INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS

44th Course: **THE LOGIC OF NATURE, COMPLEXITY AND NEW PHYSICS: FROM QUARK-GLUON PLASMA TO SUPERSTRINGS, QUANTUM GRAVITY AND BEYOND**

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**CLOSING LECTURE**

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On page 209 of my book “Subnuclear Physics - the first 50 years” the following sentence is quoted: «Copying is easy, logical reasoning is difficult.»

The author being Gerardus ’t Hooft, Erice 1997.
With his statement, my great friend Gerardus, worded his view on the progress made, and progress still to be made, in theoretical physics.
On the occasion of his 60th Anniversary Celebrations I gave my own testimony on the validity of \’t Hooft’s statement in experimental physics. In fact, in experimental physics as well, it is not enough to have an original idea.
My great teacher, Patrick Blackett, used to tell us, young fellows of his group:
“We experimentalists are not like theorists: the originality of an idea is not for being printed in a paper, but for being shown in the implementation of an original experiment.”
To reach the level of performing an original experiment corresponds to bring “logical reasoning” to its asymptotic limit of reality.
Thus, both in theory and in experiment, the progress of physics is due to those who have the perseverance of not only having an original idea, but of investigating its logical structure in terms of its consequences.
Here a few examples from my own past experience follow.
The third lepton.
In the late fifties, I realized that if the pion mass was not what it was, the muon had very little chance of being so obviously present everywhere; and if a new lepton of 1 GeV mass (or heavier) would have been there, no one would have seen it; I did not limit myself to discussing this topic with a few colleagues; I followed Blackett’s teaching. And this is how I realized that the best “signature” for a heavy lepton would have been “$e\mu$” acoplanar pairs; this is how I invented the “preshower” to improve electron identification by many orders of magnitude; this is why I studied how to improve muon identification; this is how I experimentally established that the best production mechanism could not be $(p\bar{p})$, but $(e^+e^-)$ annihilation.
Matter-Antimatter Symmetry.
In the sixties, the need to check the symmetry between nuclear matter and antimatter came to the limelight. The reason being the apparent triumph of the S-matrix theory to describe strong interactions and the violation of the “well-established” symmetry operators (C, P, CP, T) in weak interactions and in the K-meson decay physics. When the discovery of scaling in Deep Inelastic Scattering (DIS) and the non-breaking of the protons in high energy collisions come in the late sixties, the basic structure of all Relativistic Quantum Field Theories (RQFT) were put in serious difficulties, and therefore the validity of the celebrated CPT theorem. On the other hand, the basic reason why nuclear antimatter had to exist was CPT.
In the early sixties the first example of nuclear antimatter, the antideuteron, had been searched for and found not to be there at the level of one antideuteron per $10^7$ pions produced.

I did not limit myself to saying that it would have been important to build a beam of negatively charged “partially separated” particles in order to have a very high intensity. I did not limit myself to suggesting a very advanced electronic device in order to increase, by an order of magnitude, the accuracy for time-of-flight (TOF) measurements. I did bring all my ideas to the point of full implementation in a detailed experiment, where the antideuteron was found, thus proving nuclear matter-antimatter symmetry.

Therefore credence could be given to CPT and to RQFT.
\[ \theta_{PS} \neq \theta_{V} \neq 0 \]
This is what Dick Dalitz defined the most significant results from all mesonic physics.
In homage to Richard Dalitz let me show Figure 1.

\[ \theta_{PS} = -10^\circ \]
\[ \theta_{PDB}^{PDB} = +39^\circ \]
\[ \theta_{V}^{GT} = +51^\circ \]

\[ \theta_{PS}^{GT} = +10^\circ \]

PDB = Particle Data Book
GT = Gerardus 't Hooft

\[ \theta_{PS} \neq \theta_{V} \]

Direct: Not Using Mass Formulae
The problem of concern in the physics of strong interactions was the "mixing" in meson physics. It was necessary to know why the vector mesons (ρ, ω, φ) did not show the same behaviour as the pseudoscalar mesons (π, η, η').

