time directions.

2.5 Comparison of standard view about TQC with the TGD view

It is useful to compare the standard view about TQC with its TGD counterpart.

1. Qubits as states are replaced by representations of the braid group characterized by the value of the topological charge and of the quantum group G assignable to the Chern-Simons action.

   Quantum groups [A3, A1, A2] are discussed from the TGD point of view in [K10] and in chapters about possible role of von Neumann algebras known as hyperfinite factors of type II_1 in TGD [K21, K12].

   Quantum group $SU(2)_q$ quantum group characterized by quantum phase $q = exp(i\pi/k)$, $k = 5$, is the simplest option. One can say that anyons correspond to electrons assignable to the orbits of 2-D systems, whose time evolution could be described by Chern-Simons action.

   In TGD, these 3-surfaces would correspond to the light-like orbits of partonic 2-surfaces which for larger values of h_{eff} can have rather large size. For $h_{gr} = GMm/v_0$ the gravitational Compton length for a particle with mass m is $GM/v_0 = r_s/2v_0$ independent of the mass of the particle and for Earth this gives .45 cm for $v_0 = c$, one half of the Schwartschild radius.

2. Topological qubits correspond to topological charges such as the already mentioned parity for condensed matter Majorana electrons, which would have degenerate energies because they correspond to momentum vectors k and $-k$ differing by lattice momentum.

3. Quite generally, quantum measurements are Hilbert space projections. Measurement of qubit corresponds to a measurement of a topological charge. The qubit can be measured by a fusion process for the representations of the gauge group G. Fusion means a formation of a tensor product of representations and could result as a final state of TQC. Measurement means a projection to a particular representation characterized by a topological charge.

   One can also consider the opposite operation in which one decomposes a given representation to a direct sum of product representations and projects out one particular product representation by measuring topological charges for the composites.

4. Fibonacci TQC with quantum group $SU(2)_q$ for quantum phase $q = exp(i\pi/5)$, serves as the simplest candidate for an interesting TQC. Condensed matter Majorana fermions could correspond to Fibonacci anyons with $q = exp(i\pi/5)$ (`https://phys.org/news/2014-12-fibonacci-quasiparticle-basis-future-quantum.html`). The fusion for Fibonacci anyons is non-commutative and non-associative. These properties are coded by a non-commutative R matrix and non-trivial F matrix (see Appendix). For a fusion of N representations the number of degenerate ground states is N:th Fibonacci number.

This has a counterpart in TGD.

1. In the TGD framework, Galois group elements in general change the value of cosmic time as a real part of the root of the polynomial defining the mass shell in M^8 and its image in H. Therefore the associated virtual quark states are not energy degenerate.

   That mass squared values for anyons are different conforms with the idea of time-like braiding as a genuine quantum state rather than time evolution of quantum state, which is natural in ZEO. One can of course challenge this assumption. For states containing N particles with the same polynomial P and represented as an iterate $P \circ .... \circ P$ mass squared values as roots approach to Julia set for P, and this could give rise to approximate degeneracy of mass squared values and corresponding values of light-cone proper time a.

   One can also consider a situation in which one has several roots with the same real part (say roots of a second order polynomial). One can ask whether the analogs of condensed matter Majorana fermions correspond to these kinds of states.

2. The topological structure in question would be realized in terms of the space-time topology as a monopole flux tube not possible in Maxwellian electrodynamics. Also the strings assignable to the flux tubes and corresponding string world sheets as representation of time-like braiding inducing space-like braiding would play a key role. Chern-Simons action would be assigned to the light-like 3-surfaces defining the orbits of partonic 2-surfaces and string world sheets would connect these orbits.

3. The quaternionic automorphism group, defining the analog of the Galois group and having $SU(2)$ or its quantum variant as a covering group, serves as the analog of the gauge group G and acts in the normal space of the space-time surface. Discrete and finite subgroups assignable to the Platonic solids and regular polygons define the natural finite discretizations of this group.

   The braid group could be replaced with a subgroup identifiable as the Galois group for an extension of rationals or for extension of extension of rationals. Also this group can be non-Abelian and would be naturally represented as a subgroup of the braid group.

