"The important thing is not to stop questioning": the relevance of this Einstein quote in natural sciences is exemplified in physics and related mathematics.

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["It isn't that they can't see the solution. It is that they can't see the problem."
G. K. Chesterton (1874 - 1936) ("The Point of a Pin" in *The Scandal of Father Brown* (1935))
Problem: the Standard Model of elementary particles could be a colossus with clay feet
(cf. Bible, Daniel **2**:41-43, interpretation by Belteshazzar ≡ Daniel of Nebuchadnezzar's dream).
The physical consequences of the approach described here might be revolutionary but in any case there are,
in the mathematical tools required to jump start the process, potentially important developments to be made.]

`http://monge.u-bourgogne.fr/dsternh/papers/sternheimer2WGMPd1.pdf`

Abstract

Modern science is a Babel tower, the foundations of which are too often forgotten. Yet revolutions may occur when one takes seriously an essential question: "Is it necessarily so?" Indeed a successful model is based on assumptions that are sufficient to explain existing data, but may not be necessary. That is the mathematical curse of experimental sciences, since one tends not to argue with success (or with what one has been taught) unless one is forced to.
In 1960 Wigner (who in 1963 got the Nobel Prize in physics for "the discovery and applications of fundamental symmetry principles") marvelled about "the unreasonable effectiveness of mathematics in the natural sciences," referring mainly to physics.
We shall exemplify all this by first explaining how a posteriori relativity and quantum mechanics can be obtained from previously known theories using the mathematical theory of deformations. Then we describe some main features of the standard model of elementary particles and how it arose from empirically guessed symmetries.

Finally we indicate how, questioning its foundations, its symmetries might be obtained from those of relativity using deformations (including quantization), which poses hard mathematical problems and might eventually question half a century of particle physics. A similar approach could be used to try and explain the Dark Universe.

https://arxiv.org/pdf/1303.0570.pdf (Maligranda, Jerusalem 1960)

Moshe Flato (17/09/1937 – 27/11/1998), Noriko Sakurai (20/02/1936 – 16/10/2009),

Paul A.M. Dirac (08/08/1902 – 20/10/1984) & Eugene P. Wigner (17/11/1902 – 01/01/1995)

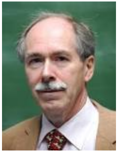
A Babel tower with a common language

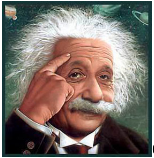
Eugene Paul Wigner, *The unreasonable effectiveness of mathematics in the natural sciences*, Comm. Pure Appl. Math. **13** (1960), 1–14].
"[...] Mathematical concepts turn up in entirely unexpected connections. Moreover, they often permit an unexpectedly close and accurate description of the phenomena in these connections. Secondly, just because of this circumstance, and because we do not understand the reasons of their usefulness, we cannot know whether a theory formulated in terms of mathematical concepts is uniquely appropriate. [...]"
The role of invariance principles in natural philosophy, pp. ix-xvi in Proc. Internat. School of Phys. "Enrico Fermi", Course XXIX, Varenna. Academic Press, (1964).

Sir Michael Atiyah (at ICMP London 2000): "Mathematics and physics are two communities separated by a common language". That language is increasingly used in many other fields of Science (often with very different grammars and accents).

Misha Gromov, *Crystals, proteins, stability and isoperimetry*, Bull. AMS 48 (2011), 229–257: "We attempt to formulate several mathematical problems suggested by structural patterns present in biomolecular assemblies."

’t Hooft on “Salam’s Grand Views”, two Einstein quotes





Gerard ’t Hooft, in “The Grand View of Physics”, Int.J.Mod.Phys.A23: 3755-3759, 2008 (`arXiv:0707.4572 [hep-th]`).
To obtain the Grand Picture of the physical world we inhabit, to identify the real problems and distinguish them from technical details, to spot the very deeply hidden areas where there is room for genuine improvement and revolutionary progress, courage is required. Every now and then, one has to take a step backwards, one has to ask silly questions, one must question established wisdom, one must play with ideas like being a child. And one must not be afraid of making dumb mistakes. By his adversaries, Abdus Salam was accused of all these things. He could be a child in his wonder about beauty and esthetics, and he could make mistakes. [...]

Two Einstein quotes: *The important thing is not to stop questioning. Curiosity has its own reason for existing.*

You can never solve a [fundamental] problem on the level on which it was created.

Dirac quote

"... One should examine closely even the elementary and the satisfactory features of our Quantum Mechanics and criticize them and try to modify them, because there may still be faults in them. The only way in which one can hope to proceed on those lines is by looking at the basic features of our present Quantum Theory from all possible points of view. Two points of view may be mathematically equivalent and you may think for that reason if you understand one of them you need not bother about the other and can neglect it.
But it may be that one point of view may suggest a future development which another point does not suggest, and although in their present state the two points of view are equivalent they may lead to different possibilities for the future. Therefore, I think that we cannot afford to neglect any possible point of view for looking at Quantum Mechanics and in particular its relation to Classical Mechanics. Any point of view which gives us any interesting feature and any novel idea should be closely examined to see whether they suggest any modification or any way of developing the theory along new lines.

