

# TOPOLOGICAL QUANTUM COMPUTING

## The “TQC Shock Wave” and Its Impact on University Computer Science Teaching

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### **Abstract**

*Topological Quantum Computing (TQC) promises to make quantum computers robust, and hence scalable, in the next few years. Quantum computers are exponentially more powerful than today's classical computers, so a successful TQC will revolutionize computer science, necessitating that the principles of TQC be taught in thousands of computer science departments around the world. Unfortunately, understanding these principles requires a PhD level knowledge of topics in pure mathematics and theoretical physics. Since most university computer science departments stop teaching math and physics at undergraduate level, the need to upgrade their teaching of these fields to PhD level will generate*

*shock waves in their teaching policy and faculty hiring. This article shows how a pioneering university in southern China is coping with this problem.*

The idea of Quantum Computing (QC), with its exponentially superior computing capacities, compared with classical computers, has been around for a quarter century [Feynman 1982]. However, storing a (qu)bit of information in a very small region (e.g. on the spin of a single electron) makes such storage highly vulnerable to disturbance from the environment (a phenomenon called *decoherence*) [Nielsen & Chuang 2000]. The new Topological Quantum Computing (TQC) [Collins 2006, Day 2005, Das Sarma et al 2006] stores the information topologically, i.e. globally, in the topological invariants of “topological quantum fields”, and is thus far more robust against noise, making quantum computing practical, using phenomena in the Fractional Quantum Hall Effect (FQHE) [van Degrift et al 1992].

However, teaching computer science students the principles of TQC, implies that they be taught PhD level mathematical physics and pure mathematics. Computer science students will need to learn a lot more mathematical physics. This will make the study of computer science *a lot more intellectually demanding* and give it a higher status than it enjoys today. University computer science departments will have to hire or collaborate with professors in pure mathematics, and in theoretical physics, and change their curricula to adapt to the TQC revolution.

## *Quantum Computers*

For many decades, computer scientists felt that computation was a branch of applied mathematics. However, in the 1980s, a new viewpoint grew up, namely that “*New physics implies new computation*”. This means that by employing new phenomena in physics, one can compute more powerfully than with traditional Boolean-logic-based classical computing. By exploiting the quantum mechanical phenomena of *superposition* and *entanglement*, it is possible to perform quantum computing, which can calculate  $2^N$  things simultaneously (where  $N$  is the number of (qu)bits in the computer’s (quantum) register, and thus vastly outperform a classical computer, which can only calculate one thing at a time.

If quantum computers can be built successfully, and with large  $N$ , then our whole culture will be changed radically. For example, biology will be revolutionized, because quantum computers will be able to simulate large molecules and even cells. Classical computers cannot simulate large molecules, because they cannot simulate large quantum systems. For example, every time one adds an atom to a molecule to be simulated, that molecule’s Hilbert space (in quantum mechanical terms) doubles in size. Quantum chemists can only use classical computers to simulate small molecules. But with quantum computers, every time one adds a qubit to the quantum register, the number of calculations that that register can perform simultaneously doubles. Hence as the size of a simulation problem doubles by adding another atom to the molecule,

by adding another qubit to the quantum register, so too does the computational capacity of the quantum computer. Therefore quantum computers can simulate large molecules. As  $N$  increases,  $2^N$  becomes astronomically large. Hence one can imagine simulating DNA molecules, protein folding, cellular components, whole cells, organs, etc. Our whole technological culture will be changed radically, given the exponentially superior computational capacities of quantum computers.

### *Decoherence*

However, this dream of exponentially superior quantum computers has a catch, and that is that quantum computers, as they have been conceived until recently, are *fragile*. In a “traditional” quantum computer, a (qu)bit of information is stored highly locally, e.g. on the spin (up or down) of a single electron. This form of highly local information storage is particularly vulnerable to disturbance from the environment, i.e. other atoms and fields in the neighborhood can interact with the electron and change its state, thus losing the information stored in that state.

Quantum error correcting codes were invented in the mid 1990s to correct such errors [Shor 1995], but only if the probability of error was very low, i.e. about one part in ten thousand. In practice, this is very difficult to achieve. So after a quarter century since the invention of the idea of quantum computation, we still do not have operational quantum computers with large  $N$ .