4. Time reversed fusion corresponds to a cognitive measurement cascade consisting of unitary evolutions followed by SSFRs as counterparts of "weak" measurements. Cognitive measurement cascade and its reversal are initiated by a BSFR changing the arrow of time. Two subsequent BSFRs would correspond to fusion and its reversal and the time evolution between them would correspond to the braiding as a unitary evolution. In TGD inspired theory of conscious experience, the sequence of SSFRs gives rise to the flow of consciousness.

5. Quantum group $SU(2)_q$ for Fibonacci TQC has an interpretation as quantum automorphism. What makes this biologically highly interesting is that the twist $exp(i\pi/5)$ is realized geometrically in the structure of the DNA. This suggests that DNA and dark DNA could involve TQC. One can wonder whether genes with N codons correspond to a fusion of N Fibonacci representations.

2.6 Could the MB of DNA perform intentional TQC?

In TQC and also in AI as human endeavours, human intention plays a key role. This fact has been often forgotten by AI extremists. The braiding defining the TQC would be constructed using technological tools developed by humans. What about the situation at the level of DNA based TQC? Could the MB of DNA play the role of humans to some degree? What kind of quantum computations could the MB of DNA perform?

1. When the braid ends can participate in the flow defined by cellular water or by 2-D liquid defined by the lipids of the cell membrane in liquid crystal phase, one can consider the possibility that the MB induces this flow and in this way builds time-like TQC program, which is also stored as spatial braiding to memory.

   As will be found in the next section, this situation would be true for braids possibly defined by the gravitational flux tubes connecting the oxygens of phosphates of DNA with the lipid ends of nuclear or cell membrane containing also phosphates. Also the GTPs and GDPs of microtubules contain phosphates and their oxygens could be connected with those of lipid phosphates.

   The braiding would serve a memory storage purpose. If MB can induce the flow of water or of lipids, one can say that it can build TQC programs. For instance, a representation of function involving two registers could be constructed by starting from entangled register and using the flow of water or lipids to induce the needed braiding for the second register implying the entangled state $\sum |n\rangle\langle f(n)|$. The TQC ending with cognitive state function reduction cascade would define a conscious cognitive representation of the flow.

2. It will also be found that A-G base pairs by the N...H-N $\leftrightarrow$ N-H...N symmetry of gravitational flux tubes define candidates for HBs assignable to TQC. In this case the braid ends cannot move but the reconnections of braid strands could produce braiding and TQC. Similar situation is true for the sequence of identical DNA codons of, say, genes. They could define an orbit of the Galois group and give rise to its representation. There would be 63 types of orbits which could decompose to separate representations corresponding to various codons. Besides single electron states also many electron states would be possible.

   In this kind of situation, the cognitive measurement cascade would give rise to a conscious cognition at DNA level. In ZEO, reconnections would be forced by the preferred extremal property and unavoidable by the 4-D character of the space-time surface. Therefore they would reflect the underlying physics. The failure of the strict determinism could be interpreted as a selection between a finite number of alternatives at the frames defining the space-time surface as a 4-D analog of soap film. The analog of TQC would give rise to a sensory perception accompanied by cognition.

Factorization of integers into primes is one of the most interesting applications of QC. At first, it looks unlikely that the MB of DNA could be able to do something like this. However, finite groups have a prime decomposition to a product of finite groups and in the same way Galois groups have a decomposition to a product of relative Galois groups, which do not have a similar decomposition.

Group theoretical prime decomposition is analogous but more general than the prime decomposition of integers and more general composition of algebraic numbers to algebraic primes. Since groups with a prime number of elements are certainly prime groups, prime factorization would follow as a consequence and would be a side product of any cognitive SSFR cascade. This conforms with the paradoxical finding that idiot savants, who do not have any idea about the notion of prime, can factorize large integers [K11].

Could Quantum Fourier Transform (QFT) have any analog at the level of DNA? The states in the irreps of the Galois group serve as candidates for the plane waves defining Fourier components. Could cognitive measurements naturally involve a measurement of these quantum numbers as eigen values for maximal set of commuting Galois group elements acting as a minimal Galois transformation. For instance, a rotation by $exp(i2\pi/n)$ would be analogous to this kind of transformation in Z_n. These measurements would induce a localization to a single Fourier component and repeated measurements of the same state would give the probabilities of various Fourier components. These states are superpositions of states at mass shells with varying mass squared and involve time delocalization making sense by the finite non-determinism. A repeated measurement of Galois momenta would make it possible to find the factors of an integer as in the ordinary QC.

