Discovery Of
The God Particle

A Good Bang
For
Your Buck?

S. A. JABEEN

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To my parents

I am nothing but what they made me.

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Preface (2017)

I wrote these pages in 2013, after the Higgs discovery was announced in 2012. All of us working on the Large Hadron Collider, or affiliated with the particle physics in general, were intensely emotional. It was easy to put those thoughts on the paper then.

In the Fall of 2013, I started teaching physics at the University of Maryland, College Park, and these pages stayed in a forgotten folder on my laptop.

The 2016 U.S. election was an eye opener. The political news today shows signs of a tectonic shift in the U.S. policy and the public opinion on some very important issues. The departments of science, energy, and environment are already feeling the tremors.

In the last few years, the higher education and the demand for a rational argument have somehow become synonymous with elitism. Given the state of affairs, one has to worry about the response of the incoming representatives towards science in general, and towards the fundamental, basic science in particular.

So, here I am—adding my voice to my vote, however feeble it may be.

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Preface
(2013)

In July 2012, CERN announced the discovery of a new sub-atomic particle, the Higgs-like boson. This is the laboratory at the border of Switzerland and France, and houses the current largest particle accelerator in the world, the Large Hadron Collider, A few months later I gave a presentation at the Fermi National Laboratory, near Chicago, intended for the general audience, answering three questions:

- Why this discovery is important?
- Is it justified spending billions of dollars of tax-payer's money on such endeavors?
- What comes next? Is this the end of a science, or the beginning of a new era?

Answers to these questions involve exploring ideas in science that changed our outlook towards our universe and its physical appearance. These are the ideas that challenged our understanding of the nature of nature itself. Ideas that prompted Einstein to say,

God does not play dice.

It is impossible to convey the full beauty and the mystery of these concepts, and these pages by no means explore a full account of the relevant details. I have only followed a couple of threads in the complex and fascinating tapestry of the history of science, and even that very briefly. Above all, what you will find in these pages is my own feeling of awe at the realization of how wonderfully mysterious and magnificent this universe and our own existence is.

Answers to these questions also involve exploring selfishness of scientists. Do they really just want to do what they like to do, and not what really matters for the society? Worse, have taxpayers pay for this indulgence?

What is wrong with them?

This is a question I have been asking myself for a while now. Why I feel so strongly about the way I do about this sort of research? And why I am affected the way I have been by these ideas?

How can a dry graph of numbers can make people cry and weep with joy? What is it that makes some of us spend nights testing boring code? Or fixing experimental apparatus? All in the hope of a tiny glimpse into nature?

I am not the only one who feels this way.

Do the scientists want to explore nature for the sake of exploration, learning, and personal satisfaction? Aren't they interested in finding solutions to the huge problems humanity is facing today?

Are we really that selfish?

This has now become one of those deep questions about the nature of nature that I would like to know the answer to.

S. A. Jabeen

April 2013

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Part I

The Myth

Time-Traveling Higgs Destroys The LHC

The date is 19 September 2008, and the place is the border of Switzerland and France. The weather is a bit chilly. Mont Blanc is visible and beautiful, as it is on most clear days.

Just 9 days ago, the world's largest, the most complex scientific experiment started its operation.

For the inauguration ceremony, the French Prime Minister François Fillon and the Swiss President Pascal Couchepin were among the dignitaries. More than 60 countries have collaborated and contributed to the making of this extraordinary machine at CERN (the European Organization for Nuclear Research).

This instrument is called the Large Hadron Collider, or LHC, for short.

During the historic ceremony CERN Director General Robert Aymar declared:

> *Today is a day for CERN to thank its Member States for their continued support for basic*

> *science, and for providing the stable framework that makes science of this kind possible,*
>
> *It is also a day for CERN and the global particle physics community to take a sense of pride in the achievement of bringing this unique facility from dream to reality, a process that has taken over two decades of careful planning, prototyping and construction, culminating with the successful circulation of the machine's first protons in front of a global audience on 10 September this year.*

The LHC is, as the LHC Project Leader Lyndon Evans put it, the largest and the most sophisticated scientific instrument ever built:

> *We can now look forward to a new era of understanding about the origins and evolution of the universe.*

Our latest time machine was ready to take us on a journey to discover things no one has seen since the Big Bang, 14 billion years ago. A miracle of technology, more than 30 years in the making, and costing more than 4 billion dollars of taxpayers' money from America to Europe to Asia.

On September 10, the very first beam of sub-atomic particles, protons, was successfully directed around the 27-kilometer tunnel of the Large Hadron Collider.

That was just 9 days ago.

At midday, September 19, during the testing of the machine, an electrical failure caused a serious accident inside the underground tunnel, delaying the LHC operation by almost a year.

While this horrible incident was shocking and disappointing for most in the scientific community, to some this destruction was prophesied.

In the years leading up to the start of the LHC operation in 2008, for many the LHC and destruction were becoming synonymous.

Some people were worried about the radiation from the proton beams and the collisions. But an even bigger fear was that LHC will produce black holes big enough to engulf the whole world.

Or that it might produce some strange new particles that might render the earth lifeless.

Or that it could produce objects that could destroy matter, essentially destroying the world we know.

The LHC is perhaps the first scientific experiment that faced a lawsuit even before it started operating. In 2008, before the LHC turned on, Walter Wagner, a retired nuclear safety officer, along with a Spanish journalist, Luis Sancho, filed the lawsuit to stop the LHC. The lawsuit was dismissed due to a failure to show a *credible threat of harm*, by the judge.

Later, there were also claims that severe flooding in 2009 was also a direct effect of the LHC operation.

But perhaps the most interesting claim of destruction came from couple of physicists.

The story starts in July 2007, with a paper written by two physicists, Holger B. Nielsen and Masao Ninomiya. The paper was titled, *Search for Effect of Influence from Future in Large Hadron Collider.[1]*

In this paper they suggested,

We propose an experiment which consists of

> *drawing a card and using it to decide restrictions on the running of Large Hadron Collider (LHC for short) at CERN, such as luminosity, and beam energy. There may potentially occur total shut down. …….. Since LHC will produce particles of a mathematically new type of fundamental scalars, i.e., the Higgs particles, there is potentially a chance to find unseen effects, such as on influence going from future to past, which we suggest in the present paper.*

On 19 September 2008, only 9 days after the LHC turned on, the famous accident in the LHC tunnel took place.

During the powering tests of some of the circuits of the LHC, a fault in the electrical connection resulted in a release of tons of liquid helium (used to keep the magnets cool) into the tunnel. The escaping vapors expanded with an explosive force, damaging over thirty superconducting magnets and their mountings, and contaminating the vacuum pipe. Most of these magnets weighed more than 30 tons.