A point of view which naturally suggests itself is to examine just how close we can make the connection between Classical and Quantum Mechanics. That is essentially a purely mathematical problem – how close can we make the connection between an algebra of non-commutative variables and the ordinary algebra of commutative variables? In both cases we can do addition, multiplication, division..." **Dirac**, *The relation of Classical to Quantum Mechanics* (2^{nd} Can. Math. Congress, Vancouver 1949). U.Toronto Press (1951) pp 10-31.

Physical Mathematics vs. Mathematical Physics

A scientist should ask himself three questions: Why, What and How.
Work is 99% perspiration and 1% inspiration. Finding how is 99% of the research work, but it is important to know what one is doing and even more why one does such a research. It should not be enough to rely on a "guru", or even an adviser, for the latter two, as happens too often in physics, more than in mathematics.
There are other differences in the approaches in mathematics and in physics. What we call "physical mathematics" can be defined as mathematics inspired by physics. While in mathematical physics one studies physical problems with mathematical tools and rigor. [Theoretical physics uses mathematical language without caring about rigor.]
As to what and how to research there are important differences between mathematicians and physicists. When interested in other sciences, mathematicians tend to "look over the shoulders" of scientists in other fields and use the tools they know, while physicists (at best) search in the mathematical toolbox for something they can use. The correct (hard) attitude is that of Gromov in biology, to try and understand what are the needs of the biologists and develop original mathematical tools.

Moreover mathematicians (even when taking their inspiration from physics) tend to study problems in a general context, which may be very hard. But when the aim is to tackle physical problems, it is enough to develop tools adapted to the applications.

Why the deformation philosophy, and why use it here?

The two major physical theories, relativity and quantization, can now be understood as based on deformations of some algebras. Deformations (in the sense of Gerstenhaber) are classified by cohomologies.

The former became obvious in 1964, as soon as deformation theory of algebras (and groups) appeared, deforming the Galilean group symmetry of Newtonian mechanics $SO(3) \cdot \mathbb{R}^3 \cdot \mathbb{R}^4$ to the Poincaré group $SO(3,1) \cdot \mathbb{R}^4$. But it took a dozen more years before the latter became mathematically understood (with deformation quantization).

My present suggestion is that maybe “internal symmetries” of hadrons *emerge* from Poincaré by some kind of deformation, first to AdS and then by (deformation) quantization (at root of unity?), probably with generalized deformations (multiparameter and/or with noncommutative parameters) and frameworks (families of NC algebras depending on parameters). The question (from the 60’s) of their connection with Poincaré could be a false problem. Which may require “going back to the drawing board” and raises many questions (phenomenology, new experiments, etc.)

The tools developed for that purpose might even provide some explanation of the new phenomena attributed to a mysterious “dark universe” (95% of the total!)

Flato’s deformation philosophy

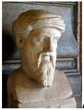
Physical theories have domain of applicability defined by the relevant distances, velocities, energies, etc. involved. The passage from one domain (of distances, etc.) to another doesn’t happen in an uncontrolled way: experimental phenomena appear that cause a paradox and contradict [Fermi quote] accepted theories. Eventually a new fundamental constant enters, the formalism is modified: the attached structures (symmetries, observables, states, etc.) *deform* the initial structure to a new structure which in the limit, when the new parameter goes to zero, “contracts” to the previous formalism. The question is, in which category to seek for deformations? Physics is conservative: if start with e.g. category of associative or Lie algebras, tend to deform in same category. But there are important generalizations: e.g. quantum groups are deformations of (some commutative) Hopf algebras.

And there may be more general structures to be developed, e.g. deformations with noncommutative “parameters” and ”families of NC algebras depending on parameters”.

The Earth is not flat

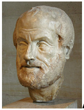
Act 0. Antiquity (Mesopotamia, ancient Greece).

Flat disk floating in ocean, or Atlas. Similar physical assumption in (ancient) China (Φ).



Act I. Fifth century BC: Pythagoras, theoretical astrophysicist.

Pythagoras is often considered as the first mathematician; he and his students believed that everything is related to mathematics. On aesthetic (and democratic?) grounds he conjectured that **all** celestial bodies are spherical.



Act II. 3rd century BC: Aristotle, phenomenologist astronomer.

Travelers going south see southern constellations rise higher above the horizon, and shadow of earth on moon during the partial phase of a lunar eclipse is always circular: fits physical model of sphere for Earth.

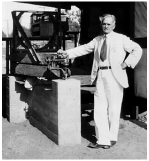
Eratosthenes "Experiment"

Act III. ca. 240 BC: Eratosthenes, "experimentalist".

Chief librarian of the Great Library in Alexandria. At summer solstice (21 June), knew that sun (practically) at vertical in Aswan and angle of $\frac{2\pi}{50}$ in Alexandria, "about" (based on estimated average daily speed of caravans of camels?) 5000 stadions "North;" assuming sun is point at ∞ (all not quite), by simple geometry got circumference of 252000 "stadions", 1% or 16% off correct value (Egyptian or Greek stadion). Computed distance to sun as 804,000 kstadions and distance to moon as 780 kstadions, using data obtained during lunar eclipses, and measured tilt of Earth's axis 11/83 of 2π.

In China, ca. same time, different context: measure similarly distance of earth to sun assuming earth is flat (the prevailing belief there until 17^{th} century).