3 DNA as quantum gravitational TQCer?

In this section a detailed model for DNA as a TQCer will be developed. The attribute "quantum gravitational" is not necessary since also smaller values of h_{eff} than h_{gr} can be considered.

3.1 Concrete questions concerning DNA TQC

Before representing a concrete model for TQC using Galois anyons as qubits, the basic questions are discussed.

3.1.1 How could DNA qubits be realized physically?

For TQC temperature topological charge identifiable replaces spin as qubit. In the TGD framework Galois charges replace topological charges and one can talk about Galois anyons.

The basic question is how DNA makes it possible to realize anyonic qubits.

1. Dark nucleons associated with dark DNA codons, that is with O...H-O type HBs cannot realize dynamical qubits in terms of spin because the codons must be fixed if they are to represent genetic code. Only in the communications based on resonant cyclotron transitions their states can temporarily change but should return back to the original state as a state of minimum (free) energy.

   One can assign to A-T, G-C pairs 1+1 asymmetric HBs, which do not allow electronic anyons. This gives rise to 3 +3 dark electrons, which could give rise to dark representation of the genetic code.

   The tentative interpretation is that the dark codons define the analog of computer hardware with a fixed ROM. The dark codons would serve as addresses in the resonance mechanism: the analogy with LISP is obvious.

2. The dynamical working memory should correspond to an anyonic realization of qubits. A dark electron associated with the quantum HB of type X...H-X +X-H...X can give rise to two

bi-localized states with odd and even Z_2 parity where Z_2 exchanges the ends of HB. These two dark electron states could serve as anyons.

This could work for electrons of O...H-O bonds between the oxygens of phosphate and water molecules. This could be also the case for the N...H-N bond of C-G base pair, which is symmetric. The HB can be assigned with C codon. In this case, the notion of Z_2 anyon makes sense and could make possible TQC using gravitational variants of symmetric HBs of C-G base pairs (hhttps://cutt.ly/WGNddJ3).

3.1.2 How could the unitary time evolution be realized?

Superpositions of HBs of type X...H-X + X-H...X could give rise to electronic anyons with bi-localized dark electrons. Depending on the situation, braiding or reconnections having, at least apparently, the same effect would define the unitary gates.

1. If the molecules containing X can move, braiding is possible. This is the case if the HBs are associated with the phosphates of lipids of the cell membrane forming a liquid crystal and connect them to the molecules of the cellular water. In the sol phase for intracellular water, the flow of water molecules could define braiding.

   The original proposal [K7, K20] was that the flux tubes connecting the oxygens of the phosphates associated with the DNA strand with the phosphates of the lipid ends would define TQCer. The flow of the lipids of the lipid layer forming a 2-D liquid could define a braiding and thus TQC program. For gravitational flux tubes this option could make sense. The oxygens of the phosphates of DNA could be also connected with the molecules of the water surrounding the DNA if they can move.

   In this case, the dance metaphor makes sense: the TQC as time-like braiding produces a log file as a spatial braiding.

2. For N..-H-H + N-H...N HBs of C-G base pairs the nitrogen atoms cannot move. The reconnections of dark braid strands could produce the same effect as braiding and induce flux tube connections between C:s and G:s belonging to distinct C-G pairs. For gravitational flux tubes these connections could be very long.

   String word sheets are fundamental objects in TGD and by the 4-dimensionality of the space-time surface, 2-D string world sheets at flux tubes representing the orbits of space-like braids intersect at a discrete set of points and for preferred extremals the reconnections are forced by topology. The non-determinism is associated with the choice whether the time-like strand pair AC+ BD transforms to AC+BD or AD+BC.

3.1.3 What about ordinary QC or TQC using electron spin of HB as qubit?

I do not understand TQC enough to say whether electron spin could also appear as a qubit when braidings and reconnections define the gates. In any case, this option meets the same objections as the QC option since a very low temperature would be needed in the standard physics framework.

1. The hyperfine splitting (https://cutt.ly/oGNdeA3), causing the 21-cm line of hydrogen, corresponds to the magnetic interaction energy of nuclear dipole moment with electron's magnetic field and is proportional to h_{eff}. The energy of hydrogen hyperfine splitting is $\Delta E = 5.89 \times 10^{-6}$ eV. This corresponds to a temperature of 5.89×10^{-2} K. If the electrons are dark, the energy of hyperfine splitting is proportional to h_{eff}. The energy is above thermal energy at room temperature for $h_{eff}/h > 5 \times 10^3$.