In Oct. 2009, Holger B. Nielsen, and Masao Ninomiya, came up with another paper, *Card game restriction in LHC can only be successful!:*

> *This previous work was concerned with looking for backward causation and/or influence from the future, which, in our previous model, was assumed to have the effect of arranging bad luck for large Higgs producing machines, such as LHC and the never finished SSC (Superconducting Super Collider) stopped by Congress because of such bad luck, so as not to allow them to work.[2]*

These papers caused a reaction, both from the scientific and the non-scientific community. The heading in the New Scientist read,

> *Time-travelling Higgs sabotages the LHC. No, really.[3]*

The New York Times reported with the heading:

> *The Collider, the Particle and a Theory About Fate.[4]*

The article goes on to say,

> *…. Sure, it's crazy, and CERN should not and is not about to mortgage its investment to a coin toss. The theory was greeted on some blogs with comparisons to Harry Potter. But craziness has a fine history in a physics that talks routinely about cats being dead and alive at the same time and about anti-gravity puffing out the universe….*

Until then, the Higgs boson, also known as the God Particle, was *the giver of life*, or of mass, to be precise. All of a sudden, it was now being cast as the Terminator.

Perhaps no scientific concept in the history has stirred such non-scientific emotions.

★★★

So, how this story ends?

Did the Higgs particle destroy the universe?

In case you haven't guessed the answer yet, the LHC was fully operational within a year. In 2010, 2011, and 2012, LHC detectors collected the data from the most energetic, controlled particle collisions ever produced in any experiment on earth.

These data were then used to discover the Higgs boson, the God Particle.

Since then a lot more data have been collected.

No side effects of the Higgs boson production have been reported so far.

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Part II

The Truth

Summer 2012—Physicist's Stone Is Found

The summer of 2012 was hot, in more than one way.

It was June 13. CERN was bustling with hushed excitement. The conference room 222 was packed with anxious scientists. Around four hundred individuals were assembled in a room meant for two hundred people. An even greater number of people were connected from around the world, via video link.

Two big projection screens were glowing on the front wall. People, who arrived early, were occupying the blue chairs. Latecomers were either standing near the back and along the sides, or, like me, sitting on the ground between the two aisles.

Chattering let up as soon as the speaker began her presentation.

Silence deepened with every new sentence. One slide after the other—everything looked excellent. Every assumption meticulously analyzed and every step methodically validated. Each piece fit with the other seamlessly.

Finally, the adrenalized speaker took a deep breath and asked,

Are you ready? Are you really ready?

The crowd broke into a nervous laughter.

With the trembling fingers, she pressed the clicker to move to the next slide.

And there it was.

A small bump on otherwise nearly smooth curve—like a pregnant belly—causing a collective gasp from the audience.

The gentleman sitting next to me sighed heavily with relief: *It hasn't disappeared.*

After a few moments of reflective silence, the hall erupted into joyous, exuberant clapping.

People were looking at one another—red faces, pounding hearts. It was undeniable, it was there—this little bump of ours was what we had been looking for, for decades.

This bump was undoubtedly one of the most beautiful things anyone of us had ever seen.

This bump could be the key to answering one of the most fundamental questions about our own existence.

This bump could be the Higgs boson or, as it is more commonly known, the God Particle.

Some people pretended to clear their eyes of invisible specks. Others were too absorbed in the moment to even pretend.

Some of us might even have felt the urge to go out in the streets of Geneva, shouting Eureka, Eureka—fully clothed, of course.

On July 4th, 2012, CERN officially announced the discovery of a Higgs-like boson. The unveiling of these new, long awaited, exciting, and invigorating results was relayed all over the world. Spokespersons of the ATLAS and the CMS collaborations presented details of their data analysis. They explained how they reached the conclusion that they had observed a sub-atomic particle that looked very similar to the Higgs boson we have been looking for.

At the end of the seminars the conference hall reverberated with thunderous clapping, whistles, and jubilant shouting.

As someone commented later, in that moment we were not physicists admiring the historical outcome of an experiment, or coming to age of a wonderful theoretical concept—we were fans cheering at a rock concert.

Peter Higgs, one of the scientists who developed the theory of the Higgs boson, and after whom this particle is named, was flown to CERN especially for this event. After the presentations, he was given the microphone to comment on the discovery. Though he did say a few words, his tears said much more.

Seeing his and others efforts over the last 40 years coming to fruition was an overwhelming experience. One can only imagine what he felt at that moment when he saw the bump that represented an abstract mathematical idea these scientists gave life to, decades ago.

After the two seminars, the director general of CERN got to the microphone for his remarks, and he commented on the hour-long presentations with only one sentence:

I think we have got it; do you agree?

His question was answered by another resounding round of applause.

Just two days ago, on July 2nd, Fermi National Accelerator Laboratory near Chicago had announced its summer results, also suggesting the presence of a similar particle.

It was incredible—four independent experiments in the world had observed exactly the same phenomenon. This was marvelous, even miraculous—but that is exactly how science is supposed to work.

With the observation of this small bump, a particle that in almost all respects looked and felt like the long-sought Higgs boson, humanity had taken yet another giant leap.

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In a press conference after the seminars, reporters from all around the world asked questions about the implications of this discovery.

During the conference, and in the days that followed, the discussion mainly revolved around two questions:

- What is so great about discovering the God Particle?
- Should we be spending hard-earned taxpayer dollars on such endeavors, which, apparently, are undertaken just to satisfy our curiosity?

These are the questions I am attempting to answer in the next pages.

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What Is All The Fuss About?

> *The Higgs went to a church and the people there told him,*
>
> *Oh, but you don't exist.*
>
> *Higgs smiled and said,*
>
> *If I don't exist how can you have Mass?*

Get it?

This is the joke my son told me during our stay at CERN in the midst of the Higgs boson discovery in summer 2012. It essentially sums up the whole affair.

One of the reasons this discovery is a big news is of course because scientists are saying so. We are claiming that this discovery is a very big deal. We are calling it a step forward for the human race, and comparing it with the other giant leaps that have changed humanity.

So, what is all the fuss about?

Let us start from the beginning.

Since the beginning of our time, human beings have tried to understand the world around, asked questions and have tried to answer those questions.

How everything came into being?

What is everything made of?

How this universe started? How it will end?

We know that human beings have tried to come up with answers to such questions since the beginning. The search for the fundamental elements, for example, is as old as our recorded history. We always tried to understand and explain the large variety of objects around us in terms of some basic elements. Even today, if you stand at the corner of a busy street, and ask people what are the building blocks of this universe? Some of them might answer: Earth, Water, Air, and Fire—from the age-old theory about the basic elements of matter.