Relativity




Paradox coming from Michelson & Morley experiment (1887) resolved in 1905 by Einstein with special theory of relativity. Experimental need triggered theory. In modern language: Galilean geometrical symmetry group of Newtonian mechanics ($SO(3) \cdot \mathbb{R}^3 \cdot \mathbb{R}^4$) is deformed, in Gerstenhaber's sense, to Poincaré group ($SO(3,1) \cdot \mathbb{R}^4$) of special relativity.
A deformation parameter comes in, c^{-1}, c being a *new fundamental constant*, velocity of light in vacuum. Time has to be treated on same footing as space, expressed mathematically as a purely imaginary dimension. A counterexample to Riemann's conjecture about infinitely great. General relativity: *deform* Minkowskian space-time with nonzero pseudo-Riemannian curvature. E.g. constant curvature, de Sitter (> 0) or AdS_4 (< 0).

The beginning of quantization

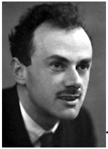


Planck and black body radiation [ca. 1900]. Bohr atom [1913]. Louis de Broglie [1924]: "wave mechanics" (waves and particles are two manifestations of the same physical reality).


Traditional quantization (Schrödinger, Heisenberg) of classical system $(\mathbb{R}^{2n}, \{\cdot,\cdot\}, H)$: Hilbert space $\mathcal{H} = L^2(\mathbb{R}^n) \ni \psi$ where acts "quantized" Hamiltonian $\mathbf{H}$, energy levels $\mathbf{H}\psi = \lambda\psi$, and von Neumann representation of CCR. Define $\hat{q}_\alpha(f)(q) = q_\alpha f(q)$ and $\hat{p}_\beta(f)(q) = -i\hbar\frac{\partial f(q)}{\partial q_\beta}$ for f differentiable in $\mathcal{H}$. Then (CCR) $[\hat{p}_\alpha, \hat{q}_\beta] = i\hbar\delta_{\alpha\beta}I \quad (\alpha, \beta = 1, ..., n)$.

Orderings, Weyl, Wigner; Dirac constraints





The couple $(\hat{q}, \hat{p})$ quantizes the coordinates (q, p). A polynomial classical Hamiltonian H is quantized once chosen an operator ordering, e.g. (Weyl) complete symmetrization of $\hat{p}$ and $\hat{q}$. In general the quantization on $\mathbb{R}^{2n}$ of a function $H(q, p)$ with inverse Fourier transform $\tilde{H}(\xi, \eta)$ can be given by (Hermann Weyl [1927] with weight $\varpi = 1$):

$$H \mapsto \mathbf{H} = \Omega_\varpi(H) = \int_{\mathbb{R}^{2n}} \tilde{H}(\xi, \eta) \exp(i(\hat{p}.\xi + \hat{q}.\eta)/\hbar)\varpi(\xi, \eta) d^n\xi d^n\eta.$$

E. Wigner [1932] inverse $H = (2\pi\hbar)^{-n}\mathrm{Tr}[\Omega_1(H)\exp((\xi.\hat{p} + \eta.\hat{q})/i\hbar)]$. Ω_1 defines an isomorphism of Hilbert spaces between $L^2(\mathbb{R}^{2n})$ and Hilbert–Schmidt operators on $L^2(\mathbb{R}^n)$. Can extend e.g. to distributions. Other orderings: standard (diff. and pseudodiff. ops., "first q then p"), normal (physics): ϖ = exp. of 2^{nd} order polynomial.

Constrained systems (e.g. constraints $f_j(p, q) = 0$): Dirac formalism [1950]. (Second class constraints reduce $\mathbb{R}^{2n}$ to symplectic submanifold, first class to Poisson.)

Deformations of algebras

DEFINITION. A deformation of an algebra A over a field $\mathbb{K}$ with deformation parameter ν is a $\mathbb{K}[[\nu]]$-algebra $\tilde{A}$ such that $\tilde{A}/\nu\tilde{A} \approx A$, where A is here considered as an algebra over $\mathbb{K}[[\nu]]$ by base field extension.
Two deformations $\tilde{A}$ and $\tilde{A}'$ are called equivalent if they are isomorphic over $\mathbb{K}[[\nu]]$. A deformation $\tilde{A}$ is trivial if isomorphic to the original algebra A (considered by base field extension as a $\mathbb{K}[[\nu]]$-algebra).
Algebras are generally supposed unital. Bialgebras are associative algebra A where we have in addition a coproduct $\Delta : A \longrightarrow A \otimes A$. Hopf algebras are bialgebras with in addition to the unit $\eta : \mathbb{K} \to A$ one has a counit $\epsilon : A \to \mathbb{K}$ and an antipode $S : A \to A$. All these are supposed with the obvious compatibility relations (commutative diagram). E.g. if $A = C^\infty(G)$, G a Lie group, then $\Delta f(x, y) = f(xy)$, $(Sf)(x) = f(x^{-1})$, $\epsilon(f) = f(1_G)$. Whenever we consider a topology on A, $\tilde{A}$ is supposed to be topologically free. The definition can (cf. e.g. Kontsevich) be extended to operads, so as to apply to the Assoc, Lie, Bialg and maybe Gerst operads, and also to the Hopf category (which cannot be described by an operad), all possibly with topologies.