### *Topological Quantum Computing (TQC)*

But, in 1997, a Russian mathematical physicist, Kitaev, conceived the idea of using a so called “quantum topological field” [Kitaev 1997] to store information in the topological invariants of that field, i.e. “spread out” over a wide region, so that if the environment were to disturb a portion of the field, the information stored in that field would not be changed. It would be robust against noise. (As a simple example of a topological invariant, consider a rubber “figure of 8” doughnut. By squashing it, twisting it, the angles and lengths change, but there is a topological property of the object that remains invariant, and that is the number of holes it has, its “genus”).

In 2000, Michael Friedman, a Fields Medal winner, for his work in topology in the 1980s, invented the mathematics of a method for performing universal quantum computation using a topological quantum field [Friedman et al 2000]. Thus the theorists had provided a new approach to quantum computing, that in theory at least could overcome the decoherence problem.

### *Anyons*

The next step, now hotly pursued, is to find phenomena in physics which obey Friedman’s mathematics. The favorite candidate is the so called “12/5 state” in a phenomenon called the “Fractional Quantum Hall Effect (FQHE)” [van Degrift et al 1992] in a specialty known as “Condensed Matter Physics”. The FQHE arises when free electrons sandwiched between two layers of Gallium Arsenide are subjected to extreme cold, and to an extremely strong

transverse magnetic field. These conditions cause the electrons to agglomerate into so-called “anyons”, i.e. quasi-particle excitations, which have weird properties, e.g. fractional charge, and non fermion-boson statistics. They are called “anyons” because they can have “any” statistics.

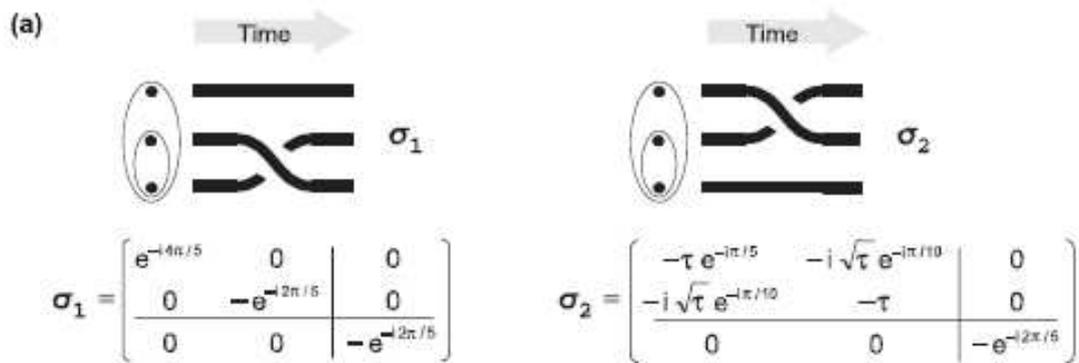
From quantum mechanics we know that when two fermions (bosons) swap positions, the total quantum state is multiplied by  $-1$  ( $+1$ ). But for the anyons, things are more complicated. If the state of a line of anyons is represented by a quantum mechanical column vector, then when two anyons swap positions, that column vector needs to be multiplied by a matrix, and the matrix will differ depending on whether the two anyons move around each other (in a 2 dimensional “sandwich”) clockwise or anticlockwise.

If one traces out the paths taken by 2 anyons as they swap positions, as “world lines” as in relativity theory, then the paths will look like a double helix, twisting either clockwise or anticlockwise as one looks down on the “upward” moving helix. This spiraling of the anyon pair is called a “braiding operation”. A sequence of such operations over  $N$  anyons is called a “braid”. The set of all possible braids for  $N$  anyons forms a mathematical group called the “braid group” [Jacak et al 2003].

Friedman and others showed that any quantum computational calculation can be approximated to any desired accuracy by performing a sequence of braiding operations on anyons. A sequence of braiding operations corresponds to multiplying the initial state of the anyons by the appropriate sequence of matrices. The longer the sequence, the greater is the possible accuracy of the calculation. In traditional quantum computing, an initial

quantum state is multiplied by a unitary matrix, to create a new state, which is then measured to give the result of the (quantum) computation. Thus Friedman showed that any unitary matrix can be approximated by multiplying by the matrices that correspond to the sequence of braiding operations. I call these “elementary braiding operations” EBOs.

Bonesteel et al [Bonesteel et al 2005] found anyon EBO sequences that approximate the building blocks that can be used to perform any quantum computation (e.g. single qubit phase change gates, and the CNOT (controlled NOT) gate). Fig. 1 shows elementary anyon anti-clockwise and clockwise braiding operations (EBOs), and their corresponding matrices.



