Gerard 't Hooft

Centre for Extreme Matter and Emergent Phenomena,
Science Faculty, Utrecht University,
POBox 80.089, 3508 TB, Utrecht
The Netherlands

Closing Remarks

International School of Subnuclear Physics,
"FROM GRAVITATIONAL WAVES TO QED, QFD AND QCD",
"Ettore Majorana" Foundation and Centre for Scientific Culture,
Erice, Sicily, Italy,
June 2018

The 20^{th} century stands out as

the Century of Science and technology

physics, astronomy, biology, chemistry, nanoscience, information technology, air travel, space travel, medicine, etc.

Physics in particular:

Planck's light quantization (1900), Einstein's 3 revolutions (1905), his General Theory of Relativity (1915), Rutherford's atom model (1911), etc. etc.

How does the 21^{st} compare with that?

The 20^{th} century stands out as

the Century of Science and technology

physics, astronomy, biology, chemistry, nanoscience, information technology, air travel, space travel, medicine, etc.

Physics in particular:

Planck's light quantization (1900), Einstein's 3 revolutions (1905), his General Theory of Relativity (1915), Rutherford's atom model (1911), etc. etc.

How does the 21^{st} compare with that?

The Higgs particle finally discovered (2012),

predicted since the 1960s;

Gravitational waves detected (2015), *predicted since 1916 . . .*

Many exoplanets found *(the first already in 1988 . . .)*

The 20^{th} century stands out as

the Century of Science and technology

physics, astronomy, biology, chemistry, nanoscience, information technology, air travel, space travel, medicine, etc.

Physics in particular:

Planck's light quantization (1900), Einstein's 3 revolutions (1905), his General Theory of Relativity (1915), Rutherford's atom model (1911), etc. etc.

How does the 21^{st} compare with that?

The Higgs particle finally discovered (2012),

predicted since the 1960s;

Gravitational waves detected (2015), *predicted since 1916 . . .*

Many exoplanets found *(the first already in 1988 . . .)*

This century is not doing as well as the previous . . . !

There was a surprise (comparable to Michelson and Morley . . .):

The Standard Model works much better than anyone had foreseen !

Is science in a crisis?

There was a surprise (comparable to Michelson and Morley . . .):

The Standard Model works much better than anyone had foreseen !

Is science in a crisis?

No! Today there are more scientists than ever before.
They're just not doing so well, considering their numbers . . .

How to explain that ??

There was a surprise (comparable to Michelson and Morley . . .):

The Standard Model works much better than anyone had foreseen !

Is science in a crisis?

No! Today there are more scientists than ever before.
They're just not doing so well, considering their numbers . . .

How to explain that ??

Perhaps science is becoming harder . . .
and we expect more from science than what is reasonable;
our expectations were too high . . .
we are suffering from the $20^{\rm th}$ century's successes!

Painful lesson from the history of science:

There was a surprise (comparable to Michelson and Morley . . .):

The Standard Model works much better than anyone had foreseen !

Is science in a crisis?

No! Today there are more scientists than ever before.
They're just not doing so well, considering their numbers . . .

How to explain that ??

Perhaps science is becoming harder . . .
and we expect more from science than what is reasonable;
our expectations were too high . . .
we are suffering from the $20^{\rm th}$ century's successes!

Painful lesson from the history of science: more scientists and larger budgets do not always guarantee faster progress.
Scientists often tend to *stick to procedures and approaches that once have been successful in the past.* For instance:

It was observed that the Standard Model is based on mathematical methods where *symmetry features* (local as well as global) are central. One therefore concludes that all future progress will be based on symmetries.

If a symmetry is "beautiful", it must apply to the real world!

It was observed that the Standard Model is based on mathematical methods where *symmetry features* (local as well as global) are central. One therefore concludes that all future progress will be based on symmetries.

If a symmetry is "beautiful", it must apply to the real world!

Supersymmetry is indeed a beautiful mathematical construction. But does this suffice to prove that there fore Nature will be supersymmetric?

Ancient Greeks thought that the *number 5* generates beautiful patterns. Does this suffice to argue that, therefore, matter must come in *5 elements?*

It was observed that the Standard Model is based on mathematical methods where *symmetry features* (local as well as global) are central. One therefore concludes that all future progress will be based on symmetries.
If a symmetry is "beautiful", it must apply to the real world!