Deformation formulas

For associative (resp. Lie) algebras, the definition tells that there exists a new product $*$ (resp. bracket $[\cdot,\cdot]$) such that the new (deformed) algebra is again associative (resp. Lie). Denoting the original composition laws by ordinary product (resp. $\{\cdot,\cdot\}$) this means that, for $u_1, u_2 \in A$ (we can extend this to $A[[\nu]]$ by $\mathbb{K}[[\nu]]$-linearity) we have:

$$u_1 * u_2 = u_1 u_2 + \sum_{r=1}^{\infty} \nu^r C_r(u_1, u_2) \quad (1)$$

$$[u_1, u_2] = \{u_1, u_2\} + \sum_{r=1}^{\infty} \nu^r B_r(u_1, u_2) \quad (2)$$

where the C_r are Hochschild 2-cochains and the B_r (skew-symmetric) Chevalley-Eilenberg 2-cochains, such that for $u_1, u_2, u_3 \in A$ we have $(u_1 * u_2) * u_3 = u_1 * (u_2 * u_3)$ and $\mathcal{S}[[u_1, u_2], u_3] = 0$, where $\mathcal{S}$ denotes summation over cyclic permutations.

Deformations of bialgebras, Hopf algebras; quantum groups

For a (topological) *bialgebra*, denoting by $\otimes_\nu$ the tensor product of $\mathbb{K}[[\nu]]$-modules we can identify $\tilde{A}\hat{\otimes}_\nu\tilde{A}$ with $(A\hat{\otimes}A)[[\nu]]$, where $\hat{\otimes}$ denotes the algebraic tensor product completed with respect to some topology (e.g. projective for Fréchet nuclear topology on A). We similarly have a deformed coproduct $\tilde{\Delta} = \Delta + \sum_{r=1}^{\infty} \nu^r D_r$, $D_r \in \mathcal{L}(A, A\hat{\otimes}A)$, satisfying $\tilde{\Delta}(u_1 * u_2) = \tilde{\Delta}(u_1) * \tilde{\Delta}(u_2)$. In this context appropriate cohomologies can be introduced. Natural additional requirements for Hopf algebras.

"Quantum groups" are deformations of a Hopf algebra.

E.g. $A = C^\infty(G)$ or "its dual" (in t.v.s. sense) $A' = \mathcal{U}(\mathfrak{g})$ (or some closure of it), G being a Lie group equipped with a "compatible" Poisson bracket P (making it a Poisson manifold) and $\mathfrak{g}$ its Lie (bi)algebra. (Coproduct $\Delta : A \to A\hat{\otimes}A$, $\Delta f(g,h) = f(gh)$ for $A = C^\infty(G)$, antipode $Sf(g) = f(g^{-1})$ and compatible "counit" $\epsilon : A \to \mathbb{K}$.)

The notion arose around 1980 in Faddeev's Leningrad group in relation with inverse scattering and quantum integrable systems, was systematized by Drinfeld and Jimbo, and is now widely used in many contexts.

The framework of deformation quantization

Poisson manifold (M, π), deformations of product of functions.

Inspired by deformation philosophy, based on Gerstenhaber's deformation theory.

[M. Gerstenhaber, Ann.Math. '63 & '64. Flato, Lichnerowicz, Sternheimer; and Vey; mid 70's. Bayen, Flato, Fronsdal, Lichnerowicz, Sternheimer, LMP '77 & Ann. Phys. '78]

• $\mathcal{A}_t = C^\infty(M)[[t]]$, formal series in t with coefficients in $C^\infty(M) = A$. Elements: $f_0 + tf_1 + t^2 f_2 + \cdots$ (t formal parameter, not fixed scalar.)
• Star product $\star_t : \mathcal{A}_t \times \mathcal{A}_t \to \mathcal{A}_t$; $f \star_t g = fg + \sum_{r \geq 1} t^r C_r(f, g)$
- C_r are bidifferential operators null on constants: $(1 \star_t f = f \star_t 1 = f)$.
- $\star_t$ is associative and $C_1(f, g) - C_1(g, f) = 2\{f, g\}$, so that $[f, g]_t \equiv \frac{1}{2t}(f \star_t g - g \star_t f) = \{f, g\} + O(t)$ is Lie algebra deformation.

Basic paradigm. Moyal product on $\mathbb{R}^{2n}$ with the canonical Poisson bracket P: $F \star_M G = \exp\left(\frac{i\hbar}{2} P\right)(F, G) \equiv FG + \sum_{k \geq 1} \frac{1}{k!}\left(\frac{i\hbar}{2}\right)^k P^k(F, G)$.

This is Quantization

Equation of motion (time τ): $\frac{dF}{d\tau} = [H, F]_M \equiv \frac{1}{i\hbar}(H \star_M F - F \star_M H)$
Link with Weyl's rule of quantization: $\Omega_1(F \star_M G) = \Omega_1(F)\Omega_1(G)$.
A star-product provides an *autonomous* quantization of a manifold M.

BFFLS '78: Quantization is a deformation of the composition law of observables of a classical system: $(A, \cdot) \to (A[[t]], \star_t)$, $A = C^\infty(M)$.