**Fig. 1 Two Elementary Braiding Operations (EBOs) and Their Corresponding (Anyon Quantum State Changing) Matrices**

Condensed matter physicists have already confirmed experimentally that the quasi-particle excitations of the

FQHE act as anyons, e.g. the  $5/2$  excitation. It is also known that only “non-Abelian” (i.e. the two matrices A and B corresponding to two braid operations do not commute, i.e.  $AB \neq BA$ ) anyons can perform universal quantum computation. The  $5/2$  excitation is non-Abelian, but unfortunately is incapable of universal quantum computation for other reasons. However, mathematical simulations have shown that the  $12/5$  anyon is non-Abelian, and is capable of performing universal quantum computation, so the experimental condensed matter physicists are now feverishly conducting experiments to confirm that the  $12/5$  excitation is in fact a non-Abelian anyon, and hence could serve as the corner stone of topological quantum computing.

Not surprisingly, interest in TQC has *skyrocketed*, now that it looks likely that a physical means to implement the already established TQC theory is at hand. Workshops on the topic have popped up like mushrooms in the past year or two, in the US, UK, China etc. Governments are starting to get interested, since if the condensed matter physicists confirm that computationally universal non-Abelian anyons exist in reality, as is strongly expected, then the prospect of implementing topological quantum computers becomes much more realistic. The creation of scalable topological quantum computers will have profound technical, economic and cultural impact.

### *The Educational Impact of TQC*

But, there is an educational price to be paid. Ordinary Quantum Computing (QC) is usually taught at senior

undergraduate and/or first year master's level, because the level of mathematics and physics knowledge needed to understand QC is at that level, e.g. using linear algebra, Hilbert spaces, etc. However TQC requires a much higher level of knowledge of pure mathematics and theoretical physics. For example, deriving the matrices that correspond to the braiding operations (EBOs) described briefly above uses such notions as the R and F matrices and the pentagonal and hexagonal relations of "Quantum Groups" and "Conformal Field Theory", which is PhD level pure math and theoretical physics.

Given the critical importance of TQC to humanity's future, computer science departments at thousands of universities around the world will come under pressure from national governments to teach the principles of TQC, and this in turn will send shock waves through these departments as they come to terms with the reality of the level of difficulty of the pure math and theoretical physics needed to teach it.

As a consequence, computer science (CS) as a specialty will quickly gain a new reputation, i.e. as being one of the toughest and most intellectually demanding specialties on campus, comparable with that of pure mathematics and mathematical physics. In fact, CS will need both, as well as the usual notions of computing.

In time, the status of computer science as a specialty will rise, as the average intelligence level of the students studying it rises, as it must. Today's average computer science graduate student will not be able to cope with the high level of mathematical abstraction needed to understand such TQC topics as quantum groups, conformal

field theory, quantum field theory, topological quantum field theory, algebraic topology, etc.

### *TQC Courses*

Computer science departments will have to hire or collaborate with pure math and mathematical physic professors to teach TQC related topics. Computer science deans and heads of department will have to restructure their CS courses, and so will need guidance on how to do this. What now follows is a list of those topics that will need to be taught in CS departments in order for graduate students to understand TQC. It includes a detailed time table of the TQC type courses that were originally planned to be taught at my university (i.e. Xiamen (pronounced “She Ah Men”) University, in the south of China). These pipelined courses take 4 years (e.g. a 3-year master’s course, plus 1 year of PhD, or a 2 year master’s course, plus 2 years of PhD). See Fig. 2 for details. This time table and course list may be useful to deans and department heads who are considering doing something similar for their universities. In China, it is referred to as the “Xiamen Model” (for TQC teaching).

	Tues	Wed	Thurs	Fri
Year 1 Semester 1		<b>Mp1</b>		<b>Mm1</b>
Year 1 Semester 2		<b>Mp2</b>		<b>Mm2</b>
Year 2 Semester 3		<i>Mp1</i> <b>Mp3</b>		<i>Mm1</i> <b>Mm3</b>
Year 2 Semester 4		<i>Mp2</i> <b>Mp4</b>		<i>Mm2</i> <b>Mm4</b>
Year 3 Semester 5		<i>Mp1</i> <b>Mp5</b>	<i>Mp3</i> <i>Mm3</i>	<i>Mm1</i> <b>Mm5</b>
Year 3		<i>Mp2</i>	<i>Mp4</i>	<i>Mm2</i>