We also understood that there are forces of nature at play. Long ago they were called the forces of love (attraction) and hate (repulsion).

Today we know quite a bit more about the universe around us. We have theories that are very successful in answering many of the questions.

So, what *do* we know?

As of today, we know there are four fundamental forces in the universe:

1. **The Electromagnetic** force holds atoms and molecules together making up the stuff around us. It is the force of attraction between the positive and negative charges, or the North and South poles of a magnet. It is also the force of repulsion between the

two positive or two negative charges, and two North poles or two South poles.

2. **The Strong** force is stronger than the electromagnetic force. It is strong enough to hold the same charge particles, which are electromagnetically repellant, inside the nucleus of an atom. Keeping the nucleus one piece. It is also the force that binds neutrons (electrically neutral particles) with protons inside the nucleus.
3. **The Weak** force is called weak because, well, it is weak. It is weaker than both the strong force and the electromagnetic force. This force is responsible for the processes inside the sun resulting in the sun's energy, and hence our existence on earth.
4. **Gravity** is the weakest force of all and, as you know, it makes apples fall on the ground—and, incidentally, keeps the rest of the universe from falling apart.

These forces provide sort of a glue that holds the matter in the form of the universe we see around.

Two of these forces, gravity and the electromagnetic force, have theoretically infinite range of influence. For, example, The distance between the earth and the sun is about 100 million miles, but even at this distance the gravitational force between the two is enough to keep the earth in an orbit around the sun.

The other two forces, the strong and the weak nuclear force, are effective only at very short distances. This distance is even smaller than the radius of an atom. This is one of the reasons their existence was discovered so late.

Just to put things in perspective, if the strength of the strong force is 1 then electromagnetic force is about 100 times weaker. And the weak force is about 10,000 times weaker than even the electromagnetic force.

Can you guess how weak is the force of gravity? A whopping 1/10000.... times weaker than the strong force, where "...." means 35 more zeroes.

Do you see the pattern here?

Great! You have made a big discovery—compared to gravity, all the other forces have similar strengths. Interestingly, it turns out that this pattern also shows up in the theoretical formulation used describe the interactions governed by these forces.

Saying gravity is week, sounds a bit strange because gravity is something most notable in everyday life and seems quite strong. It makes everything fall towards earth, and keeps a big object like the earth revolving around the sun. No other force seems to have such an effect.

But think about a small magnet that can pick up an iron nail from the ground— demonstrating clearly that the electromagnetic force of a small magnet is much stronger than the gravitational pull of the much, much larger object like our home planet.

Currently, as far as the theories that describe the physical phenomena in the universe are concerned, we live in two different worlds:

- A world involving the largest of structures: stars, galaxies, and clusters of galaxies.
- A world involving the smallest of particles: atoms, nuclei, quarks, leptons—all the smallest known building blocks of matter.

In the case of small particles, mass is so small that gravity has a negligible effect. This is a world that is described by the laws of quantum mechanics, and a theory called the Standard Model of particle physics, or SM. This is the world involving the other three forces.

In the case of large objects made up of zillions of particles, mass is immense and quantum mechanical effects average out at this level. This is the domain where the force of gravity rules. This aspect of the visible universe is described by the theory of general relativity and other theories included in the branch of physics like astrophysics and cosmology.

The Standard Model is one of the most successful scientific theories in the human history, and breathtaking in its predictions. When I say breathtaking, I really mean it. The accuracy with which this theory can predict the observed phenomena, is mind boggling—you sit there thinking that it cannot just be the outcome of some mathematical equations, rather, somehow, we are reading God's own mind. It is truly an awe-inspiring experience.

But even though it takes your breath away, this theory is incomplete.

Most importantly, this theory, in its purest form, has a huge flaw: all the matter particles in the theory that make up our universe, are mass-less.

What does this mean?

Mass is the property of matter, when combined with the effects of gravity, gives the weight of that matter.

You might be thinking, *Cool, if everything turns out to be massless, I do not have to worry about my weight anymore—finally a theory of physics that does something for humanity.*

Fortunately, or unfortunately, mass is an important property of matter. It is hard to imagine a universe like ours if nothing had mass.

So, this problem with the theory must be fixed.

Currently, the best this theory does to fix this problem, is to incorporate a mechanism to give masses to all the matter particles. This mechanism introduces a new field called the *Higgs field*, and a new sub-atomic particle called the *Higgs boson*.

The way it works is something like a hand shake.

Consider every single point in space, in all the universe, filled with these Higgs bosons. Every particle in the universe gets to shake hand with this particle—the firmer the hand shake, the more mass a particle gets. Simple as that. (OK, it is not as simple as that, but good enough for our purpose.)

This is the origin of the Higgs boson.

The reason it is called the God Particle comes from the fact that all the other particles get mass when they interact with it. This term was introduced by the Nobel Laureate, Leon Lederman, in his book with the same name:[5]

> *This boson is so central to the state of physics today, so crucial to our final understanding of the structure of matter, yet so elusive, that I have given it a nickname: the God Particle. Why God Particle? Two reasons. One, the publisher wouldn't let us call it the Goddamn Particle, though that might be a more appropriate title, given its villainous nature and the expense it is causing. And two, there is a connection, of sorts, to another book, a much*

older one ...

The Standard Model has been one of the most successful theories of our time. Its predictions have been tested to great accuracy. Including the *top* quark discovery in 1995 at the Fermi National Accelerator Laboratory, and the subsequent measurements of its properties since then.

After the *top* quark discovery, the Higgs boson was the only significant piece of the puzzle left that needed experimental verification. Given that this missing piece was the particle that supposedly gives mass to the rest of the matter, it was imperative that we find this particle.

This is the *Philosopher's Stone* the physics community have been looking for, for about half a century.

Our beloved Standard Model has been very successful, may be too successful, but there are questions that this theory does not answer.

Even if the particle discovered is *the* Higgs boson, the particle predicted by the theory, it still does not explain many of the observed features in the particle world. Including, Why the masses of particles are what they are? or How the observed mass of neutrinos fit in the bigger picture? as they are considered massless within the Standard Model. The theory is incomplete as it relates three forces, but leaves the fourth one, gravity, out. Then there are relatively recent experimental observations of *Dark Matter* and *Dark Energy* that are also not part of this theory.

To summarize, at this point, physics models are living in two different worlds: one exists on the atomic level, and the other works only on larger scale. Both described by very different theories—one not interfering or in need of the other, for the most part.

The thing is, these two theories are extraordinary. We have not observed one single experimental fact that could contradict, beyond any doubt, any of the predictions of these two theories. But they are incomplete in that they explain only parts of the observed universe.