Star-product $\star$ ($t = \frac{i}{2}\hbar$) on Poisson manifold M and Hamiltonian H; introduce the star-exponential: $\mathrm{Exp}_\star(\frac{\tau H}{i\hbar}) = \sum_{r\geq 0} \frac{1}{r!}(\frac{\tau}{i\hbar})^r H^{\star r}$.
Corresponds to the unitary evolution operator, is a singular object i.e. belongs not to the quantized algebra $(A[[t]], \star)$ but to $(A[[t, t^{-1}]], \star)$. Singularity at origin of its trace, Harish Chandra character for UIR of semi-simple Lie groups.
Spectrum and states are given by a spectral (Fourier-Stieltjes in the time τ) decomposition of the star-exponential.

Paradigm: Harmonic oscillator, HO: $H = \frac{1}{2}(p^2 + q^2)$, Moyal product on $\mathbb{R}^{2\ell}$.
$\mathrm{Exp}_\star(\frac{\tau H}{i\hbar}) = \left(\cos(\frac{\tau}{2})\right)^{-1} \exp\left(\frac{2H}{i\hbar}\tan(\frac{\tau}{2})\right) = \sum_{n=0}^{\infty} \exp\left(-i(n+\frac{\ell}{2})\tau\right)\pi_n^\ell$.
Here ($\ell = 1$ but similar formulas for $\ell \geq 1$, L_n is Laguerre polynomial of degree n)
$\pi_n^1(q,p) = 2\exp\left(\frac{-2H(q,p)}{\hbar}\right)(-1)^n L_n\left(\frac{4H(q,p)}{\hbar}\right)$. $H, pq, p^2 - q^2$ close to HO rep. of $\mathfrak{sl}(2,\mathbb{R})$

Symmetries in physics: Wigner, Racah, Flato and beyond

The Master

Thesis of Moshé Flato by Maurice Kibler, `arXiv:math-ph/9911016v1`

`http://monge.u-bourgogne.fr/gdito/cmf1999/toc1999.html`

In atomic and molecular physics we know the forces and their symmetries.

Energy levels (spectral lines) classified by UIRs of $SO(3)$ or $SU(2)$, and e.g. with crystals that is refined (broken) by a finite subgroup. [Flato's M.Sc., Racah (1909-1965) centenary conferences, e.g. Saragossa and Jerusalem.]
And beyond: Symmetries of equations (e.g. Maxwell), of physical states.
Classification symmetries ("spectrum generating algebras", nuclear and particle physics), "electroweak" ($U(2)$), "standard model" ($\mathfrak{su}(3) \oplus \mathfrak{su}(2) \oplus \mathfrak{u}(1)$) with dynamics (QCD) inferred from empirically found symmetries,

and Grand Unified Theories (GUT). Plus a lot of phenomenology on these bases.

Modern particle physics: in the beginning; 1961

A cartoon presentation of how it all happened. At first only few particles (mainly nucleons). Isospin (Heisenberg 1932, Wigner 1937). Then "particle explosion" (40's and especially 50's; Fermi botanist quote).
In 1947 and later, it was noticed that some particles (e.g. Λ^0) created in pairs at (relatively) high rate, decayed strangely slowly (lifetime $\geq 10^{-10}$s instead of expected 10^{-21}s). So Gell'Mann (PR 1953) and (independently) Nishijima and Nakano suggested new quantum number (called "strangeness" in 1955), conserved in strong but violated in weak interactions. Yet then (Gell'Mann) "Strange particles were not considered respectable, especially among the theorists". To put some order, in 1956 Sakata suggested that p, n, Λ^0 are "fundamental" and other hadrons are composites.
Early 1961 : Rank 2 Lie group for particle spectroscopy (Salam, Sakurai). The UPenn "1961 gang of 4" (Fronsdal, Ben Lee, Behrends, Dreitlein) too thorough RMP paper: "Since it is as yet too early to establish a definite symmetry of the strong interactions, both because of the lack of experimental data and the theoretical uncertainties about the way in which the symmetries will manifest themselves, the formalism developed is left quite flexible in order to accommodate a wide range of conceivable symmetries." These were $SU(n)$ (in particular $SU(3)$), and types $C_2 = B_2$ and G_2.
At the same time Ne'eman (subject given by Salam) proposed only $SU(3)$, immediately followed independently by Gell'Mann who coined "eightfold way" for the octet of spin $\frac{1}{2}$ baryons ($p, n, \Sigma^{\pm 1,0}, \Lambda^0, \Xi^{\pm 1}$) and octets of scalar and vector mesons.

The first $SU(3)$, 1964: quarks and color. Flavors and generations. SM.

Initial success of $SU(3)$: There are baryons (spin $\frac{1}{2}$) and scalar and vector mesons octets (spin 0,1) that fit in adjoint representation of $SU(3)$.

Early 50's, big stir. Spin $\frac{3}{2}$ baryons discovered, first $\Delta^{\pm 1,0,++}$ in Fermi group (Fermi: "I will not understand it in my lifetime"; Fermi died in 1954...), then $\Sigma*$, $\Xi*$ families. Fit in dim. 10 rep. of $SU(3)$ with "decuplet" completed with predicted scalar Ω^-, found in 1964 at BNL. Also in 1964: Gell'Mann and (independently) Zweig suggest that baryons are composites of "quarks", associated with fundamental rep. (dim. 3) of $SU(3)$.