Semester 6		<b>Mp6</b>	<i>Mm4</i>	<b>Mm6</b>
Year 4+	<i>PhDp7</i>	<i>Mp1</i>	<b>Mp3</b>	<i>Mm1</i>
Semester 1	<i>PhDm7</i>	<i>Mp5</i>	<i>Mm3</i>	<i>Mm5</i>
Year 4+	<i>PhDp8</i>	<i>Mp2</i>	<i>Mp4</i>	<i>Mm2</i>
Semester 2	<i>PhDm8</i>	<b>Mp6</b>	<i>Mm4</i>	<i>Mm6</i>

**Fig. 2 The “Xiamen Model” TQC Teaching Schedule**

The above table requires some explanation. The “M” refers to a master level course. The “PhD” refers to a PhD level course/seminar. The “m” following an M refers to a math course, and a “p” to a physics course. The numbers refer to the semester number over 4 years, i.e. 8 semesters, e.g. Mp3 is the master’s level course in physics in the 3<sup>rd</sup> semester.

At my university, our strategy was that I would teach all courses at least once, to give me experience of all the TQC based courses. However, since the courses are pipelined over 4 years, if I were to teach all courses, the total teaching load would become unreasonably large, so I teach each new course once, then pass it the following year to a colleague in the math or physics department. However, I do teach the quantum computing course in Mp3 and the topological quantum computing, and condensed matter quantum field theory course in Mp6, and all the PhD TQC courses.

The courses in Fig.2 in *italics* in a given year are taught by professors in the math or physics department after they have been taught once by me. Courses in **bold** in a given year are taught by me in that particular year and for the first time. Courses in ***bold italic*** are taught by me permanently.

Students are offered the “TQC/MPC” (Topological Quantum Computing/Math-Physics-Computing) specialty as an “orientation”. Once they enroll in it, they commit themselves to spending 3 years of their master degree and a further year or two in a PhD program (if they continue to a doctorate degree) taking TQC/MPC courses. The first year at the master’s level is a “prerequisite” year, in which CS students learn topics from undergraduate level math and physics that are needed to understand TQC. Math and physics students are allowed to take the courses and get credit.

The actual contents of these courses are now listed. Each course is for 3 lecture hours per week, for about 18 weeks.

## **Year 1**

### *1st Semester*

Math (Mm1): Vector Analysis, Real Analysis, Complex Analysis, Fourier Analysis

Physics (Mp1): Electromagnetic Theory, Special Relativity, Statistical Mechanics

### *2nd Semester*

Math (Mm2): Finite Group Theory, Differential Geometry, Basic Topology

Physics (Mp2): Analytical Mechanics, Quantum Mechanics

## **Year 2**

Once the “TQC/MPC orientation” masters students have completed their first “*prelims*” year, they then begin more serious study of TQC/MPC topics at master’s level.

### *3rd Semester*

Math (Mm3): Algebraic Topology

Physics (Mp3): Quantum Computing

### *4th Semester*

Math (Mm4): Lie Groups/Algebras and Representations

Physics (Mp4): General Relativity

## **Year 3**

### *5th Semester*

Math (Mm5): Knot Theory, Braid Groups, etc.

Physics (Mp5): Quantum Field Theory (QFT)

*6th Semester*

Math (Mm6): Manifold Theory

Physics (Mp6): Topological Quantum Computing (TQC),  
Condensed Matter Quantum Field Theory (CMQFT)

### **Year 4 (PhD Level) and Beyond**

At my university, about half of the master's students continue into a PhD program. PhD level TQC/MPC courses take the form of weekly “research seminars” in which students study and discuss advanced text books and research papers on the following topics.

Math (PhDm7,8): Conformal Field Theory (CFT), Kac-Moody Algebras, Operator Algebras, Quantum Groups, etc.

Physics (PhDp7,8): Topological Quantum Field Theory (TQFT), Advanced Topological Quantum Computing (TQC), Gauge Theory, String Theory, etc.

### **Two Years of Teaching TQC : Lessons Learned**

This section was written (Oct 2009) two years after the paragraphs written above in this article. It describes the actual experiences of the author in teaching TQC courses to masters level math, physics and computing.

I moved to Xiamen University, (Xiamen, Fujian Province, China) early in 2008, and under contract I started to teach a set of TQC courses, similar to those mentioned above. I had been told before I moved to Xiamen that the masters courses at Xiamen University lasted 3 years, so I prepared the TQC courses to be spread over 3 years, as shown in the above section. When the time came to actually start teaching, the person in charge of organizing the teaching roster for the school explained to me that in fact there was only half that time available. I was then forced to compress the set of TQC masters courses to last only 3 semesters. So the new plan that was concocted is shown below.