Supersymmetry is indeed a beautiful mathematical construction. But does this suffice to prove that there fore Nature will be supersymmetric?

Ancient Greeks thought that the *number 5* generates beautiful patterns. Does this suffice to argue that, therefore, matter must come in *5 elements?*

What seems "beustiful" for one generation, may look old-fashioned to the next.

This is *not* to argue that we should no longer use symmetry arguments as important leads towards new theories,
but simply that they should not always get priority.

When attempting to reconcile the weak force with electromagnetism, we ended up wth a theory where the weak force and electromanetism were "unified". This was followed by vigorous attempts also to unify this structure, now called 'electro-weak', with the strong force, based on $SU(3)$.

But point $\#$ 1:

When attempting to reconcile the weak force with electromagnetism, we ended up wth a theory where the weak force and electromanetism were "unified". This was followed by vigorous attempts also to unify this structure, now called 'electro-weak', with the strong force, based on $SU(3)$.

But point # 1: the electroweak theory is not a true unification (It is still composed of a $U(1)$ group and $SU(2)$, with two coupling parameters g_1 and g_2). It is rather an (interesting) *mixture* between $U(1)$ and $SU(2)$.

And point # 2:

When attempting to reconcile the weak force with electromagnetism, we ended up wth a theory where the weak force and electromanetism were “unified”. This was followed by vigorous attempts also to unify this structure, now called ‘electro-weak’, with the strong force, based on $SU(3)$.

But point # 1: the electroweak theory is not a true unification (It is still composed of a $U(1)$ group and $SU(2)$, with two coupling parameters g_1 and g_2). It is rather an (interesting) *mixture* between $U(1)$ and $SU(2)$.

And point # 2: the strong force is based on $SU(3)$ and as such ‘already’ unified with electro-weak, though it carries again another coupling parameter, g_3.

When attempting to reconcile the weak force with electromagnetism, we ended up wth a theory where the weak force and electromanetism were "unified". This was followed by vigorous attempts also to unify this structure, now called 'electro-weak', with the strong force, based on $SU(3)$.

But point # 1: the electroweak theory is not a true unification (It is still composed of a $U(1)$ group and $SU(2)$, with two coupling parameters g_1 and g_2). It is rather an (interesting) *mixture* between $U(1)$ and $SU(2)$.

And point # 2: the strong force is based on $SU(3)$ and as such 'already' unified with electro-weak, though it carries again another coupling parameter, g_3.

In the quest for true "Grand Unification", one searches for a large gauge group with only one coupling parameter.

Fine, let's try it.

One notes that the Grand Unified group $SO(10)$ works somewhat better than $SU(5)$. I think that the argument that

> *the three fermionic representations are all a spinorial representation of $SO(10)$, while they are already a spinorial representation of $SO(3,1)$,*

is a elegant and original argument, favoring $SO(10)$, but again, not conclusive. It does not work for $SU(5)$.

One notes that the Grand Unified group $SO(10)$ works somewhat better than $SU(5)$. I think that the argument that

> *the three fermionic representations are all a spinorial representation of* $SO(10)$*, while they are already a*
> *spinorial representation of* $SO(3,1)$*,*

is a elegant and original argument, favoring $SO(10)$, but again, not conclusive. It does not work for $SU(5)$.

But symmetry patterns invented by men, are often not followed by Nature. By far the best approach to scientific mysteries has alway been:

try to argue with more logic than your predecessors in the past.

> People, even scientists, including this lecturer,
> are often not good at logic.

Conclusion:

One notes that the Grand Unified group $SO(10)$ works somewhat better than $SU(5)$. I think that the argument that

> *the three fermionic representations are all a spinorial representation of $SO(10)$, while they are already a spinorial representation of $SO(3,1)$,*

is a elegant and original argument, favoring $SO(10)$, but again, not conclusive. It does not work for $SU(5)$.

But symmetry patterns invented by men, are often not followed by Nature. By far the best approach to scientific mysteries has alway been:
try to argue with more logic than your predecessors in the past.

> People, even scientists, including this lecturer,
> are often not good at logic.