"Three quarks for Muster Mark!/ Sure he hasn't got much of a bark/ And sure any he has it's all beside the mark." (James Joyce's Finnegans Wake). Then had 3 "flavors" (up, down, strange). But quarks must have fractional charge. Being spin $\frac{1}{2}$ they cannot coexist (Fermi exclusion principle for fermions) so Greenberg proposed in 1964 to give them color (now called blue, green and red). Harari's "rishons", Feynman's "partons". (Finn Ravndal `arXiv:1411.0509`. Adler '94.) Later, in the second generation, strangeness was completed by another flavor (charm) and a third generation was found (2 more flavors, bottom and top), predicted in 1973 by Kobayashi and Maskawa to explain CP violation in kaon decay, "observed" at Fermilab in 1977 and 1995 (resp.), Nobel 2008 with Nambu (for his 1960 symmetry breaking),

Hence SM with 3 generations of quarks in 3 colors (and 6 flavors).

Questions, further developments and problems. Is it necessarily so?

In the 60's, a natural question that was raised: is there any connection between "external symmetries" (the Poincaré group) and the (empirically found) "internal symmetries" of hadrons. Answered by the negative (too quickly, see later).

Then came the question of dynamics (field theory) based on the symmetries. In the 70's appeared the electroweak theory (Weinberg, Glashow and Salam), combining QED ($U(1)$ "gauge") with weak interactions ($SU(2)$ gauge, Yang-Mills), completed by 't Hooft and Faddeev. For strong interactions: dynamics (QCD) built around "color" and $SU(3)$ multiplets (assuming no connection...). That eventually gave the Standard Model (SM), with (Gauge) symmetry $SU(3) \oplus SU(2) \oplus U(1)$ and the dynamics built around it, and GUT (e.g. Yanagida's $SU(5)$). Built upside down, like Jussieu.

It isn't that they can't see the solution. It is that they can't see the problem.

G. K. Chesterton (1874 - 1936) ["The Point of a Pin" in *The Scandal of Father Brown* (1935)]

Problem: the SM could be a colossus with clay feet (Daniel 2:41-43, Nebuchadnezzar's dream).

What if, concerning symmetries, the present SM was "all beside the mark"?? Cf. the last verse of Gell'Mann's quote from James Joyce.)

Poincaré and Anti de Sitter "external" symmetries

1930's: Dirac asks Wigner to study UIRs of Poincaré group. 1939: Wigner paper in Ann.Math. UIR: particle with positive and zero mass (and "tachyons"). Seminal for UIRs (Bargmann, Mackey, Harish Chandra etc.)

Deform Minkowski to AdS, and Poincaré to AdS group SO(2,3). UIRs of AdS studied incompletely around 1950's. 2 (most degenerate) missing found (1963) by Dirac, the singletons that we call Rac$= D(\frac{1}{2}, 0)$ and Di$= D(1, \frac{1}{2})$ (massless of Poincaré in 2+1 dimensions). In normal units a singleton with angular momentum j has energy $E = (j + \frac{1}{2})\rho$, where ρ is the curvature of the AdS_4 universe (they are naturally confined, fields are determined by their value on cone at infinity in AdS_4 space).

The massless representations of $\mathrm{SO}(2,3)$ are defined (for $s \geq \frac{1}{2}$) as $D(s+1, s)$ and (for helicity zero) $D(1,0) \oplus D(2,0)$, for a variety of reasons. They are kinematically composite (FF Thm for "Stringies", LMP 1978):
$(\mathrm{Di} \oplus \mathrm{Rac}) \otimes (\mathrm{Di} \oplus \mathrm{Rac}) = (D(1,0) \oplus D(2,0)) \oplus 2 \bigoplus_{s=\frac{1}{2}}^{\infty} D(s+1, s)$.
Also dynamically (QED with photons composed of 2 Racs, FF88).

Note: $(\mathrm{Di} \oplus \mathrm{Rac}) = \mathrm{D(HO)} \otimes \mathrm{D(HO)}$, $\mathrm{D(HO)} = D(\frac{1}{4}) \oplus D(\frac{3}{4})$ (reps. of $\mathfrak{sl}(2, \mathbb{R})$)

Composite leptons and flavor symmetry

The electroweak model is based on “the weak group”, $S_W = SU(2) \times U(1)$, on the Glashow representation of this group, carried by the triplet $(\nu_e, e_L; e_R)$ and by each of the other generations of leptons.

Now make the following phenomenological Ansatz:
(a) There are three bosonic singletons $(R^N R^L; R^R) = (R^A)_{A=N,L,R}$ (three “Rac”s) that carry the Glashow representation of S_W;

(b) There are three spinorial singletons $(D_\varepsilon, D_\mu; D_\tau) = (D_\alpha)_{\alpha=\varepsilon,\mu,\tau}$ (three “Di”s). They are insensitive to S_W but transform as a Glashow triplet with respect to another group S_F (the “flavor group”), isomorphic to S_W;

(c) The vector mesons of the standard model are Rac-Rac composites, the leptons are Di-Rac composites, and there is a set of vector mesons that are Di-Di composites and that play exactly the same role for S_F as the weak vector bosons do for S_W: $W^B_A = \bar{R}^B R_A$, $L^A_\beta = R^A D_\beta$, $F^\alpha_\beta = \bar{D}_\beta D^\alpha$.

