A Simple Proof That Finite Quantum Theory And Finite Mathematics Are More Fundamental Than Standard Quantum Theory And Classical Mathematics, Respectively

Felix M. Lev

Abstract

Standard quantum theory is based on classical mathematics involving such notions as infinitely small/large and continuity. Those notions were proposed by Newton and Leibniz more than 300 years ago when people believed that every object can be divided by an arbitrarily large number of arbitrarily small parts. However, now it is obvious that when we reach the level of atoms and elementary particles then standard division loses its meaning and in nature there are no infinitely small objects and no continuity. In our previous publications we proposed a version of finite quantum theory (FQT) based on a finite ring or field with characteristic $p$. In the present paper we first define the notion when theory A is more general than theory B and theory B is a special degenerate case of theory A. Then we prove that standard quantum theory is a special degenerate case of FQT in the formal limit $p \to \infty$. Since quantum theory is the most general physics theory, this implies that classical mathematics itself is a special degenerate case of finite mathematics in the formal limit when the characteristic of the ring or field in the latter goes to infinity. In general, introducing infinity automatically implies transition to a degenerate theory because in that case all operations modulo a number are lost. So, even from the pure mathematical point of view, the very notion of infinity cannot be fundamental, and theories involving infinities can be only approximations to more general theories. Motivation and implications are discussed.

Keywords: classical mathematics, finite mathematics, quantum theory

1 Remarks on arithmetic

By definition, finite mathematics is a branch of mathematics which contains theories involving only finite sets. In particular, those theories cannot involve even the set of all natural numbers, to say nothing about the set of all rational numbers and the set of all real numbers (because those sets are infinite). Known examples are theories of finite fields and finite rings described in a vast literature.

The goal of the present paper is to give a mathematical proof that finite mathematics is more fundamental than classical one. At the same time, we believe
that to better understand the problem it is important to discuss philosophical aspects of such a simple problem as operations with natural numbers.

In the 20s of the 20th century the Viennese circle of philosophers under the leadership of Schlick developed an approach called logical positivism which contains verification principle: *A proposition is only cognitively meaningful if it can be definitively and conclusively determined to be either true or false* (see e.g. Refs. [1]). On the other hand, as noted by Grayling [2], "The general laws of science are not, even in principle, verifiable, if verifying means furnishing conclusive proof of their truth. They can be strongly supported by repeated experiments and accumulated evidence but they cannot be verified completely". Popper proposed the concept of falsificationism [3]: *If no cases where a claim is false can be found, then the hypothesis is accepted as provisionally true.*

According to the principles of quantum theory, there should be no statements accepted without proof and based on belief in their correctness (i.e. axioms). The theory should contain only those statements that can be verified, at least in principle, where by "verified" physicists mean experiments involving only a finite number of steps. So the philosophy of quantum theory is similar to verificationism, not falsificationism. Note that Popper was a strong opponent of the philosophy of quantum theory and supported Einstein in his dispute with Bohr.

The verification principle does not work in standard classical mathematics. For example, it cannot be determined whether the statement that $a + b = b + a$ for all natural numbers $a$ and $b$ is true or false. According to falsificationism, this statement is provisionally true until one has found some numbers $a$ and $b$ for which $a + b \neq b + a$. There exist different theories of arithmetic (e.g. Peano arithmetic or Robinson arithmetic) aiming to solve foundational problems of standard arithmetic. However, those theories are incomplete and are not used in applications.

From the point of view of verificationism and principles of quantum theory, classical mathematics is not well defined not only because it contains an infinite number of numbers. For example, let us pose a problem whether $10+20$ equals $30$. Then one should describe an experiment which gives the answer to this problem. Any computing device can operate only with a finite number of bits and can perform calculations only modulo some number $p$. Say $p = 40$, then the experiment will confirm that $10+20=30$ while if $p = 25$ then we will get that $10+20=5$.