   Note that the temperature T at the MB of DNA is assumed to be very low but during aging identified as an approach to thermal equilibrium with the biological body T is assumed to increase and approaches the Hagedorn temperature assignable to the flux tubes of MB [L29].

2. If spin serves as a qubit, the manipulation of electronic qubits by changing their spin direction using photons or braiding or reconnection, which at least apparently seems to have the same effect as braiding, would be needed. Both braiding and reconnection involve the replacement $A \to C + B \to D$ with $A \to D + B \to C$ but reconnection involves temporary touch of the braid strands which might have some effect.

3.2 Number theoretical generalization of Kitaev's proposal

Kitaev [B2, B1] has proposed an elegant model for TQC using as qubits the two states of condensed matter Majorana fermion [D1] with two bi-localized states, which have parities +1 and -1 under Z_2 symmetry.

3.2.1 Galois group as subgroup of braid group and Galois anyons

In the TGD framework, the representations of the Galois group would naturally replace these representations and one could speak of TQC which is also number theoretic as far as anyon-like states are considered.

Topological robustness would be replaced by number theoretical robustness due to the fact that the extension of rationals depends only weakly on the polynomial: this is obvious from the fact, the number of extensions is finite for a polynomial of given degree. $M^8 - H$ duality [L9, L10] indeed implies that a given space-time region is determined by a polynomial. In QFT approximation one is forced to replace many-sheeted space-time with ordinary space-time and the nice picture is lost. One might however hope that in TQC this loss is fatal.

1. Galois group replaces Z_2. Instead of topological charges, one can speak of number theoretical charges. Representations of the Galois group would correspond to number theoretical qubits. Number theoretical anyon would be identified as a superposition of states localized at points of orbit of Galois group Z_2 associated with DNA double strand.

   As already found, the Galois ground state corresponding to $h_{eff} = h = n_0 h_0$ is not completely unique but would naturally correspond to a polynomial $P_g = Q_g \circ P_2$ where P_2 is second order polynomial, all roots of $P = P_1 \circ P_g$ appear in pairs $x \pm y$ and Z_2 permutes the members of the pairs. Fibonacci polynomial $P_F = X^2 - x - 1$ is highly attractive candidate for P_2 and would give the roots $(1 \pm \sqrt{5})/2$ as roots of all polynomials P. Also the twisting geometry of DNA favors Fibonacci TQC, which is also the minimal option.

2. Hydrogen bonds X...H-X and X-H...X are symmetric and their possibly gravitationally dark variants, could give rise to states with opposite parity. The electron of the hydrogen could define the number theoretic anyon.

3. The gravitational flux tubes as counterparts of H-bonds could define the braid strands but alsos smaller values $h_{eff} \geq h$ assignable to electromagnetic flux tubes could work. Braiding would take place for these strands.

4. What about the protonic option for X...H-X type HBs based on the identification of anyons as delocalized states of the dark proton with opposite parity? Also now one can consider a superposition of N-H...N and N...H-N gravitational bonds and two different parity states with respect to Z_2. The quantum gravitational model for the metabolic energy quanta however suggests that the dark proton is localized mostly in the interior of the gravitational flux tube so that the dark proton should not have a large amplitude at the ends of the flux tube.

Hydrogen bonded structures of type X...H-X populate living matter. Water and DNA and the first examples that come into mind.

1. The hydrogen bonds between water molecules are of type O..H-O. Hydrogen bonded water molecule clusters could give rise to multiply localized anyonic states of electrons and serve as TQCers.

2. The HBs of the oxygens of phosphate atoms with oxygens of water molecules allow poly-localized electrons if the HB is superposition of O-...H-= and O-H...H. This would allow to associate electronic anyons and TQC also with the dark nucleon triplet codons, which cannot have dynamical spin.

3. G-C base pair has one N..H-N type HBs (`hhttps://cutt.ly/WGNddJ3`). N-H...N ↔ N...H-N are could be possible for $h - eff > h$ HBs, and could lead to the delocalization so that one could assign anyonic state with Galois Z_2 symmetry with it. The G-C base pairs of the DNA double strand could define a sequence of topological qubits. Note that the splitting of

the N-H...N bond in the G-C base pair leading to N + H-N is known to occur during DNA transcription and replication and also in the temporary splitting of the HB [L27].