These are initially massless, massified by interaction with Higgs.

Composite leptons massified

Let us concentrate on the leptons ($A = N, L, R$; $\beta = \varepsilon, \mu, \tau$)

$$(L^A_\beta) = \begin{pmatrix} \nu_e & e_L & e_R \\ \nu_\mu & \mu_L & \mu_R \\ \nu_\tau & \tau_L & \tau_R \end{pmatrix} . \tag{3}$$

A factorization $L^A_\beta = R^A D_\beta$ is strongly urged upon us by the nature of the previous phenomenological Ansatz. Fields in the first two columns couple horizontally to make the standard electroweak current, those in the last two pair off to make Dirac mass-terms. Particles in the first two rows combine to make the (neutral) flavor current and couple to the flavor vector mesons. The Higgs fields have a Yukawa coupling to lepton currents, $\mathcal{L}_{\rm Yu} = -g_{\rm Yu}\bar{L}^\beta_A L^B_\alpha H^{\alpha A}_{\beta B}$. The electroweak model was constructed with a single generation in mind, hence it assumes a single Higgs doublet. We postulate additional Higgs fields, coupled to leptons in the following way, $\mathcal{L}'_{\rm Yu} = h_{\rm Yu} L^A_\alpha L^B_\beta K^{\alpha\beta}_{AB} + {\rm h.c.}$. This model predicts 2 new mesons, parallel to the W and Z of the electroweak model (Frønsdal, LMP 2000).

Do the same for Dark Matter, with very heavy "dark Higgs"? Or maybe sterile neutrinos (Kusenko)?

Quantum groups at root of unity and generalizations

Fact: quantum groups at root of unity have finite dimensional UIRs. (The Hopf algebra is *finite dimensional*.
Maybe the successes of the SM can be derived (or a better SM built) by starting with such procedures, e.g. (multiparameter) qAdS at 6^{th} root(s) of 1.
There could be a part of self-fulfilling prophecy when experimental data are phenomenologically interpreted in the framework of a model. At present the pieces of the "puzzle" fit remarkably well, though some "cracks" appear in the SM. And it could be that different interpretations of the present experimental data fit even better. E.g. interpretations based on generalized deformations where the "parameter", instead of being a scalar (the algebra of a one-element group) would belong to the algebra of a finite group (e.g. the center $\mathbb{Z}/n\mathbb{Z}$ or the Weyl group (S_n) of some SU(n)) or be quaternionic. The core of the success of unitary groups as classification symmetries, appearing in the SM, is maybe number-theoretic, making it possible to develop similar (or better) explanations from suitably deformed (and quantized) space-time symmetries and to base the interpretation of the present data on firmer "space-time ground".

THE DEFORMATION CONJECTURE. *Internal symmetries of elementary particles arise from their relativistic counterparts by some form of deformation (including quantization).*

The Erik Verlinde approach to the Dark Universe

Erik Verlinde (November 2016), “Emergent Gravity and the Dark Universe,” `arXiv:1611.02269`. J.M. Bardeen, B.Carter and S.W. Hawking, “The Four laws of black hole mechanics,” Commun. Math. Phys. 31, 161 (1973): The emergent nature of spacetime and gravity comes from the laws of black hole thermodynamics.
New theoretical framework: spacetime geometry represents the entanglement structure of the microscopic quantum state. Gravity emerges from this quantum information theoretic viewpoint as describing the change in entanglement caused by matter. Spacetime and gravity emerge together from quantum information, via the entanglement structure of an underlying microscopic theory, These novel ideas are best understood in Anti-de Sitter space, relying on the area law for entanglement entropy. Strategy: apply the same general logic as in AdS, making appropriate adjustments to take into account the differences that occur in dS spacetimes.
One of the backgrounds of this approach is to introduce a one parameter deformation of Minkowski space-time to AdS and dS. In the spirit of what precedes, why not be more audacious and consider multiparameter deformations (in particular 3 parameter, since so far we have 3 generations of particles, but maybe more to take “darkness” into account)? And/or go even further and consider quantum AdS (or dS), possibly with more than one parameters, and maybe at roots of unity where one gets finite-dimensional Hopf algebras. Even more work to do ...

A tentative "road map" for a well-based particle physics, I. Maths.

I. "Mathematical homework".

a. Study representations and (some of) their tensor products for qAdS at (some) root of unity. Maybe start with $q\mathfrak{sl}(3)$ instead of qB_2 (or qC_2, which could be different, especially for AdS real forms).

b. Use Connes tensor product of bimodules (cf. e.g. NCG book), contains theory of subfactors. Cf. Jones, Section 5.3 in *In and around the origin of quantum groups*, Contemp. Math. **437**, 101-126 (2007) (much entangled quantum systems, Wasserman's fusion of loop group reps., Inventiones 1988).

c. Multiparameter quantum groups at roots of 1. E.g. qAdS with 3 Abelian parameters at some roots of 1 (e.g. sixth for all 3, but maybe different), their representations and (some of) the tensor products of these.

d. Reshetikihin-Turaev (& Quantum Chern-Simons) theories with such gauges (Andersen).

e. Define & study "quantum deformations" with quaternionic "parameters", or in the group algebra of e.g. S_n. Maybe start with commutative param. and "quantize" param. space ("third quantization"). Or families of NC alg. depending on param.

f. Gerstenhaber (new) deformations of "path algebras" on Riemannian manifold, associate wave to particle moving in phase space.