If we want one single theory that can explain everything, from the smallest to the largest, we either need to combine these two theories, or need a fundamentally different theory to take their place. This so-called *Theory of Everything* is something physicists have been looking for, for a long time.

To put things in perspective, if the Higgs boson is the *Philosopher's Stone* that gives mass to everything it *touches,* then the theory of everything is the *Holy Grail* of physics, and knights like Einstein have spent part of their lives looking for it.

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With the Higgs boson discovery, we finally have the Philosopher's stone in our hand.

And this is exactly what the fuss is about.

If we discover the origin of mass, which at this point we think the recently discovered particle could be a key to, we would make a long stride in our search for the Holy Grail of physics. Many of the mysteries of this universe will start unraveling themselves.

Trying to understand the principal mechanism of this mysterious universe, and the underlying laws that give rise to these mysteries, is what is keeping thousands of people awake at night.

To understand the importance of this discovery and its place in our quest for the Holy Grail, let me take you on a trip down the memory lane.

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Little Bit Of History

Ok, I will not go through the whole history of physics here. The end of the 19th century sounds like a great place to start.

By the end of the 19th century, we already had very good understanding of most of the physical phenomena observed in everyday life. From the progress made in the fields of mechanics, thermodynamics, electricity and magnetism, and optics, a somewhat coherent picture of observable universe was emerging. And this picture was beautiful and simple:

> *Everything is made up of either (discrete) particles or (continuous) waves.*

The common belief at the time was that atom is indivisible. It has some movable parts, whose motion is responsible for the atomic spectral lines, but, on the whole, atom cannot be taken apart. This belief was held until the discovery of electron in 1899 by J. J. Thomson. It was evident that at least one part of atom, the electron, is separable.

The classical physics, as we now call it, was successful at explaining almost all the physical observations except a few.

One of the major insights of the classical theory was the understanding that all the branches of physics, previously considered mostly unrelated, in fact stemmed from only two basic ideas. All the physical phenomena that these fields of physics dealt with, could be either described by the atomic theory, or by the theory of fields.

On the whole, this scientific picture was quite successful in describing most of the experimental observations at the time. In fact, it was so successful that, in 1894, the prominent physicist, Albert Michelson, noted,[6]

> *It is never safe to affirm that the future of physical science has no marvels in store which may be even more astonishing than those of the past; but it seems probable that most of the grand underlying principles have now been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice.*
>
> …………
>
> *An eminent physicist has remarked that the future truths of physical science are to be looked for in the sixth place of decimals.*

Apparently, the only thing remained for the physicists to do was to make more precise measurements of what we already knew—there was nothing more to be discover.

At the time, it did not appear to be such an out of place statement as there were only a few observations that could not be explained satisfactorily using the current theoretical concepts. We could explain almost everything else. And the expectation was that, eventually, the same theoretical framework will bring us the solutions for these problems as well.

These few, unexplainable, observations could have been a small problem—only they were not.

Among the problematic phenomena observed were *Photoelectric Effect, Black body Radiation* and *Atomic Spectra*.

When light falls on a metal surface, it can make the electrons in the metal leave the surface of the metal. This is known as the Photoelectric Effect. According to the classical physics, this emission of electrons should only depend on how intense the light is, or how long it shines on the metal surface. Surprisingly though, it depended instead on the frequency of the incident light. Below a certain frequency no emission was observed, no matter how intense the light was.

A body that absorbs all radiations looks black, and hence is called a Black Body. When a black body is heated, it would radiate back all the radiation it has absorbed. The more we heat an object the hotter the radiation that comes out—like a hot iron rod that changes color with its temperature. According to the classical theory, the amount of the emitted radiations depends on the frequency of the radiation—the higher the frequency the greater the radiation emitted. This leads to prediction of arbitrarily high amounts of radiation at very high frequencies. But the observation of well-behaved distribution of the emitted radiation did not match such predictions.

And lastly, the observed atomic spectra were not what was expected from the classical physics. According to the wave theory, an electron, which is a charged particle, circling a nucleus, should radiate energy. That means its orbit would keep getting smaller, giving off a continuous range of emitted wavelengths. But the experimental observations disagreed with this picture.

The classical theory of physics, which regarded light as a continuous wave, could not account for these important observations.

This is where we stood at the end of 19th century.

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The beginning of the 20^{th} century was, as they say, the worst of times and the best of times.

This was the time in the history of physics when there were unexplained experimental observations, for which, the otherwise quite successful classical physics failed to provide a satisfactory explanation.

This was also the time when we experienced the two great revolutions—*relativity* and *quantum mechanics*.

These revolutions challenged us on multiple levels—from our understanding of space and time to our understanding of reality and causality. This is the time when debates of determinism and locality moved from the philosophical realm to mathematical notations. This is what led to Einstein's famous words:

God does not play dice.

The three problems mentioned above were solved in one leap—the quantum leap.

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The Quantum Leap

As the story goes, in 1875 a young man of 17 was seeking career advice. He was very enthusiastic about science and wanted to learn as much as he can about nature.

But to his surprise, and some disappointment, he was told that nothing significant was left to accomplish in the field of theoretical physics. There was nothing to work on except for the details. There is nothing left to discover, he was told.

The young man, one Max Planck, went ahead anyway, and discovered a new physics instead of looking for new discoveries in the old one.

Planck perhaps didn't realize at the time, but he had sown a seed that blossomed into a revolution. He had an insight that changed, forever, the way we look at our universe and our own lives.

Whether light is wave or particles, has been a subject of debate since the beginning.

Democritus, the first known person to use the word *atom*, believed everything including light was made of indivisible particles.

Aristotle, on the other hand, believed light is a wave.

Alhazen, the first scientist who described the reflection and refraction of light, and the operations of a pinhole lens, assumed light to be a wave.

The situation was still unclear even in the 17^{th} century. Newton described these natural phenomena of reflection and refraction using the particle nature of light. Whereas, Robert Hooke and Christian Huygens described these same observations considering light as a wave.

The debate was on, until, finally, Thomas Young in 1801 discovered that the light from the two close slits interferes. The resulting pattern of interference, being strictly a wave phenomenon, established the wave nature of light—putting an end to this discussion—at least for another century.

In 1860s, Maxwell's theory of electromagnetism presented light as electromagnetic radiation, which was a continuous medium or wave. This idea was one of the basic pillars of the classical theory of electromagnetism. Maxwell's theory for electromagnetic waves was successful experimentally—not leaving much room for further arguments on this topic.

The nature of light came under discussion again at the end of the 19^{th} and the beginning of the 20th century. The three unexplained problems were solved by establishing that light, after all, *does* behave like a particle.