4. Benzene allows delocalized states of electron pairs, which could be poly-localized and be analogous to Z_6 anyons. Also Z_2 and Z_3 anyons can be considered. The atoms of the aromatic ring could be connected by flux tubes with $h_{eff} > h$ and perhaps even $h_{eff} = h_{gr}$.

   In DNA , the sequences of the aromatic 5- and 6-rings, possibly defining Z_5 and Z_6 anyons, could give rise to a delocalization of the anyonic states along DNA strands possibly involving gravitational analogs of valence bonds.

5. In DNA strand nucleotides A and G contain aromatic 5- and 6- rings glued together whereas T and C contain aromatic 6-ring (`hhttps://cutt.ly/WGNddJ3`). The members of base pairs contain fused 5- and 6-ring and 6-ring respectively. One can wonder whether the Galois representations associated with these structures in the double DNA strand structure could make possible TQC. Also the side chains of amino acids Phe, Tyr, and Trp contain aromatic rings and HBs between oxygens of water molecules might be relevant for information processing at, say, microtubular level.

3.2.2 The non-symmetric HBs of base pairs and possible new dark realizations of the genetic code

The symmetric HBs of C-G base pairs (`hhttps://cutt.ly/WGNddJ3`) would be in a very special role. What about the remaining non-symmetric HBs associated with codons?

1. Besides N..H-N HB there are 3+3 electrons per codon with asymmetric HB of form X..H-Y, with X,Y= O,N or N,O. The proposal that an electronic variant of metabolism is realized, leads to the question of whether the spins of these 6 electrons could realize genetic code as a 6-bit code. Now only the analogs of DNA codons would be realized.

2. For asymmetric HBs, anyonic dynamics for electrons is not possible but the electronic dark codons could serve as addresses in the resonance mechanism of communication based on the transformation of Josephson radiation to pulse sequences by cyclotron resonance [L28, L27]. This is possible if the electrons are dark so that the energy of the hyper-fine splitting is scaled so that it is higher than thermal energy. This would require $h_{eff} \geq 50$.

   One can also imagine resonance-based communications between dark electron 6-plets and dark nucleon triplets using dark photons.

3. The dark proton at flux tube and dark electron at the hydrogen end could define an analog of dark H atom. Dark H would have 4=3+1 spin states with spins 1 and 0 and these states could define the analogs of nucleotides in 1-1 correspondence with A,T,C,G. C as a special codon would naturally correspond to the spin singlet. Hyper-fine splitting for this dark atom would distinguish between triplet and singlet. For large h_{eff} the energy this splitting would be above thermal energy so that the spin configurations would be stable.

These observations challenge the details of the earlier view [L28] about the genetic code.

1. The dark nucleon realization of the genetic code [L28] predicts both DNDA, DRNA, DtRNA, and DAAs. One can criticize the realization since also neutrons are required.

   The model of the code has several variants but the most recent model [L27] requires dark variants of both neutron and proton residing at the gravitational flux tube defining gravitational HB connecting the oxygens of phosphate and water. The charge of the delocalized dark proton would not be visible in the scale of DNA so that its replacement with dark neutron would not affect the situation in this scale.

   Dark protons would be generated from ordinary protons in Pollack effect [I2, I1, I4, I3]. They could transform to dark neutrons by the dark variant of strong interactions or of weak interactions at the gravitational flux tubes. Dark weak interactions could be realized in even cellular scales and imply that dark variants of weak bosons are massless in the scales below the dark Compton length of weak bosons. This would explain chiral selection of biomolecules difficult to understand in the standard model.

The conserved vector current hypothesis (CVC) and partially conserved axial current hypothesis (PCAC) [K19] relate the descriptions of hadrons in terms of strong and weak interactions, which suggests that these views might provide dual descriptions. The duality might in fact reduce to M^8-H duality. The interpretation of anyonic electron as a color octet electro-pion [K19] involving color octet meson-like state associated with the gravitational flux tube was already discussed.

If HB is associated with oxygen of phosphate (water molecule), the hydrogen of phosphate (water molecule) would look negatively charged. For anyonic states the electron of H would spend half of the time near the two oxygens involved implying that negative charge would be delocalized in a longer scale.

2. Could the standard genetic code be associated with the electron triplets at HB associated with base pairs rather than with the phosphate water HBs? One can imagine two realizations.