*So the statements that $10+20=30$ and even that $2 \cdot 2 = 4$ are ambiguous because they do not contain information on how they should be verified.* On the other hands, the statements

$$10 + 20 = 30 \pmod{40}, \quad 10 + 20 = 5 \pmod{25},$$

$$2 \cdot 2 = 4 \pmod{5}, \quad 2 \cdot 2 = 2 \pmod{2}$$

are well defined because they do contain such an information. So, from the point of view of verificationism and principles of quantum theory, only operations modulo a number are well defined.
We believe the following observation is very important: although classical mathematics (including its constructive version) is a part of our everyday life, people typically do not realize that classical mathematics is implicitly based on the assumption that one can have any desired amount of resources. So classical mathematics is based on the implicit assumption that we can consider an idealized case when a computing device can operate with an infinite number of bits. In other words, standard operations with natural numbers are implicitly treated as limits of operations modulo $p$ when $p \to \infty$. Usually in mathematics, legitimacy of every limit is thoroughly investigated, but in the simplest case of standard operations with natural numbers it is not even mentioned that those operations can be treated as limits of operations modulo $p$. In real life such limits even might not exist if, for example, the Universe contains a finite number of elementary particles.

Classical mathematics proceeds from standard arithmetic which does not contain operations modulo a number while finite mathematics necessarily involves such operations. In the present paper we prove that, regardless of philosophical preferences, finite mathematics is more fundamental than classical one. In Sec. 2 we define a criterion when one theory is more fundamental than the other, and the proof of the main statement is given in Sec. 3.

2 Comparison of different theories

A belief of the overwhelming majority of scientists is that classical mathematics (involving the notions of infinitely small/large and continuity) is fundamental while finite mathematics is something inferior what is used only in special applications. This belief is based on the fact that the history of mankind undoubtedly shows that classical mathematics has demonstrated its power in many areas of science.

The notions of infinitely small/large, continuity etc. were proposed by Newton and Leibniz more than 300 years ago. At that time people did not know about existence of atoms and elementary particles and believed that any body can be divided by an arbitrarily large number of arbitrarily small parts. However, now it is obvious that standard division has only a limited applicability because when we reach the level of atoms and elementary particle the division operation looses its meaning. In nature there are no infinitely small objects and no continuity because on the very fundamental level nature is discrete. So, as far as application of mathematics to physics is concerned, classical mathematics is only an approximation which in many cases works with very high accuracy but the ultimate quantum theory cannot be based on classical mathematics.

A typical situation in physics can be described by the following

**Definition:** Let theory $A$ contain a finite parameter and theory $B$ be obtained from theory $A$ in the formal limit when the parameter goes to zero or infinity. Suppose that with any desired accuracy theory $A$ can reproduce any result of theory $B$ by choosing a value of the parameter. On the contrary, when the limit is already taken then one cannot return back to theory $A$ and theory $B$ cannot reproduce all results of
theory A. Then theory A is more general than theory B and theory B is a special degenerate case of theory A.

Probably the most known example is that nonrelativistic theory (NT) can be obtained from relativistic theory (RT) in the formal limit $c \to \infty$ where $c$ is the speed of light. RT can reproduce any result of NT with any desired accuracy if $c$ is chosen to be sufficiently large. On the contrary, when the limit is already taken then one cannot return back from NT to RT, and RT can reproduce results of RT only in relatively small amount of cases when velocities are much less than $c$. Therefore RT is more general than NT, and NT is a special degenerate case of RT. Other known examples are that classical theory is a special degenerate case of quantum one in the formal limit $\hbar \to 0$ where $\hbar$ is the Planck constant, and Poincare invariant theory is a special degenerate case of de Sitter invariant theories in the formal limit $R \to \infty$ where $R$ is the parameter defining contraction from the de Sitter Lie algebras to the Poincare Lie algebra.

In our publications (see e.g. Refs. [4, 5]) we discussed an approach called Finite Quantum Theory (FQT) where quantum theory is based not on classical but on finite mathematics. Physical states in FQT are elements of a linear space over a finite field or ring, and operators of physical quantities are linear operators in this space. It has been argued that FQT is more general than standard quantum theory and the latter is a special degenerate case of the former in the formal limit when the characteristic of the field or ring in FQT goes to infinity. In Sec. 3 of the present work we give a rigorous mathematical proof of this statement. Since quantum theory is the most general physics theory then, as a consequence

**Main Statement:** Even classical mathematics itself is a special degenerate case of finite mathematics in the formal limit when the characteristic of the field or ring in the latter goes to infinity.

Note that this statement is meaningful only if in applications finite mathematics is more pertinent than classical one while if those theories are treated only as abstract ones than the statement that one theory is more fundamental than the other is meaningless. In other words, the problem what mathematics is the most fundamental is the problem of physics, not mathematics.