I did not limit myself to saying that the most appropriate way to study this problem [(e^+e^-) colliders did not yet exist], was to measure with the best possible accuracy the electromagnetic decay rates of the vector mesons

(ρ → e^+e^-),
(ω → e^+e^-),
(φ → e^+e^-),

and to see if the heaviest meson (known at that time with the symbol X^0) was decaying into two γ’s (X^0 → γγ).
These were times when experimental physics was dominated by bubble chambers.

I designed and built a non-bubble-chamber detector, NBC; it consisted of an original neutron missing mass spectrometer coupled with a powerful electromagnetic detector which allowed to clearly identify all final states of the decaying mesons into \((e^+e^-)\) or \((\gamma\gamma)\) pairs. The mass of the meson (be it pseudoscalar or vector) was measured by the neutron missing mass spectrometer.

The two “mixing angles”, the pseudoscalar \(\theta_{PS}\) and the vector \(\theta_V\), where directly measured (without using the masses) to be, not as expected by \(SU(3)_{uds}\), i.e. \(\theta_{PS} = \theta_V = 0\), but, \(\theta_{PS} \neq 0\), \(\theta_V \neq 0\) and totally different \(\theta_{PS} \neq \theta_V\).

Many years were needed and the Gerard’s Instantons to explain why \(\theta_{PS} \simeq 10^\circ\) and \(\theta_V \simeq 51^\circ\).
The proton does not break into 3 quarks despite 1968 Panofsky
When in 1968 I heard Pif (W.K.H.) Panofsky reporting in Vienna on (ep) deep-inelastic-scattering, whose immediate consequence was that “partons” inside a proton behaved as “free” particles, I did not limit myself to saying that it would have been interesting to check if, in violent (pp) collisions, “free” partons were produced. Since the “partons” were suspected to be the quarks earlier suggested by M. Gell-Mann and G. Zweig (we now know that partons can also be gluons), the experiment needed was a search for fractionally charged particles in the final states of violent (pp) interactions at the CERN ISR. To perform the experiment, a new type of plastic scintillator was needed, with very long attenuation length since the counters had to be put inside a very big magnet. These scintillators did not exist on the market. We studied the problem and built the most powerful and sensitive scintillators. The result was that free quarks were not produced, despite the violent (pp) collisions.
The Gribov QCD Light
When the physics of strong interactions finally became the physics of quarks and gluons, **QCD had a problem**, defined by Gribov as being its “**hidden side**”: i.e., the large number of different final states produced by different pairs of interacting particles, such as \((\pi p, pp, \bar{p}p, Kp, e^+e^-, \nu p, \mu p, ep, \text{etc.})\). I did not limit myself to suggesting that a totally different approach was needed to put all these final states on the same basis. I found what this basis could be and this is how the “**Effective Energy**” became the correct quantity to be measured in each interaction. To perform this study, it was necessary to analyze tens of thousands of \((pp)\) interactions at the ISR. This was done despite all the difficulties to be overcome. And this is how QCD light was discovered.
Figure 2
Figure 3
So, when a new problem appears, the only way out is to bring the logical reasoning – be it of experimental, theoretical or technical nature – to the deepest level of consequences.
This is how progress is made in advanced research.
CONCLUSIONS
Conclusion – 1
In the last few years I have investigated the two basic experimental evidences which characterize Complexity.

In fact “Complexity” is “ill-defined”; nevertheless people speak of “Complexity” as a source of new insights in Physics, Biology, Geology, Cosmology, Social Sciences and all those intellectual activities which look at the world through the lens of a standard analysis in terms of either Simplicity or Complexity.
I have reviewed the present status of all we know in the Reductionistic achievements together with our present understanding of the rigorous attempts towards the basic features which allow Complexity to exist, i.e. AFB phenomena and UEEC events.
The conclusion is that Complexity exists at the Fundamental Level.
We do not know what will be the final outcome of String Theory.
What we do know is that all these attempts to understand the Logic of Nature appear to be very “simple” when compared with the “Complexity” of the World we are part of.
This is shown in Figure 4 where the various components of our knowledge which make up the apparently very different domains of our world are specified.
The conceptual understanding of the constituents of the Universe after 400 years of Reductionism are shown in Figure 5.
SUPERWORLD

\[ F = B \]

THREE COLUMNS AND THREE FUNDAMENTAL FORCES

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s : t : m : E : \sigma : Q
Space  Time  Mass  Energy  Spin  Charges
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“Subnuclear Colour” Charges (generating the Fundamental Forces).