   (a) For both dark DNA strands, both dark proton triplet and dark electron triplet would have 2^3 dark entangled states and together they would combine to form 64 states. Could they provide a dark realization of the genetic code consistent with the chemical genetic code?

   (b) Could the dark protons at the HBs associated with base-pairs pair with dark electrons at their ends give rise to analogs of dark H atoms? This could give 64 states perhaps allowing an interpretation as a dark realization of genetic code.

   There are objections against both proposals. The counterparts of RNA,tRNA, and AAs are not predicted so that the correspondence with the chemical realization of the genetic code is not plausible. Dark codons would have integer spin varying from 0 to 3 and the code table does not show any grouping of codons to these multiplets containing an odd number of states.

To sum up, it would seem that several realizations of the genetic code are possible as indeed suggested by the proposed universality of the genetic code [L19, L28].

3.2.3 Could protonic and electronic anyons define a pair of registers?

Two registers are needed to represent a Boolean function $x \rightarrow y = f(x)$ in terms of entanglement (see Appendix). n qubits represent the values of x and y. The simplest representation of f is as a maximally entangled state $\sum |n\rangle\langle f(n)|$. In this representation quantum Fourier transform (QFT) is exponentially faster than the ordinary fast Fourier transform. Also the quantum counterparts of number theoretic algorithms such as finding prime factors and greatest common divisor are faster than their classical counterparts.

How could one realize these registers in the recent case? There should be a natural interaction inducing the entanglement between qubits. The realization of the genetic code fixes the states of dark proton and electron triplets completely for a given codon so that these qubits are non-dynamical.

In the case of HBs of type X...H-X, this however leaves the anyonic degrees of freedom assignable to the dark electron as Z_2 degeneracy and perhaps also with dark protons as a similar degeneracy. The entanglement between electronic and protonic anyons would commute with the spin degrees of freedom. Could the two registers correspond to electronic and protonic anyons? Could the braidings of the flux tube, possibly induced by reconnections, generate entanglement between these anyons? The objection is that the anyonic dark protons would not be delocalized in long scales as the model for metabolic energy quantum requires. The metabolic dark proton states would correspond to different states concentrated near the top of the gravitational flux tube.

4 Appendix: Basic concept and ideas of quantum computation

I am not a specialist in quantum computation and since some readers might also have the same problem, I have added some remarks about QC, which I believe to be relevant for this article. I have discussed the TGD view about TQC for about 13 years ago [K8, K7, K20]. These chapters reflect my views at that time and a lot has happened in the TGD based view of quantum biology after that. Perhaps I also have a little bit deeper understanding of TQC now.

4.1 About key ideas of QC

In the following the basic ideas QC and TQC are briefly described.

4.1.1 Gates as unitary transformations

Quantum computation can be seen as circuits consisting of gates, which realize unitary transformations assigning to n incoming qubits $n = m$ outgoing qubits: unitary forces $m = n$. For qubits, which reduce to ordinary bits one obtains as a special case Boolean functions from n to n bits.

Unitarity forces $m = n$ but by using control qubits for which nothing happens in the the gate but the outcome from the remaining qubits depends on the value of the control qubit, one can realize also gates which for bits reduce to Boolean maps from n bits to a smaller number of bits so that ordinary logic circuits can be realized as a special case.

n-gates with $n = 1, 2, 3$ are enough for obtaining a universal set of gates. The interested reader can learn details from the slides of Viterbi: for instance the slides at `https://cutt.ly/EGNsmcR` describe Quantum Fourier Transform.

1. 1- port represents a unitary transformation of a single qubit.
   (a) Phase gate, Hadamard gate and rotations by Pauli spin matrices are basic gates of this kind. Discrete rotation as $SU(2)$ transformation represents the general unitary transformation. Rotation is specified by two orthogonal rotation axes and by 3 rotation angles.
   (b) Discrete subgroups of rotation group assignable to Platonic solids and regular polygons define especially interesting selections for the set of possible quantization axes and for the possible directions of spin representable as a point of Bloch sphere. For Platonic solids the subgroup of $SU(2)$ is discrete. These subgroups can produce unitary transformation in a finite accuracy only but one can consider the possibility of transformations obtained as products of elements of these subgroups.
   (c) Quantum variant of $SU(2)$ emerges in TQC and also the braid group defines a quantum variant of the permutation group as a finite covering of the braid group. The gates in topological computation correspond to the elements of the braid group. In the TGD framework, $SU(2)$ has a representation as the covering of the automorphism group of quaternions (analogous to Galois group) acting in the normal space of the space-time surface.
2. Arbitrary $N \times N$-D unitary transformation can be constructed as a product of 2-D unitary transformations. In the $N = 2^n$ case, the transformation can be represented at qubit level and using control gates one can represent unitary transformations by using qubit representation with $N < 2^n$.