## **Masters Level TQC Courses**

### **Year 1**

#### *1st Semester*

Math (Mm1) : (an accelerated prerequisite course of undergrad level mathematics topics) - Finite Group Theory, Complex Analysis, Fourier Analysis, Differential Geometry.

Physics (Mp1) : (an accelerated prerequisite course of undergrad level physics topics) Special Relativity, Electromagnetic Theory, Statistical Mechanics, Analytical Mechanics, Quantum Mechanics

## *2nd Semester*

Math (Mm2) : Manifold Theory, Algebraic Topology

Physics (Mp2) : Quantum Computing, General Relativity

## **Year 2**

### *3rd Semester*

Math (Mm3): Lie groups/algebras, representations, braid groups, knot theory

Physics (Mp3) : Quantum Field Theory (QFT), Topological Quantum Computing (TQC)

## **PhD Level Courses**

Those students wanting to do a PhD in TQC can attend seminars in later years in :-

*PhDm1* (Conformal Field Theory (CFT), Kac-Moody algebras, etc);

*PhDp1* (Topological Quantum Field Theory (TQFT), advanced Topological Quantum Computing (TQC));

*PhDm2* (operator algebras, quantum groups, etc);

*PhDp2* (gauge theory, string theory, etc).

### *What Actually Happened*

From the courses mentioned in the above list, one sees that the first two courses, taught in the first semester, were effectively an accelerated introduction to essential topics in undergraduate math (finite groups, complex variables, fourier analysis, differential geometry), and to undergraduate physics (special relativity, electromagnetism, statistical mechanics, analytic mechanics, quantum mechanics).

The following semester I needed to devote more time to my primary research activity, i.e. artificial brains, so I only taught one course. It was the physics course, which crammed both quantum computing and general relativity into one semester, i.e. double the usual rate. Not surprisingly, I suppose, the only people in the class (only a handful) were from the physics department.

The computer science students who had been in the previous semester's classes, felt that such obvious (and difficult) physics subjects were not particularly relevant to their (near) future computer science careers. Mostly they thought that the master physics courses (especially general relativity) were too difficult for computer scientists.

At the time of writing this section (Oct 2009) I am currently teaching an Artificial Brains course to masters students, something that I need to teach once a year. Hence in practice my TQC teaching has been reduced to a half the

rate at which I had originally planned (i.e. only one course instead of four per year, but taught at twice the speed).

### *TQC Grad Students Will Need a Minimum IQ of 150*

It is generally thought amongst mathematical physics researchers and professors who specialize in TQC that a minimum IQ of about 150 [150IQ] is needed to be able to fully master the material in TQC (e.g. particularly difficult topics such as conformal field theory, quantum groups, advanced algebraic topology, topological quantum field theory, etc). An IQ of 150 is roughly that of university professors in the sciences. (In the US, the average IQ of theoretical physics professors is 170, i.e. 4.7 standard deviations above the mean).

It is these high IQ levels required for TQC mastery that is the source of the “*TQC Shock Wave*” mentioned in the title of this article. This greater intelligence level that is required is also the reason why the general status level of computer science will go up significantly in future years.

The best masters students in theoretical physics and pure mathematics at top universities in China such as Beijing University or Tsinghua University would have those ability levels, whereas the average masters student in most of today’s computer science departments around the world will not have such levels of intelligence, therefore, speaking bluntly, most of today’s computer science masters students are simply *not bright enough* to study TQC (hence the “*shock wave*”, as computer science deans and department heads come to terms with this new requirement.

We will probably have to wait until TQC has become a reality (i.e. that large-N quantum computers have been built), and for ministers of education and technology around the world to start putting real pressure on the best universities to teach TQC. Only then will pressure be placed on the best students to move into computer science (instead of theoretical physics and pure mathematics, as is largely the case today).

As a result of that pressure, computer science departments will see their general prestige level rise, for the simple reason that the topics they teach (that they have to teach, under severe pressure from government ministries) are a lot more intellectually demanding than they were before the TQC revolution. Computer science students will be smarter and so will their professors. Computer science will become as prestigious as the traditionally brightest specialties, i.e. theoretical physics and pure mathematics, and for good reason, and that is that computer science will have become largely a branch of pure mathematics and theoretical physics.