“Subnuclear Flavour” Charges (responsible for the stability of Matter).

REDUCTIONISM

Figure 5
The key point is that we have reached this extremely “simple” understanding of the fundamental natural phenomena via an incredible series of ABF and UEEC events (Sarajevo-type).
Furthermore it should be pointed out that the apparently simple structure of the hypothetical goal, the Superworld, is full of problems to be solved and, once again, it has been obtained with a remarkable set of AFB and UEEC events.
Moreover if we try to formulate the simplest version of our rigorous logic to describe Nature, i.e. the Platonic GUT and the Platonic Supersymmetry, the result is that nothing in the real world looks like it, not even the Standard Model.
Conclusion – 2
Present trend: from Reductionism to Holism.
Is Holism the way to understand the origin of Complexity?
Is Big Numbers the way to understand the origin of Complexity?
We have a few fundamental sources of Big Numbers.
Big Numbers come from the ratio of Space, Time, Mass-Energy and Action.
Space ≡ \frac{S_{Universe}}{Planck\ Length} \approx 10^{62}
\[
\tau_p \equiv \frac{10^{33} \cdot \pi \times 10^7 \text{ sec}}{10^{-43} \text{ sec}} = 10^{40} \text{ sec} = 10^{83}
\]
Mass-Energy

\[ M_{\text{Universe}} \equiv \frac{M^U}{M_\nu} \approx \frac{10^{80} \text{GeV} \cdot 10^2}{10^{-4} \text{eV}} = \]

\[ = 10^{91} \text{eV} \]

\[ = 10^{95} \text{eV} \]
\[
\text{Action} \quad \Rightarrow \quad \frac{h_{\text{Universe}}}{h_{\text{Planck}}} = 10^{123}
\]
With these Big Numbers compete those coming from the Mathematical Model of Brain. According to some models, in order to produce new ideas the number of possible combinations is much larger than $10^{123}$. 
What about the Number of Constituents?

There is a recent experimental finding where the number seems not to be relevant. The decodification of the Human Genome has shown that it contains only about 25,000 genes. Where is the seat of Human Species Complexity since the number of genes is similar to that of many other Living organisms? The number of genes does not seem to play a role as far as Complexity levels are concerned.

What seems to play an important role is the network of interactions between Genes and Proteins.
Conclusion – 3
So far, no new fundamental forces have been discovered by those fellows engaged in the study of Complex Systems.
COMPLEX SYSTEMS

The Critical Opalescence
Turbulence in the Atmosphere
Earthquakes and Seismicity
Brain Activity
Brain Neural Network
Traffic Flux
Internet Network
Immune System
Social and Economic Systems
The Behaviour of Financial Markets
The Kondo Problem
Biological Phenomena
The Virtual Phenomena
Cosmological Structures
Self-Gravitating Systems
Human Genome

Figure 6
Conclusion – 4
We have shown that the experimental foundations for the existence of Complexity are found in the Galilean study of the Logic of Nature. It is therefore not correct to claim that holism is the right way to go in order to understand Complexity. In fact Complexity exists at the fundamental level.
• Therefore **Totally Unexpected Effects** should **show up**.
• **Effects**, which are impossible to be predicted on the basis of **present knowledge**.
• Where these effects are most likely to be, no one knows.
• **But**, with the advent of the ALICE experiment at the LHC it will be possible to study the properties of the Quark-Gluon-Coloured-World (QGCW).
At this point Gerardus would ask me the question:

“How do we detect the totally unexpected effects?”
An example is illustrated in the Figure below where beams of known particles (p, n, \( \gamma \), e, \( \mu \)) bombard the QGCW and a special set of detectors measures the properties of the outcoming particles.
QGCW

Incoming
p, n, γ, e, μ

Outcoming particles
In the following years, much before the second 60th Gerardus Anniversary, we could celebrate another Gerardus Anniversary with the discovery of a totally unexpected effect.

It would be great if this happened using the ALICE apparatus at LHC.

This should indeed be the case if Nature follows the Logic of Complexity at the Fundamental level.