In 1901, Max Planck published an analysis that succeeded in reproducing the observed the spectrum of the light emitted by a glowing object. He proposed that the energy of the radiation can be discrete rather than a continuum, and used this assumption to solve the black body radiation puzzle.

Only a few years later, in 1905, Einstein refined Planck's idea by proposing that it is the electromagnetic radiation itself that is quantized, and not the energy of radiating atoms. In other words, light is actually made of particles or small chunks or discrete packets of energy.

Einstein used this idea to explain the observed photoelectric effect (emission of electrons in response to light falling on a metal surface).

Notably, the most radical proposal in the Einstein's historic paper [7] was not the law of photoelectric effect, as his Nobel Prize of 1921 suggests. The more revolutionary idea was that light is made up of particles or quanta of light (we now know as photons).

This was the beginning of a revolution.

The inference that light is made of particles was not taken up at once. This was such a radical notion that most of the scientist of the time dismissed it. It was even remarked that Einstein has *missed the target* by proposing such an idea.

The difference between Planck and Einstein's approach was that Planck's quantization refers to matter or, more precisely, interaction of matter and wave where matter can emit or absorb radiation. Planck himself was fully convinced that what happens in vacuum is fully described by Maxwell's equations. In contrast, Einstein's proposal did not just refer to interactions, but challenged the notion of the wave nature of the electromagnetic field itself.

The resistance to this idea was rooted in the fact that the wave theory of light was already very well established, and verified to a great degree experimentally. Agreeing with Einstein meant throwing that all away.

Almost no one was ready for that radical step, not yet anyway.

On another front, the phenomenon of radioactivity was already discovered in 1896. In 1902, Ernest Rutherford and Frederick Soddy proposed that radioactivity in fact is a result of unstable atoms.

The next big blow to the classical concepts came in 1911. Rutherford, Hans Geiger, and Ernest Marsden performed experiments by shooting alpha particles from radioactive material on to a very thin gold foil.

Based on the observations in their experiments, Rutherford set up a model of atom. This was a model very much like a solar system.

According to Rutherford's model:

- Atom consists of a positively charged, heavy nucleus.
- Negatively charged electrons surround the nucleus.
- The most of the space inside an atom is empty.

Even though the early experiments established the preliminary validity of the Rutherford model of atom, it was soon clear that the model conflicted with the laws of classical physics.

According to classical physics, a negatively charged electron orbiting around positively charged nucleus would continuously lose its energy by emitting radiation. As a result, electron will spiral down into the nucleus.

This has fatal consequences—everything made of matter, including us, is not stable.

Just think about the possibility that you are sitting with your friend having a good time, and suddenly your friend starts to disintegrate. His electrons are radiating energy and falling into the nucleus, destroying the very building blocks we are made of.

In fact, if this were true, we wouldn't even get that far—we wouldn't even have the universe made up of atoms anymore. This of course is not the case, as you might have noticed by now.

Experimental observations pointed to this discrepancy as well. The observed emission spectrum from the Hydrogen gas was found to be discrete.

Rutherford's model was missing some vital piece of information about the way nature works.

That missing piece was found by Bohr.

It took Niels Bohr only two years to use the newly found concepts of light-quanta and re-define the atomic model in terms of quantum mechanics.

He published his revolutionary papers in 1913, in which he used his new model to describe the atomic structure of Hydrogen atom, and explained the emission of discrete atomic energy spectra.[8]

Bohr's model for an atom is like Rutherford's except that, according to Bohr, electrons would not radiate energy unless they jump from one orbit to another orbit. Bohr's model could calculate the orbits, and how many electrons could stay there.

By suggesting that the motion of an electron in an orbit around the nucleus is stable, and it only radiates quanta of light when it jumps from one orbit to another, Bohr could explain the experimental observations with remarkable accuracy for Hydrogen and singly ionized Helium (having one electron in the orbit, like Hydrogen, instead of two).

Bohr's new explanation replaced Rutherford's atomic model, and became the basis of what we now know to be the old quantum theory.

Bohr's theory had two main features: quantization of energy and indeterminacy.

According to Bohr, it was impossible to predict when the electron would jump from one stable orbit to another.

This is the first time we come across the notion of indeterminism in quantum mechanics—an unforeseen consequence of quantum mechanics, and a concept that has troubled physicists since then.

By the third decade of the 20th century, all the building features of quantum mechanics were clearly on the table, along with their consequences. This is when it occurred to many founding fathers of the theory that they have unleashed a monster. But the genie was out of the bottle by then. Soon it became clear that no matter how unbelievable these new ideas were, the theory was here to stay.

The direct experimental verification of the idea of light-quanta itself, however, did not come until a decade later when, in 1923, Arthur Compton confirmed the quantum nature of light.

Einstein was already convinced of the significance of the concept of light-quanta. In 1909, he stated,

> *It is my opinion that the next phase of theoretical physics will bring us a theory of light that can be interpreted as a kind of fusion of the wave and the …[particle] theory.*

Apparently, Einstein already understood where we were headed, only he didn't realize the full extent of its implications.

Compton's 1923 paper [9] includes results of an experiment in which he could scatter a photon off an electron, showing that indeed the quanta of light behaves like a particle with discrete values for energy and momentum. A part of that energy is then imparted to the electron, initially at rest. He measured the wavelength of the scattered photon by considering the photon a particle, and assuming conservation of energy and momentum in the process of collision. The measurement matched the theoretical predictions very nicely.

This important result was a confirmation of Einstein's radical idea, and won Compton the Nobel Prize for physics in 1927.

Louis-Victor de Broglie strengthened this idea further by generalizing Einstein's proposal, and formulated what we now know as the *de Broglie hypothesis*:

> *Not only waves have particle nature but all particles have wave like nature as well.*

When a particle, for example an electron, is moving in space, it has a wave associated with it and this wave has the same properties as any other wave.

The confirmation of de Broglie's idea came in 1927, from the experiments done by Clinton Davisson, Lester Germer, and George Thomson. In these experiments they observed the diffraction, a wave phenomenon, of electron beams from a nickel crystal—demonstrating the wave-like properties of particles for the first time. Soon after these experiments, similar observations were made by others using different materials.

De Broglie was awarded the Nobel Prize in physics in 1929, after his hypothesis was confirmed experimentally. Later, Thomson and Davisson shared the Nobel Prize for their experimental work as well.

During the same period, Wolfgang Pauli, introduced a new principle:

> *Two electrons with the same known quantum properties could not be in the same state (obit).*

This is called *Pauli's exclusion principle.*

This meant our current picture of electrons of same mass and charge occupying the same orbit, could not be correct. Unless electrons have another property, hitherto unknown, which, according to Pauli's exclusion principle, was different for the two otherwise similar electrons, allowing them to be in the same orbit.