### 3 Proof of the main statement

Classical mathematics starts from natural numbers but here only addition and multiplication are always possible. In order to make addition invertible we introduce negative integers and get the ring of integers $\mathbb{Z}$. However, if instead of all natural numbers we consider only a set $R_p$ of $p$ numbers $0, 1, 2, \ldots, p-1$ where addition and multiplication are defined as usual but modulo $p$ then we get a ring without adding new elements. In our opinion the notation $\mathbb{Z}/p$ for $R_p$ is not quite adequate because it may give a wrong impression that finite mathematics starts from the infinite set $\mathbb{Z}$ and that $\mathbb{Z}$ is more general than $R_p$. However, although $\mathbb{Z}$ has more elements than $R_p$, $\mathbb{Z}$ cannot be more general than $R_p$ because $Z$ does not contain operations modulo
a number.

Since operations in $R_p$ are modulo $p$, one can represent $R_p$ as a set \{0, \pm1, \pm2, ..., \pm(p-1)/2\} if $p$ is odd and as a set \{0, \pm1, \pm2, ..., \pm(p/2-1), p/2\} if $p$ is even. Let $f$ be a function from $R_p$ to $Z$ such that $f(a)$ has the same notation in $Z$ as $a$ in $R_p$. If elements of $Z$ are depicted as integer points on the $x$ axis of the $xy$ plane then, if $p$ is odd, the elements of $R_p$ can be depicted as points of the circumference in Fig. 1. and analogously if $p$ is even. This picture is natural since $R_p$

![Figure 1: Relation between $R_p$ and $Z$](image)

has a property that if we take any element $a \in R_p$ and sequentially add 1 then after $p$ steps we will exhaust the whole set $R_p$ by analogy with the property that if we move along a circumference in the same direction then sooner or later we will arrive at the initial point.

We define the function $h(p)$ such that $h(p) = (p - 1)/2$ if $p$ is odd and $h(p) = p/2 - 1$ if $p$ is even. Let $n$ be a natural number and $U(n)$ be a set of elements $a \in R_p$ such that $|f(a)|^n \leq h(p)$. Then $\forall m \leq n$ the result of any $m$ operations of addition, subtraction or multiplication of elements $a \in U(n)$ is the same as for the corresponding elements $f(a)$ in $Z$, i.e. in this case operations modulo $p$ are not explicitly manifested.

Let $n = g(p)$ be a function of $p$ and $G(p)$ be a function such that the set $U(g(p))$ contains at least the elements $\{0, \pm1, \pm2, ..., \pm G(p)\}$. In what follows $M > 0$ and $n_0 > 0$ are natural numbers. If there is a sequence of natural numbers $(a_n)$ then standard definition that $(a_n) \to \infty$ is that $\forall M \exists n_0$ such that $a_n \geq M \forall n \geq n_0$. By analogy with this definition we will now prove

**Statement 1:** There exist functions $g(p)$ and $G(p)$ such that $\forall M \exists p_0 > 0$ such that $g(p) \geq M$ and $G(p) \geq 2^M \forall p \geq p_0$.

**Proof.** $\forall p > 0$ there exists a unique natural $n$ such that $2^n \leq h(p) < 2^{(n+1)}$. Define
$g(p) = n$ and $G(p) = 2^n$. Then $\forall M \exists p_0$ such that $h(p_0) \geq 2^{M^2}$. Then $\forall p \geq p_0$ the conditions of Statement 1 are satisfied.

The problem of actual infinity is discussed in a vast literature. The technique of classical mathematics does not involve actual infinities and here infinities are understood only as limits. However, the basis of classical mathematics does involve actual infinities. For example, $Z$ is not treated as a limit of finite sets, i.e. it is treated as actual and not potential infinity. Moreover, classical set theory considers infinite sets with different cardinalities.

Statement 1 is the proof that the ring $Z$ is the limit of the ring $R_p$ when $p \to \infty$, and the result of any finite combination of additions, subtractions and multiplications in $Z$ can be reproduced in $R_p$ if $p$ is chosen to be sufficiently large. On the contrary, when the limit is already taken then one cannot return back from $Z$ to $R_p$, and in $Z$ it is not possible to reproduce all results in $R_p$ because in $Z$ there are no operations modulo a number. According to Definition in Sec. 2 this means that the ring $R_p$ is more general than $Z$, and $Z$ is a special degenerate case of $R_p$.