Despite all the above considerations, I continue to teach these TQC courses but at a slower rate, arguing to myself (and to my students) that when TQC *does* come of age, my university will be able to *boast* to the world that it was the first university on the planet to teach a comprehensive set of TQC courses, and can be proud of that fact. Right now, I claim that although the *students* will not learn much TQC in the limited time they have, *I* will. I'm learning the topics in math, physics, and computing (MPC), that are needed to teach graduate level TQC courses. When TQC finally does come of age, I will be

ready, and can then push my university for a faster teaching rate, and to invest in a greater commitment to TQC teaching in general.

But before that happens, we will probably have to wait a few years for the condensed matter physicists to discover the appropriate anyon with the requisite computational properties and then to use it in a scaled up (large-N) quantum computer. Then all hell will break loose.

(Actually, a very recent experimental physics paper (January 2009), dealing with the detection of non Abelian anyons, claimed that “we may see the first topological quantum bit within a year.” Perhaps the rise of TQC will be sooner than we think.)

## References

### *Popular*

[Collins 2006] “Computing with Quantum Knots”, Graham P. Collins, *Scientific American*, April 2006, pp 56- 63, <http://info.phys.unm.edu/~thedude/topo/sciamTQC.pdf>

[Day 2005] “Devices Based on the Fractional Quantum Hall Effect May Fulfill the Promise of Quantum Computing”, Charles Day, *Physics Today*, October 2005, pp 21-24. <http://info.phys.unm.edu/~thedude/topo/phystodayTQC.pdf>

[Das Sarma et al 2006] “Topological Quantum Computation”, Sankar Das Sarma, Michael Freedman, Chetan Nayak, *Physics Today*, July 2006, pp 32- 38.

<http://info.phys.unm.edu/~thedude/topo/phystodayTQC2.pdf>

*(More) Technical*

The *best source* of research papers on TQC can be obtained using the following steps.

- a) Go to the website <http://xxx.arxiv.org>
- b) Click the Search button.
- c) In the search window entitled “Experimental full text search” type in (with quotation marks) “topological quantum computation (or computers, or computing)” in the left hand “Search for :” window.
- d) In the right hand button, after the “in”, select “Everything”.
- e) You should get over 400 hits.

[Bonesteel et al 2005] “Braid Topologies for Quantum Computation”, [N. E. Bonesteel](#), [Layla Hormozi](#), [Georgios Zikos](#), [Steven H. Simon](#), *Phys. Rev. Lett.* 95, 140503 (2005), <http://arXiv:quant-ph/0505065>

[das Sarma et al 2007] “Non-Abelian Anyons and Topological Quantum Computation”, Sankar Das Sarma, Michael Freedman, Chetan Nayak, Steven H. Simon, Ady Stern,

[http://www.arxiv.org/PS\\_cache/arxiv/pdf/0707/0707.1889v1.pdf](http://www.arxiv.org/PS_cache/arxiv/pdf/0707/0707.1889v1.pdf) (This paper is one of the best in the TQC literature for an overview of the whole field - math, physics, computing.)

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<http://www.cs.berkeley.edu/~christos/classics/Feynman.pdf>

[Friedman et al 2000] “A Modular Functor Which is Universal for Quantum Computation”, Michael H. Freedman, Michael Larsen, Zhenghan Wang, *Commun. Math. Phys.* 227, 605 – 622 (2002)

[http://arxiv.org/PS\\_cache/quant-ph/pdf/0001/0001108v2.pdf](http://arxiv.org/PS_cache/quant-ph/pdf/0001/0001108v2.pdf)

(This very difficult paper by Fields Medal winner, Michael Friedman, provides the mathematical proof that TQC is doable.)

[Jacak et al 2003] “[Quantum Hall Systems: Braid Groups, Composite Fermions, and Fractional Charge](#)” (*The International Series of Monographs on Physics, 119*) by Lucjan Jacak, Piotr Sitko, Konrad Wieczorek, and Arkadiusz Wojs, 2003.