Soon after, Ralph Kronig, G. Uhlenbeck, and S. Goudsmit separately proposed a non-classical concept for this property, known as spin (the direction of rotation).

Recalling this discovery 50 years later, Uhlenbeck wrote,[10]

> *How one student who was undecided whether to pursue a career in physics or history and another who had not taken his mechanics exam came to identify the fourth atomic quantum number with a rotation of the electron. …….*
>
> *…. Note that I do not use the modish words "revolution" or "breakthrough." It was really a consolidation of many lines of thought, which admittedly occurred in the rather short period say from 1923 till 1928, but which required about twenty years of preparation.*
>
> *It will be a great but very difficult task to write a proper history about this period. Sam is very skeptical about it and perhaps one must wait till more materials, (such as the letters of Wolfgang Pauli) become available.*

Spin of a particle is a quantum property which cannot be understood in classical terms.

In classical physics, a body of mass moving in a straight line, the *linear* momentum, *p,* is defined to be mass times velocity ($p=mv$).

A similar quantity is associated with a body moving in an angular motion, called *angular* momentum. For a spinning figure skater or a spinning top, we can calculate the angular momentum given the mass and the shape of the spinning object.

How this works for an electron?

This is something we have never encountered before in classical physics. We are talking about angular momentum associated with spinning of a particle that does not have a shape, as fundamental particles are considered point particles, with no shape.

So, what does spinning of a point in space mean? We have no idea. At least, I don't.

But, amazingly, we can physically measure this spin and, adding to the puzzle, this quantity itself seems to be quantized—electron spin can only have two values $+\frac{1}{2}$ and $-\frac{1}{2}$.

This proposal was revolutionary in that it meant there are properties of quantum systems that have no counterparts in classical physics.

That is, the theory of quantum mechanics is not a continuation of classical mechanics, or some other underlying theory, of which the classical physics is a limiting case—quantum mechanics is fundamentally different.

What could Pauli's new degree of freedom mean?

Since electron is a charged particle, its spinning would imply that the associated magnetic energy would have to be considered as well. Even though this concept could not be readily reconciled with the observations of the atomic spectra, but the most of the scientists of the time were convinced that this was the right way to go.

Even Bohr, who was originally skeptical, in a letter to Ehrnfest, wrote that he had become the prophet of the electron magnet Gospel.

Discrepancies with experimental observations were successfully explained within a year, when it was realized by Llewellyn H. Thomas that earlier calculations of this energy did not account for the relativistic effects. Once these effects were taken into account, the problem was solved.

The new theory was successful in solving many problems, but this early version of the theory did not explain everything observed in experiments.

Theoretically, quantum mechanics, with the Newtonian description of space and time, conflicted with special relativity. Even though, by that time, relativity was believed to be the correct description of space and time.

Experimentally quantum mechanics explained the emission spectra, but not completely.

Within the next few years, Bohr, Heisenberg, Schrodinger, Born and many others formulated what is now known as the modern quantum theory.

In 1925, Heisenberg, who was Bohr's assistant in Copenhagen at the time, proposed the first mathematical formulation of quantum theory.

The following year, Schrödinger presented an alternative formulation of quantum mechanics, in a more familiar form of wave mechanics. He gave a simpler picture of the theory. He assumed that an electron in an atom could be represented as an oscillating charge cloud, evolving continuously in space and time according to a wave equation.

Schrodinger's formulation of quantum mechanics provided the basis for at least visualizing what quantum mechanics meant.

By using the wave picture, we could now apply the concepts like position, time, energy, and momentum to a quantum mechanical system. Schrodinger's formulation attaches a wave-function, denoted by the symbol ψ, to every particle. We could now use wave mechanics to solve atomic and sub-atomic problems.

It turns out that the two formulations of quantum mechanics, given independently by Heisenberg and Schrodinger, were equivalent. Apparently, nature could only be explained by the same concept even when approached from different directions.

That same year, Max Born proposed a consistent, statistical interpretation of quantum mechanics. He suggested that the square of the absolute value of the wave function, $|\psi|^2$, expresses the probability to find the particle in a certain state.

Physically observable quantities in quantum mechanics are *probabilities*. Probabilities are all we can determine in any given experiment.

This was an earth-shattering consequence of quantum mechanics.

People were startled by the probabilistic interpretation of quantum mechanics. Schrodinger himself was taken aback by these unforeseen consequences, and was heard saying,

> *I don't like it, and I'm sorry I ever had anything to do with it.*

But it was clear that there was no escape—quantum mechanics and probabilities seemed to be the choice of nature.

Like many others, Schrodinger also admitted this. In a letter to Einstein he wrote,

> *God knows I am no friend of probability theory, I have hated it from the first moment when our dear friend Max Born gave it birth. For it could be seen how easy and simple it made everything, in principle, everything ironed and the true problems concealed. Everybody must jump on the bandwagon [Ausweg]. And actually not a year passed before it became an official credo, and it still is.*

As the story goes, Bohr and Heisenberg had fierce debates about interpretation of quantum concepts until they were fully exhausted.

Finally, Bohr left Heisenberg alone, and went to a ski trip to Norway. Within few days of being left alone, Heisenberg came up with his famous uncertainty relationship, which he presented in 1926.

To understand uncertainty principle, consider the following famous joke, which has gained popularity in the circles even outside scientific community.

> Heisenberg was driving when a policeman stopped him:
>
> *Do you know how fast you were going?* the policeman asked.
>
> Heisenberg answered, "*No, but I know 'exactly' where I am.*"

This is Heisenberg's uncertainty principle.

According to this principle, there are some pairs of observables; the more precisely you measure the value of one member, the less certain you are about the value of the other.

It is impossible to measure exact values of all the properties of a particle simultaneously.

The momentum (speed times mass) of a body and its position, constitute one such pair.

Take the example of an electron. You can observe the position of an electron by shining the light with small enough wavelength. But when the photon hits the electron, it changes electron's momentum. So, at that precise moment, you can measure the position as accurately as possible, but in doing so, the momentum of the electron has changed. And so, the more precisely you measure the position, less precise is the measurement of momentum, and vice versa.

The Heisenberg uncertainty principle is one of the most fundamental concepts in quantum mechanics. It has very interesting implications for the way everything in the universe behaves, including the vacuum, that is, empty space devoid of everything.

Like many other features of quantum mechanics, the exact interpretation of the uncertainty principle is still under debate. What we do understand is that these properties have inherent uncertainty, and because of that we can never measure them exactly, at the same time.