When $p$ is very large then $U(g(p))$ is a relatively small part of $R_p$, and in general the results in $Z$ and $R_p$ are the same only in $U(g(p))$. This is analogous to the fact mentioned in Sec. 2 that the results of NT and RT are the same only in relatively small cases when velocities are much less than $c$. However, when the radius of the circumference in Fig. 1 becomes infinitely large then a relatively small vicinity of zero in $R_p$ becomes the infinite set $Z$ when $p \to \infty$. This example demonstrates that once we involve infinity and replace $R_p$ by $Z$ then we automatically obtain a degenerate theory because in $Z$ there are no operations modulo a number.

In classical mathematics, the ring $Z$ is the starting point for introducing the notions of rational and real numbers. Therefore those notions arise from a degenerate set. Then a question arises whether the fact that $R_p$ is more general than $Z$ implies that finite mathematics is more general than classical one, i.e. whether finite mathematics can reproduce all results obtained by applications of classical mathematics. For example, if $p$ is prime then $R_p$ becomes the Galois field $F_p$, and the results in $F_p$ considerably differ from those in the set $Q$ of rational numbers even when $p$ is very large. In particular, $1/2$ in $F_p$ is a very large number $(p+1)/2$. Since quantum theory is the most general physical theory (i.e. all other physical theories are special cases of quantum one), the answer to this question depends on whether standard quantum theory based on classical mathematics is most general or is a special degenerate case of a more general quantum theory.

As noted in Sec. 2, de Sitter invariant quantum theory is more general than Poincaré invariant quantum theory. In the former, quantum states are described by representations of the de Sitter algebras. For each algebra the representation operators of the basis elements $M^{ab}$ ($a, b = 0, 1, 2, 3, 4$, $M^{ab} = -M^{ba}$) satisfy the commutation relations

$$[M^{ab}, M^{cd}] = -2i(\eta^{ac}M^{bd} + \eta^{bd}M^{ac} - \eta^{ad}M^{bc} - \eta^{bc}M^{ad}) \tag{1}$$

where $\eta^{ab}$ is the diagonal tensor such that $\eta^{00} = -\eta^{11} = -\eta^{22} = -\eta^{33} = 1$, and the
possible choice for $\eta^{44}$ is $\eta^{44} \pm 1$. According to principles of quantum theory, from these ten operators one should construct a maximal set $S$ of mutually commuting operators defining independent physical quantities and construct a basis in the representation space such that the basis elements are eigenvectors of the operators from $S$.

The rotation subalgebra of algebra (1) is described in every textbook on quantum mechanics. The basis of the subalgebra is $(M_x, M_y, M_z) = (M^{23}, M^{31}, M^{12})$ and those operators commute as

$$[M_x, M_y] = 2iM_z, \quad [M_z, M_x] = 2iM_y, \quad [M_y, M_z] = 2iM_x$$

(2)

A possible choice of $S$ is $S = (M_z, K)$ where $K = M_x^2 + M_y^2 + M_z^2$ is the Casimir operator of the subalgebra, i.e. it commutes with all the operators of the subalgebra. Then any irreducible representation of the subalgebra is described by an integer $k \geq 0$. The basis elements $e(\mu, k)$ of the representation space are eigenvectors of the operator $K$ with the eigenvalue $k(k + 2)$ and the eigenvectors of the operator $M_z$ with the eigenvalues $\mu$ such that, for a given $k$, $\mu$ can take $k + 1$ values $\mu = -k, -k + 2, ..., k - 2, k$. Therefore all the basis elements are eigenvectors of the operators from $S$ with the eigenvalues belonging to $\mathbb{Z}$.

As shown in Refs. [4, 5]

Statement 2: For algebra (1) there exist sets $S$ and representations such that basis vectors in the representation spaces are eigenvectors of the operators from $S$ with eigenvalues belonging to $\mathbb{Z}$. Such representations reproduce standard representations of the Poincare algebra in the formal limit $R \to \infty$. Therefore the remaining problem is whether or not quantum theory based on finite mathematics can be a generalization of standard quantum theory where states are described by elements of a separable complex Hilbert spaces $H$.