[Kitaev 1997] “Fault-Tolerant Quantum Computation by Anyons”, [A. Yu. Kitaev](#), *Annals Phys.* 303 (2003) 2-30, [http://arxiv.org/PS\\_cache/quant-ph/pdf/9707/9707021v1.pdf](http://arxiv.org/PS_cache/quant-ph/pdf/9707/9707021v1.pdf)

(This famous paper initiated the whole field of TQC. It invented the concept. Kitaev is the “father of TQC”)

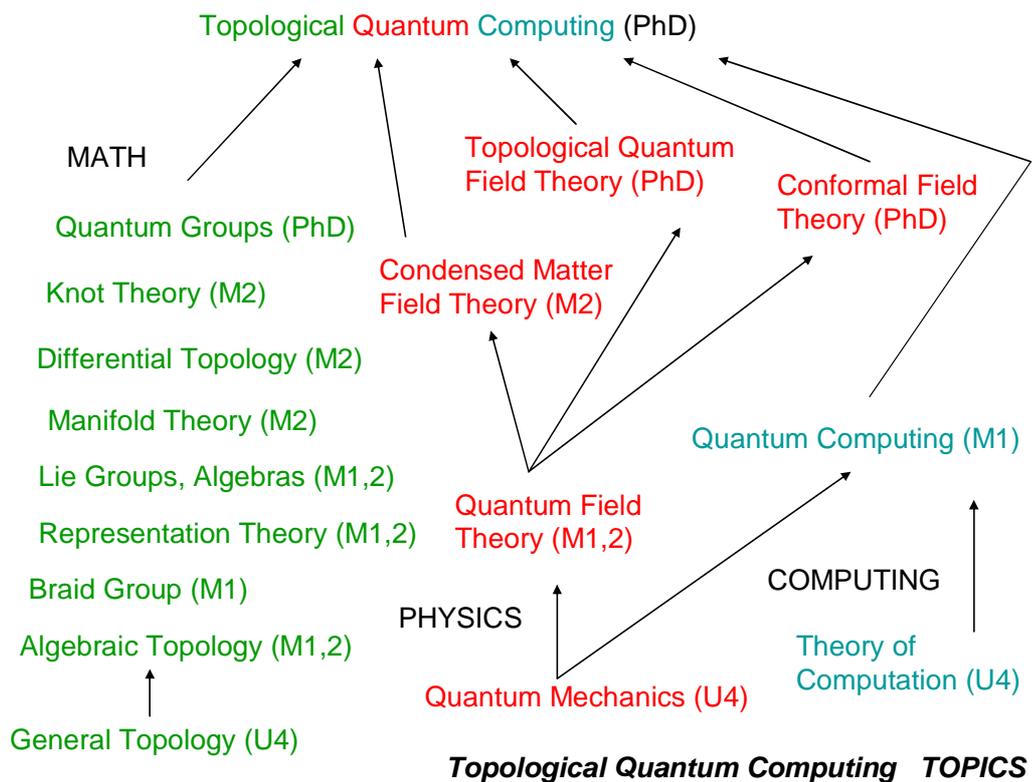
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[van Degrift et al 1992] “The Integral and Fractional Quantum Hall Effects”, [C. T. Van Degrift](#), [Steven M. Girvin](#), [M. E. Cage](#) (Eds), *American Association of Physics Teachers* (January 1992).

[150IQ] A reviewer of this article queried this IQ value, and asked for justification. The average computer science PhD student has an IQ of about 130, i.e. in the 98<sup>th</sup> percentile of the general population. The average theoretical physics or pure mathematics PhD student is smarter at about 140. The *best* of these theoretical physics or pure mathematics PhD students, capable of absorbing readily the severe abstractions of topics such as quantum

group theory, conformal field theory, Chern-Simons theory, topological quantum field theory, etc, that are needed to understand the principles of TQC would need to have an IQ above 150. The average university professor in the sciences has an IQ of about 150. The average theoretical physics professor in the US has an IQ of 170 (i.e. 4.7 standard deviations above the mean). The statement that “TQC researchers will need to have an IQ above 150” is widely held amongst TQC researchers, because TQC is considered by these people to be intellectually tougher and more demanding than the usual theoretical physics or pure mathematics topics taught in PhD courses in these fields.



## **Appendix : A Sample TQC Course Syllabus**

This appendix shows a sample *syllabus* of one of the TQC courses (of a set of such courses) offered to Xiamen masters level students in the math, physics and computer science departments. It explains briefly the importance of TQC and why it needs to be taught. Readers of this article who are thinking of teaching TQC at their universities may find it helpful.

### **Interdisciplinary “MPC” (Math Physics Computing) Lecture Course Series in “Topological Quantum Computing” (TQC)**

*Course Title* : “Manifolds and Algebraic Topology”

*Professor* : Prof. Dr. Hugo de Garis  
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*Course Level* : 1<sup>st</sup> year *Masters* students in Computer Science, Physics, Mathematics.