(All are problems of independent mathematical interest.)

A tentative "road map" for a well-based particle physics, II. Physics.

II. General ideas for physical applications.

a. Try to use I (with some qAdS) to (step by step) re-examine the phenomenological classification of elementary particles.
b. We might not need quarks. However it could be more gratifying (and it would certainly be easier to promote these ideas) if we could "consolidate" the "clay feet" of the Standard Model, e.g. with a 3 (commutative) parameters deformation of AdS (possibly at some root(s) of unity), using which we could justify the use of $SU(3)$ as "internal symmetry" and the introduction of color.
c. If we can define (possibly by "quantizing" the parameters space) a quaternionic deformation, or with "parameter" in the algebra of a finite group like S_3, use it to explain the appearance of e.g. $SU(3)$, and re-examine the Standard Model in that light.
d. Possible shortcut: look at preon models (preons = singletons?), e.g. Adler's quaternionic QM and composite quarks & leptons as quasiparticles (PLB '94).
e. Build a new dynamics based on such deformed relativistic symmetries.
f. Re-examine half a century of particle physics, from the points of view of theory, experiments and phenomenology. Apply that to Dark Matter?
g. Connection with the "String Framework"?

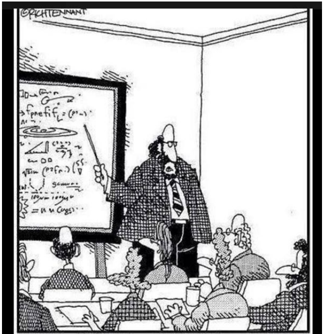
Problems worthy of attack prove their worth by hitting back.

Very few references

[See also references in all these, and more]
1. Leon Takhtajan, *Quantum Mechanics for Mathematicians* Graduate Studies in Mathematics, **95**, AMS 2008.
2. G.S. Agarwal and E. Wolf "Calculus for functions of noncommuting operators and general phase-space methods in quantum mechanics I, II, III," *Phys. Rev.* **D2** (1970), 2161–2186, 2187–2205, 2206–2225.
3. F. Bayen, M. Flato, C. Fronsdal, A. Lichnerowicz and D. Sternheimer: *Deformation Theory and Quantization: I. Deformations of Symplectic Structures*, and *II. Physical Applications*, Ann. Phys. **111**, 61–110 and 111–151 (1978). Quantum mechanics as a deformation of classical mechanics. Lett. Math. Phys. 1 (1975/77), no. 6, 521–530.
4. G. Dito and D. Sternheimer, *Deformation quantization: genesis, developments and metamorphoses*, pp. 9–54 in: *Deformation quantization* (Strasbourg 2001), IRMA Lect. Math. Theor. Phys., **1**, Walter de Gruyter, Berlin 2002.
5. E. Angelopoulos, M. Flato, C. Fronsdal and D. Sternheimer, *Massless particles, conformal group and De Sitter universe*, Phys. Rev. **D23** (1981), 1278–1289.
6. M. Flato and C. Fronsdal: Composite Electrodynamics, J. Geom. Phys. **5**(1) (1988), 37–61.
7. P. Bieliavsky P., Claessens L., Sternheimer D., Voglaire Y.: Quantized Anti de Sitter spaces and non-formal deformation quantizations of symplectic symmetric spaces, `arXiv:0705.4179v1 [math.QA]` *Poisson geometry in mathematics and physics*, 1–24, Contemp. Math., 450, Amer. Math. Soc., Providence, RI, 2008.
8. C. Frønsdal: Singletons and neutrinos, Lett. Math. Phys. **52**(1) (2000) 51–59.
9. M. Flato, A. Lichnerowicz, D. Sternheimer, Crochet de Moyal-Vey et quantification. (French) C. R. Acad. Sci. Paris Sér. A-B 283 (1976), no. 1, Aii, A19–A24.
10. P. Bonneau, M. Gerstenhaber, A. Giaquinto and D. Sternheimer, *Quantum groups and deformation quantization: explicit approaches and implicit aspects*, J. Math. Phys. **45** (2004), no. 10, 3703–3741.
11. M. Flato, C. Frønsdal, D. Sternheimer: Singletons, physics in AdS universe and oscillations of composite neutrinos, Lett. Math. Phys. **48**(1) (1999), 109–119.
12. D. Sternheimer, "A very short presentation of deformation quantization, some of its developments in the past two decades, and conjectural perspectives." Travaux mathématiques (U. Luxembourg), **20** (2012), 205–228. And: *"The important thing is not to stop questioning", including the symmetries on which is based the Standard Model.*,

Geometric Methods in Physics, XXXII Workshop 2013 in Białowieża, Trends in Mathematics, 7-37, Springer (2014).

matter



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."