Let $x$ be an element of $H$ and $(e_1, e_2, ...)$ be a basis of $H$ normalized such that the norm of each $e_j$ is an integer. Then with any desired accuracy each element of $H$ can be approximated by a finite linear combination

$$x = \sum_{j=1}^{n} c_j e_j$$

(3)

where $c_j = a_j + ib_j$ and all the numbers $a_j$ and $b_j$ ($j = 1, 2, ..., n$) are rational. This follows from the known fact that the set of such sums is dense in $H$.

The next observation is that spaces in quantum theory are projective, i.e. for any complex number $c \neq 0$ the elements $x$ and $cx$ describe the same state. This follows from the physical fact that not the probability itself but only ratios of probabilities have a physical meaning. In view of this property, both parts of Eq. (3) can be multiplied by a common denominator of all the numbers $a_j$ and $b_j$. As a result, we have

Statement 3: Each element of $H$ can be approximated by a finite linear combination (3) where all the numbers $a_j$ and $b_j$ belong to $\mathbb{Z}$.

We conclude that Hilbert spaces in standard quantum theory contain a big redundancy of elements. Indeed, although formally the description of states in
standard quantum theory involves rational and real numbers, such numbers play only an auxiliary role because with any desired accuracy each state can be described by using only integers. Therefore, as follows from Definition in Sec. 2 and Statements 1-3,

- Standard quantum theory based on classical mathematics is a special degenerate case of quantum theory based on finite mathematics.

- Main Statement formulated in Sec. 2 is valid.

4 Discussion

The above construction has a known historical analogy. For many years people believed that the Earth was flat and infinite, and only after a long period of time they realized that it was finite and curved. It is difficult to notice the curvature dealing only with distances much less than the radius of the curvature. Analogously one might think that the set of numbers describing nature in our Universe has a ”curvature” defined by a very large number \( p \) but we do not notice it dealing only with numbers much less than \( p \).

As noted in the preceding section, introducing infinity automatically implies transition to a degenerate theory because in this case operations modulo a number are lost. Therefore even from the pure mathematical point of view the notion of infinity cannot be fundamental, and theories involving infinities can be only approximations of more general theories.

In the preceding section we have proved that quantum theory based on finite mathematics is more fundamental than standard quantum theory and therefore classical mathematics is a special degenerate case of finite one in the formal limit \( p \to \infty \). The fact that at the present stage of the Universe \( p \) is a huge number explains why in many cases classical mathematics describes natural phenomena with a very high accuracy. At the same time, as shown in Ref. [5], the explanation of several phenomena can be given only in the theory where \( p \) is finite.

One of the examples is that in our approach gravity is a manifestation of the fact that \( p \) is finite. In Ref. [5] we derive the approximate expression for the gravitational constant which depends on \( p \) as \( 1/\ln p \). By comparing this expression with the experimental value we get that \( \ln p \) is of the order of \( 10^{80} \) or more, i.e. \( p \) is a huge number of the order of \( \exp(10^{80}) \) or more. However, since \( \ln p \) is ”only” of the order of \( 10^{80} \) or more, the existence of \( p \) is observable while in the formal limit \( p \to \infty \) gravity disappears.

Although classical mathematics is a degenerate case of finite one, a problem arises whether classical mathematics can be substantiated as an abstract science. It is well-known that, in spite of great efforts of many great mathematicians, the problem of foundation of classical mathematics has not been solved. For example, Gödel’s incompleteness theorems state that no system of axioms can ensure that all facts about natural numbers can be proven and the system of axioms in classical
mathematics cannot demonstrate its own consistency. Let us recall that classical mathematics does not involve operations modulo a number.

The philosophy of Cantor, Fraenkel, Gödel, Hilbert, Kronecker, Russell, Zermelo and other great mathematicians was based on macroscopic experience in which the notions of infinitely small, infinitely large, continuity and standard division are natural. However, as noted above, those notions contradict the existence of elementary particles and are not natural in quantum theory. The illusion of continuity arises when one neglects the discrete structure of matter.

However, since in applications classical mathematics is a special degenerate case of finite one, foundational problems of classical mathematics are important only when it is treated as an abstract science. The technique of classical mathematics is very powerful and in many cases (but not all of them) describes reality with a high accuracy.

Acknowledgement: I am grateful to Dmitry Logachev, José Manuel Rodríguez Caballero and Harald Niederreiter for important remarks.

References