Conclusion: use symmetries, if appropriate, but do not overestimate their importance. This could be wrong.

We do agree that the theory of the Standard Model does not accommodate for a quantized version of gravitation, and we have been searching for such a theory for (roughly) 50 years. Quantum gravity is essential for the internal logic of our theoretical understanding.

We do agree that the theory of the Standard Model does not accommodate for a quantized version of gravitation, and we have been searching for such a theory for (roughly) 50 years. Quantum gravity is essential for the internal logic of our theoretical understanding.

But we have to apply the best logical arguments available. Many researchers are making more arbitrary assumptions here than necessary, not realizing how this tremendously weakens our understanding. This is not necessary. Logic is.

We do agree that the theory of the Standard Model does not accommodate for a quantized version of gravitation, and we have been searching for such a theory for (roughly) 50 years. Quantum gravity is essential for the internal logic of our theoretical understanding.

But we have to apply the best logical arguments available. Many researchers are making more arbitrary assumptions here than necessary, not realizing how this tremendously weakens our understanding. This is not necessary. Logic is.

I frequently emphasized that, when ordinary, accepted physical laws are applied to **q̆uantum black holes**, one may run into self-contradictory predictions.

The source of the difficulty: *Quantum gravity is not renormalizable*.

Now all we need to ask for is a theory that gives black holes properties that are meaningful and unambiguous.

The laws of evolution for a black hole must be described by a unitary evolution matrix, like everywhere else in physics

> (or if such a matrix would not exist, it must be replaced by some other logical theory, but this appears to be unlikely)

One finds that

Now all we need to ask for is a theory that gives black holes properties that are meaningful and unambiguous.

The laws of evolution for a black hole must be described by a unitary evolution matrix, like everywhere else in physics

(or if such a matrix would not exist, it must be replaced by some other logical theory, but this appears to be unlikely)

One finds thatan evolution law that is compatible with the rest of physics does exist, but it does require modifications of the laws we thought we knew.

This results into new theories concerning space, time and matter. These theories differ from standard ideas concerning *unification*, and even *(super) string theories.*

And

Now all we need to ask for is a theory that gives black holes properties that are meaningful and unambiguous.

The laws of evolution for a black hole must be described by a unitary evolution matrix, like everywhere else in physics

(or if such a matrix would not exist, it must be replaced by some other logical theory, but this appears to be unlikely)

One finds thatan evolution law that is compatible with the rest of physics does exist, but it does require modifications of the laws we thought we knew.

This results into new theories concerning space, time and matter. These theories differ from standard ideas concerning *unification*, and even *(super) string theories.*

And we do hit upon new clues.

But their implications are yet to be investigated.

I have similar unpopular views about Quantum Mechanics.

In the 1920s, scientists such as Einstein, Bohr, Heisenberg, Schrödinger, came together, often in Copenhagen, to dispute about Quantum Mechanics.
They did a wonderful job.

I have similar unpopular views about Quantum Mechanics.

In the 1920s, scientists such as Einstein, Bohr, Heisenberg, Schrödinger, came together, often in Copenhagen, to dispute about Quantum Mechanics.
They did a wonderful job.

They found the precise logical rules as to how to work with Quantum Mechanics:

I have similar unpopular views about Quantum Mechanics.

In the 1920s, scientists such as Einstein, Bohr, Heisenberg, Schrödinger, came together, often in Copenhagen, to dispute about Quantum Mechanics.
They did a wonderful job.

They found the precise logical rules as to how to work with Quantum Mechanics:

How to formulate the Schrödinger equation, if you want a theory with a given classical limit;

I have similar unpopular views about Quantum Mechanics.

In the 1920s, scientists such as Einstein, Bohr, Heisenberg, Schrödinger, came together, often in Copenhagen, to dispute about Quantum Mechanics.
They did a wonderful job.

They found the precise logical rules as to how to work with Quantum Mechanics:

How to formulate the Schrödinger equation, if you want a theory with a given classical limit;
how it relates to observed phenomena (Born's probabilities);

I have similar unpopular views about Quantum Mechanics.

In the 1920s, scientists such as Einstein, Bohr, Heisenberg, Schrödinger, came together, often in Copenhagen, to dispute about Quantum Mechanics.
They did a wonderful job.