Just to be clear, this uncertainty has nothing to do with the precision of our experimental apparatus, but seems to be an inherent feature of nature itself.

Bohr's ski trip was not fruitless either. He came back with an important insight that, in Heisenberg's own words, *refined* the ideas behind his uncertainty principle:

> *Bohr has brought to my attention [that] the uncertainty in our observation …….is tied directly to the demand that we ascribe equal validity to the quite different experiments which show up in the [particulate] theory on one hand, and in the wave theory on the other hand.*

This insight is called Bohr's *complementarity principle* in quantum mechanics.

In his Como lecture in 1927, which was later published in Nature in 1928, Bohr puts the ideas of complementarity and causality in perspective:

> *The very nature of quantum theory thus forces us to regard the space time coordination and the claim of causality, the union of which characterizes the classical theories, as complimentary …*
>
> *….. the measurement of the positional coordinates of a particle is accompanied not only by a finite change in the dynamical variables, but also the fixation of its position means a complete rupture in the causal description of its dynamical behaviour, while the determination of its momentum always implies a gap in the knowledge of its spatial propagation. Just this situation brings out most strikingly the complementary character of the description of atomic phenomena which appears as an inevitable consequence of the contrast between the quantum postulate and the distinction between object and agency of measurement, inherent in our very idea of observation.[11]*

In the classical picture a particle is a particle (discrete) and a wave is a wave (continuous). In quantum mechanics, however, things are not that simple.

According to Bohr's revolutionary insight, in quantum picture, both the wave and the particle properties of an object are complementary. Both are needed to complete the picture, but cannot be observed at the same time, in the same experiment. Thus, in the quantum world, our knowledge about an object is limited.

Others, like Schrodinger, had their reservations on this topic, but Bohr, usually soft spoken, fiercely defended the idea.

As Heisenberg puts it,

> *Bohr, who was otherwise most considerate and amiable in his dealings with people. Now appeared to me almost as an unrelenting fanatic.[12]*

At this point, the debate between the reality, as seen in the everyday life (and expressed in the classical physics), and the lack of it in quantum mechanics, had become quite apparent.

The next few years mark a period in the history when Einstein and Bohr had legendary encounters and back and forth of ideas about the interpretation of quantum mechanics. Einstein would think of new experiments that could avoid the uncertainty principle or complementarity, and Bohr would come up with rebuttals.

But Einstein remained unconvinced. As he wrote to Schrodinger,

> *The soothing philosophy – or religion? – of Heisenberg-Bohr is so cleverly concocted that for the present offers the believers a soft resting pillow from which they are not easily*

> *chased away.[13].*

To which, Schrodinger replied,

> *Bohr wants to 'complement away' all difficulties.[14]*

From the ideas developed by Bohr, Schrodinger, Heisenberg, Born and others, a somewhat coherent version of quantum mechanics emerged. Since then there have been many modifications and interpretations. The most famous of these interpretations, however, remains the *Copenhagen interpretation*. The main postulates of this interpretation are:

- Wave and particle aspects are complimentary.
- For the outcome of an experiment, only probabilities can be determined.
- The state of a particle is given by the wave function ψ, and the evolution of this state in time is given by the Schrödinger's equation. This equation is like the equations of motion in the classical physics, which tell you how far your car will go in 10 minutes at a speed of 60 miles per hour.

Now think about these three statements, especially first two, and particularly, the middle one:

> *We can never be certain about the outcome of an experiment.*

This was something completely new.

In classical physics, given the equations of motion and the initial conditions, we can determine the evolution in the motion of a body on earth or of celestial objects in the sky. These equations could tell us exactly where these bodies would be after a certain time—with accuracy limited only by the uncertainties of our measuring devices.

Quantum mechanics, on the other hand, seemed to be founded on the principle that we can never have the full knowledge of any system—there will always be some ambiguity, some uncertainty.

The Copenhagen interpretation talks about particles' state when they are observed, but this interpretation says nothing about what the particle is doing when we are not *observing* it.

When not being measured or observed, a quantum system exists in a superposition of all the possible states it *can* exist in. This system evolves according to the time dependent quantum mechanics equation of motion.

However, when this system interacts with the experimental apparatus, its wave function, for the lack of a better word, *collapses*. From an observer's perspective, the state seems to *leap* to one of the basic states, acquiring the value of the property being measured. Not all the properties of a system can be measured with full certainty.

Take a few minutes and think about what it all means?

In 2002, a New York Times article, *Here They Are, Science's 10 Most Beautiful Experiments,[15]* cited a poll done by Physics World.[16]

According to the Physics World readers,

> *The most beautiful experiment in physics,…is the interference of single electrons in a Young's double slit.*

Galileo's experiments with falling bodies, came second.

In a double slit experiment, we let the light pass through two slits in a screen, and fall on a photographic film. The result is an interference pattern of alternating arrays of bright and dark bands, also called minima or maxima (like ups and downs in ocean waves).

No surprise here.

If light behaves as waves, and if the waves from the two different sources are made to interfere with one another, this is exactly what we should have observed.

When the same experiment is repeated with one slit closed, the alternating bands disappear and are replaced by one bright spot in front of the open slit.

No surprise there, either.

There is only one source of waves, so no interference is expected.

Let us now use a beam of particles, for example electrons, instead.

Surprise, surprise—they behave exactly the same as light—producing the interference pattern when made to pass through two slits.

Even more surprising—this pattern persists if we throw *one electron at a time.*

That is, one single electron at a time can produce a pattern of light and dark bands if the two slits are open—and no pattern if one slit is closed.

How is this possible?

The only way this is possible is if the single electron were passing through *both slits* at the *same time,* and interferes with *itself.*

Here lies the dilemma of quantum mechanics.

De Broglie told us that particles should have associated waves. So, if there were two electrons passing through two slits, their waves could interfere resulting in the observed pattern.

But how can this happen in case of one electron?

It is only possible if the electron was at two places at the same time.

Now, by Complementarity, we can either observe interference (considering the wave aspect of the electron), or we can know the exact path of the electron (considering particle aspect of the electron).

When closing one slit, we are certain which path the electron will take. But because of this very act of observation, or making sure that we know the exact position of the electron, the momentum measurement becomes completely uncertain, resulting in the absence of an interference pattern.

The two-slit experiment has been performed with electrons, neutrons and even whole atoms and molecules. Every time giving the same results.

Going back to the question, where the particle actually is at a given time—the square of the wave-function in the Schrodinger's equation gives us the probability of finding the particle at a given location. But while it is in motion, theory doesn't tell us which path or the full trajectory of the electron.

This is the crux of the matter.