   The representation of a general unitary transformation in dimension n requires of order $n2^n$ gates. The subset needed as unitary transformations is however believed to be much smaller than all possible transformations.
3. Swap, which permutes subsequent incoming qubits and CNOT are examples of 2-gates.
4. The notion of controlled gate generalizes to n qubits. Toffoli gate as CCNOT defines a 3-gate and together with 1- and 2-gates it defines a universal set of gates.

4.1.2 Bloch sphere and Platonic solids

Block sphere gives a parameterization for the directions of the spin quantization axis and spin has two directions for a given quantization axis. In the twistorialization of TGD at the level of M_c^8 this interpretation of the twistor sphere is natural [L9, L10].

1. In the number theoretic vision these directions correspond to sines and cosines and in the number theoretic vision these must belong to the extension of rationals considered assignable to a given space-time region. This discretization can be interpreted in terms of finite measurement resolution.

2. The allowed quantization directions are obtained from each other by the transformations of the rotation group $SU(2)$. If these rotations form a finite group, only the symmetry groups of Platonic solids and regular polygons are possible. For Platonic solids there are 4, 6, 8, 12, and 20 quantization axes corresponding to tetrahedron, octahedron, cube, icosahedron and cube.

4.1.3 Some applications of QC

Examples of the applications of QC working faster than their classical counterparts are discussed in the Wikipedia article (`https://cutt.ly/8Hs5qdG`). For instance, the following examples are discussed.

1. A very simple application is the finding of the inverse image of function by measurement the of value of function $f = f(n)$ for $\sum |n\rangle\langle f(n)|$ giving the superposition $\sum |n\rangle\langle f(n) = y|$.

   In a more general case this localization gives the inverse image of a map f of m-D discrete space to n-D discrete space. The repeated application of this algorithm can be used to find the boundary of a region of the inverse image of f.

2. Quantum Fourier transformation calculates a discrete Fourier transformation exponentially faster than ordinary fast Fourier transform. Other related applications find a prime factor of integer, period of a periodic function represented as an entangled state $\sum |n\rangle\langle f(n)|$ of two registers as, and number theoretic logarithm.

   Quantum Fourier transform (QFT) is discussed (`https://cutt.ly/EGNsmcR`) takes place exponentially faster than the classical fast Fourier transform. For $N = 2^n$ qubits the number of computation steps is $O(n)$ whereas classically it is $O(n2^n)$. The discrete Fourier transform has a huge number of both physical and number-theoretical applications.

   QFT can be represented in terms of n qubit registers as an un-entangled product of states of n qubits and this state can be constructed using only gates inducing phase rotations $R_k = ep(i2\pi/k)$ of qubits, Hadamard gates producing the superposition of 0 and 1, and control gates.

3. There is an algorithm calculating the phase produced by a unitary transformation: this algorithm involves one additional qubit, whose phase is opposite.

4. There is a search algorithm, which increases the probability of the searched integer before localization in discrete space defined by integers. The number of trials is $O(\sqrt{N})$ whereas classically it is $O(N)$.

5. Error correction algorithms localizing the logical qubits relevant for the computation to a subspace of logical qubits. These algorithms detect the error by using parity qubits and correct the error by action of a unitary gate in the case that the number of errors is below a given number.

4.1.4 Finding a period of a periodic function

One assumes that the function $f(n)$ is periodic but the period is not known. The entangled state of the registers is $\sum |n\rangle\langle f(n)|$.

1. One assumes that one has measured $y = f(x)$ and has obtained $\sum |n\rangle\langle f(n) = y|$. If f is periodic, one obtains a superposition of points $n_0 + nr$, where n_0 is the offset and r is the period, which should be measured.

2. A QFT is performed for the input register. One obtains a superposition for states with momenta mN/r.

3. The measurement of momentum this state gives momentum state with momentum $p_m = mN/r$ for some m, which is however unknown.