*Background to TQC* : Topological Quantum Computing (TQC) is a field that is currently revolutionizing computer science, by promising to make *quantum computers* robust and buildable by storing quantum bits (qubits) in topologically invariant properties of topological quantum fields that are robust to local disturbances. Quantum computers are exponentially ( $2^N$ ) times more powerful than

classical computers, so will revolutionize physics, chemistry and biology, and hence national economies. Experimental physicists have recently discovered (2005) phenomena in the Fractional Quantum Hall Effect (FQHE) that promise to make TQC (and hence QC) practical in the next few years.

*“MPC/TQC Series of Courses” Description* : TQC is so important that MPC/TQC type courses will need to be taught in thousands of universities all over the planet. This Xiamen University (XiaDa) series of MPC/TQC courses is the first of its kind in the world. In a few years, XiaDa will be able to boast that the “Xiamen Model” (of MPC/TQC teaching) started at XiaDa. Computer science students need to know enough graduate level math and physics to be able to understand the principles of TQC, so this series of courses aims to turn computer scientists into (TQC understanding) “mathematical physicists”. Masters students in Mathematics and Physics may also be interested in learning about TQC principles and wish to attend these MPC/TQC courses (and get credit for them).

*Course Description* : This is a proper first year masters mathematics course in manifolds (i.e. effectively, “surfaces” in N-dimensional space) and algebraic topology. Anyone wishing to become an expert (and get a teaching job) in topological quantum computing (TQC), needs to know a lot of topology, hence the need for this course. (Modern mathematical physicists for example, need to know a lot of topology and Lie groups/algebras.) It will cover topics such as

- a) topological spaces
- b) connectedness and compactness
- c) simplicial complexes
- d) homotopy
- e) the fundamental group
- f) the fundamental group of circles and spheres
- g) the Seifert-van Kampen theorem
- h) covering spaces
- i) classification of coverings
- j) homology
- k) cohomology

*Text Book* : The text book to be used for this course, will probably be “Introduction to Topological Manifolds”, by J. M. Lee, which is volume 202 in the Springer series of “Graduate Texts in Mathematics (GTM)”.

*Exam and Homeworks* : There will be a final exam, and regular homeworks. The exam will count for 60% of your final grade, HWs for 30%, and attendance at lectures for 10%.

*Time and Place* : This course will commence in February 2009 on the “Haiyun” Campus (Computer Science and Math Campus), in Research Building no.1, in room 509 (air conditioned), probably Wednesday or Friday afternoons at 2:30pm to 5pm. Lectures will be in English.

*Other MPC/TQC Courses in this Series* : Other MPC/TQC courses in this or future semesters are (where e.g. *Mm2*

means a *Master's math* course, semester 2, *Mp3* means a *Master's physics* course, semester 3) :- Mm1 (finite group theory, complex analysis, fourier analysis, differential geometry); Mp1 (special relativity, electromagnetic theory, statistical mechanics, analytical mechanics, quantum mechanics); Mm2 (algebraic topology, manifold theory); Mp2 (quantum computing, general relativity); Mm3 (Lie groups/algebras, representations, braid groups, knot theory); Mp3 (quantum field theory (QFT), topological quantum computing (TQC)); Mp4 (Basic string theory).

Those students wanting to do a PhD in TQC can attend seminars in later years in :- PhDm1 (conformal field theory (CFT), Kac-Moody algebras, etc); PhDp1 (topological quantum field theory (TQFT), advanced topological quantum computing (TQC)); PhDm2 (operator algebras, quantum groups, etc); PhDp2 (gauge theory, advanced string theory, etc).

*Further details* : For further details, on this course and all future MPC/TQC courses, email Prof. Dr. Hugo de Garis ([profhugodegaris@yahoo.com](mailto:profhugodegaris@yahoo.com)). Later, an MPC/TQC website will be constructed.

### **Bio :**

Prof. Dr. Hugo de Garis is a full professor of Computer Science in the Cognitive Science Department, School of Information Science & Technology, Xiamen University, Xiamen, Fujian Province, China, where he is director of the “China-Brain Project” which aims to build China’s first

artificial brain before 2012. He teaches the planet's first (4 year pipelined) comprehensive set of courses on Topological Quantum Computing (TQC). His research interests include Artificial Brains, Evolvable Hardware, and Topological Quantum Computing. He is the author of several books, and is contracted by World Scientific (Singapore) to write two text books entitled "Artificial Brains : An Evolved Neural Net Approach" (to appear 2010) and "Topological Quantum Computing : Making Quantum Computers Robust by Manipulating Quantum Bits in Topological Quantum Fields" (to appear 2011).