They found the precise logical rules as to how to work with Quantum Mechanics:

How to formulate the Schrödinger equation, if you want a theory with a given classical limit;
how it relates to observed phenomena (Born's probabilities);
how the outcome of measurements are to be understood

I have similar unpopular views about Quantum Mechanics.

In the 1920s, scientists such as Einstein, Bohr, Heisenberg, Schrödinger, came together, often in Copenhagen, to dispute about Quantum Mechanics.
They did a wonderful job.

They found the precise logical rules as to how to work with Quantum Mechanics:

How to formulate the Schrödinger equation, if you want a theory with a given classical limit;
how it relates to observed phenomena (Born's probabilities);
how the outcome of measurements are to be understood
(collapse wave function).

I have similar unpopular views about Quantum Mechanics.

In the 1920s, scientists such as Einstein, Bohr, Heisenberg, Schrödinger, came together, often in Copenhagen, to dispute about Quantum Mechanics.
They did a wonderful job.

They found the precise logical rules as to how to work with Quantum Mechanics:

How to formulate the Schrödinger equation, if you want a theory with a given classical limit;
how it relates to observed phenomena (Born's probabilities);
how the outcome of measurements are to be understood
(collapse wave function).

But then they concluded that there are questions one should not ask: *what is the reality behind Quantum Mechanics?*
Or what can we say about that reality?

Not asking questions is bad logic!

Perhaps one should turn questions around
(often leads to surprises):

Not asking questions is bad logic!

Perhaps one should turn questions around
(often leads to surprises):

Are there questions in classical physics, for which Quantum Mechanics methods are known to be the answer?

Not asking questions is bad logic!

Perhaps one should turn questions around
(often leads to surprises):

Are there questions in classical physics, for which Quantum Mechanics methods are known to be the answer?

Yes, there are!

Onsager's solution to the Ising problem, 1944.

Not asking questions is bad logic!

Perhaps one should turn questions around
(often leads to surprises):

Are there questions in classical physics, for which Quantum Mechanics methods are known to be the answer?

Yes, there are!

Onsager's solution to the Ising problem, 1944.

Quantum Mechanics is the theory you get if you *don't know the initial state* (because you cannot), and therefore, you can't know for certain the final state (it appears as a superposition).

You then discover that, when J.S. Bell formulated his famous theorem about Quantum Mechanics, he did not use the correct formulation of causality. The only correct formulation is the one used in QFT (commutators of operators that are space-like separated, must vanish).

This does lead to a loop-hole (but a tiny one!) allowing us to avoid Bell's 'no-go theorem': *The initial state of a system of atoms and/or spins, must include the description of the observers.*

This does lead to a loop-hole (but a tiny one!) allowing us to avoid Bell's 'no-go theorem': *The initial state of a system of atoms and/or spins, must include the description of the observers.*

To be precise: observers may only choose operators that all commute. *It is this information that must be included in our info about the initial state!*

The logic here is very tight, and, in disputes of this topic, often both sides have it wrong.

This does lead to a loop-hole (but a tiny one!) allowing us to avoid Bell's 'no-go theorem': *The initial state of a system of atoms and/or spins, must include the description of the observers.*

To be precise: observers may only choose operators that all commute. *It is this information that must be included in our info about the initial state!*

The logic here is very tight, and, in disputes of this topic, often both sides have it wrong.

A precise understanding of what Quantum Mechanics exactly is, will be very important also for understanding quantum gravity. And without that understanding, no "unification", no "cosmology", no "theory for the > 20 freely adjustable parameters of the Standard Model."

This does lead to a loop-hole (but a tiny one!) allowing us to avoid Bell's 'no-go theorem': *The initial state of a system of atoms and/or spins, must include the description of the observers.*

To be precise: observers may only choose operators that all commute. *It is this information that must be included in our info about the initial state!*

The logic here is very tight, and, in disputes of this topic, often both sides have it wrong.

A precise understanding of what Quantum Mechanics exactly is, will be very important also for understanding quantum gravity. And without that understanding, no "unification", no "cosmology", no "theory for the > 20 freely adjustable parameters of the Standard Model."

This may be the reason why our progress is slowing down.

THE END