4. The operation is repeated. This gives a series of outcomes $m_1, m_2, m_3, ...$ Eventually the minimum value of momentum corresponds to $m = 1$.

4.2 About key ideas and notions of TQC

It is appropriate to briefly recall the basic ideas and concepts of TQC [K8].

4.2.1 Topological gates and qubits

The topological stability of braiding guarantees that the TQC program coded by the braiding is robust against perturbations. If qubits were spins, there would still be the instability of qubits and entanglement caused by the interaction of spins with the environment, in particular thermal instability.

1. Qubits as spins are replaced by representations of the braid group characterized by the value of the topological charge and the quantum group G_q assignable to the Chern-Simons action. The quantum group $SU(2)_q$ is the simplest option. Topological charge replaces spin as qubit. One can say that anyons correspond to electrons assignable to 2-D topological structures, whose time evolution as 3-surfaces could be described by Chern-Simons action.

   The mathematics of quantum groups [A3, A1, A2] is discussed from the TGD point of view in [K10] and in the chapters about the possible role of von Neumann algebras known as hyperfinite factors of type II_1 (HFFs) in TGD [K21, K12]. Quantum groups would be assigned to the inclusions of HFFs characterizing the finite measurement resolution. Cognitive representations are an alternative way to describe the finite measurement resolution.

2. Topological qubits correspond to topological charges such as the already mentioned parity for the condensed matter Majorana electrons, which would have degenerate energies because they correspond to momentum vectors k and $-k$ differing by lattice momentum.

   The idea of Kitaev [B2, B1] [D1] is to use anyons as topological qubits instead of spin. The condensed matter Majorana electrons bi-localized at the ends of superconducting wire have two states with opposite parities associated with the exchange of the ends of the wire. These states with degenerate energies would serve as qubits, which would be much more stable than spins.

3. Topological approach allows to realize gates in terms of braiding operation. Braid group B_N as a covering of the permutation group of N braid strands would define the allowed unitary transformations induced by braidings. This implies finite accuracy but the increase of the covering improves the accuracy.

   This allows to overcome the problem of the Hamiltonian approach in which the gate Hamiltonian defining the unitary transformation must be "on" for a very precise time ΔT. It is not easy to arrange this by external interaction. A possible way to avoid this altogether is to assume a permanent Hamiltonian but allow the qubit system to move with a fixed velocity past the Hamiltonian system with a velocity, which gives the desired ΔT.

4. Non-abelianity is required since the manifold of the energy degenerate states in which the braid group would act, is determined by states and must be a higher-dimensional representation of the braid group in order to give rise to a large enough number of logical qubits. There exist no well-established candidate for the needed non-abelian anyon yet.

4.2.2 R and F matrices

R- and F matrices are central notions in TQC (https://arxiv.org/pdf/2005.03236.pdf) and characterize what happens in the fusion of the representations of quantum groups. These matrices are believed to characterize quantum phases as topological orders and were discovered in 2-D fractional quantum Hall systems.

1. Fusion corresponds to a tensor product, which is commutative and associative for ordinary group representations. For quantum groups and braid groups, the discrete group elements are replaced by flows in plane so that the situation changes. The commutativity of the product ab of the representations is lost and associativity for the product $a(bc)$ of three representations is only modulo unitary transformation: $a(bc)$ is equal to $(ab)c$ only modulo unitary transformation.

2. R matrix characterizes the braid operation, swap, in which the two braid strands are permuted by flow-like continuous transformation. Braiding as an element of B_N replaces the discrete permutation of adjacent braid strands as an element of S_N. The R-matrix characterizes the effect of the braid operation and reduces to a phase in the abelian case but is a genuine matrix in the physically more interesting non-Abelian situation.

3. F matrix characterizes the associativity modular unitary transformation for fusion operations. The F matrix is trivial for the ordinary tensor product . This means that the fusions $a(bc)$ and $(ab)c$ produce different states but do not change the state-space. F-matrix $F(a,b,c)$ relates these two states as a unitary transformation in the tensor product of the 3 state spaces.

4. Fibonacci quantum computation with quantum group $SU(2)_q$ for quantum phase $q = exp(i\pi/5)$ represents the simplest example of a non-commutative situation (https://phys.org/news/2014-12-fibonacci-quasiparticle-basis-future-quantum.html). For a fusion of N representations the number of energy degenerate ground states is N:th Fibonacci number.

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