We don't know what the electron is doing before we observe the interference pattern. As soon as we try to pin the trajectory down like closing one slit—we lose the pattern.

The mathematical formulation that explains the interference pattern, when we are not trying to see which slit the electron is passing through, is the same as when we assume that particles were passing through both slits at the same time.

Talking about the beauty of the double slit experiment, the article in Physics World, states,

> *The double-slit experiment exemplifies the wave–particle duality of light, as well as quantum physics itself. It demonstrates that light interferes with itself in passing through a pair of slits. It also shows that even single electrons – proceeding one by one – interfere. Richard Feynman is said to have remarked that it contains everything you need to know about quantum mechanics.*

About the double slit experiment, Feynman writes in his lectures,

> *We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery.*

✯✯✯

The theory of relativity and the ideas that led to quantum mechanics, started a revolution the likes of which we have not seen in science, either before or since then.

The idea that there are limits to the human knowledge, is the first lesson of quantum mechanics. A limit that has nothing to do with how precise our experimental apparatus is.

The basic ideas of physics were called into question by this new theory. Concepts that seemed to be on a concrete foundation before, like space, time, and causality, were challenged.

Einstein never believed that this was the case:

> *You believe in a God who plays dice, and I in complete law and order in a world which objectively exists, and which I in a wildly speculative way, am trying to capture.*
>
> *I firmly believe, but I hope that someone will discover a more realistic way, or rather a more tangible basis than it has been my lot to find.*
>
> *Even the great initial success of the quantum theory does not make me believe in the fundamental dice game, although I am well aware that some of our younger colleagues interpret this as a consequence of senility.[17]*

So, now the question is, does God really play dice?

Can we ever even know?

Maybe we are part of this cosmic experiment, and every time we try to determine the reality, the reality itself changes, just by the mere action of observation?

Many a great mind have lost their sleep thinking about this.

✯✯✯

Baby You Are Not Gonna Get It Tonight

And you will not be the only one.

In the last century, physicists and philosophers alike have spent countless nights awake, trying to understand interpretations and implications of quantum mechanics. Both in terms of what it means for our material world, and what its implications are for us as human beings.

And, in case you are wondering, they are all still contemplating.

Quantum mechanics is one of the most successful theories, if not *the* most successful theory, ever.

The predictive power of this theory, and the precision with which these predictions have been tested, is nothing less than miraculous.

One of Feynman's colleagues proposed an experiment to test whether quantum mechanics was a theory of nature, Reportedly, Feynman threw him out of his office (not literally, of course) saying,

> *Well, when you have found an error in quantum theory's experimental predictions, come back then, and we can discuss your problem with it.[18]*

But there is no denying that the theory itself is a challenge in terms of understanding what it exactly means.

The concept of probability and randomness, inherent in the theory, seems extremely counter intuitive to everyday experience.

It was and still is puzzling to anyone who tries to understand it.

Even before the theory of quantum mechanics started to take its current shape, a fierce debate about its interpretation was in full swing.

Given, the random and probabilistic nature of quantum mechanics, it was very hard to make a connection between the classical physics and the new theory. This made many, if not everyone, uncomfortable.

People who brought this new branch of physics to life, were, literally, fighting over its interpretation. Reportedly, Heisenberg broke into tears after one of the discussions.

Mathematics was (relatively) easy to establish, and a uniform way was adapted soon, but the interpretation of these mathematical concepts was another matter. There seemed to be a sharp contrast between these concepts and the everyday reality. Even the people leading this revolution had hard time believing its consequences and implications.

Before we can understand how drastically quantum mechanics changed our understanding, let us look at the universal rules in classical mechanics, which every system is supposed to follow—no exceptions allowed.

> *Determinism:* Once we know a system in one state (that is we know about all the external forces acting on it) we can completely and fully determine its state at some later time.
>
> *Causality:* Things don't just happen—there has to be a cause for something to happen.
>
> *Locality:* All objects are localized in space and time. Something is defined as a particle only when it can be assigned a specific space at a specific moment in time.
>
> *Non-contextuality:* The results of any experiment should be context independent. The act of observing or measuring the state of an object should not alter the outcome. There is only one unique outcome and that is what we should be able to observe.
>
> *Energy-momentum conservation:* Energy and momentum is always conserved in an isolated system.

Going back to Bohr's atomic model, one of the questions that Einstein had trouble with, as he stated in a letter to Born,

> *Bohr's opinion about radiation is of great interest. But I should not want to be forced into abandoning strict causality without defending it more strongly than I have so far. I find the idea quite intolerable that an electron exposed to radiation should choose of its own free will, not only its moment to jump off, but also its direction.[17]*

For an *electron* to decide, without any cause, what momentum and direction it is going to have, was very troublesome to many.

It is like us knowing our own future.

It is against causality—if you let causality go, that leaves a lot of room for miracles and magic.

The inherent random and in-deterministic nature of quantum mechanics is what has been the cause of a historical debate for about a century now.

Even the people who played a key role in the development of quantum mechanics, kept hoping to somehow avoid the uncomfortable features of the theory.

For example, Schrodinger kept trying to prove that waves were the real thing. He never liked the concept of probabilities either. Einstein, who proposed the particle nature of light, had hard time believing that nature can be random or probabilistic.

When Born came up with the concept of probabilities in quantum mechanical measurements—the question that *how probable is certain outcome of an experiment?* raised questions about the deterministic nature of the universe.

In his correspondence with Born, Einstein writes,

> *Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the 'old one'. I, at any rate, am convinced that He is not playing at dice.[17]*

The long debate between Bohr and Einstein on the meaning and interpretation of quantum mechanics has become a chapter of its own in the history of physics. They regarded each other with the highest respect, and were convinced of one another's brilliance and the deep understanding of the topics at hand. But they didn't see eye to eye when it came to the interpretation of the essential ideas of quantum mechanics.

Talking about contextuality and causality in quantum mechanics, Bohr asserted the dependence of an outcome of an experiment on the act of observation itself. In Bohr's own words,

> *On one hand, the definition of the state of a physical system, as ordinarily understood, claims the elimination of all external disturbances. But in that case, according to the quantum postulate, any observation will be impossible, and, above all, the concepts of space and time lose their immediate sense.*
>
> *On the other hand, if in order to make observation possible we permit certain interactions with suitable agencies of measurement, not belonging to the system, an unambiguous definition of the state of the system is naturally no longer possible, and there can be no question of causality in the ordinary sense of the word.*

He concludes:

> *The very nature of the quantum theory thus forces us to regard the space-time co-ordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively.*

Further explaining, Bohr draws a connection between quantum mechanics and relativity to their corresponding classical concepts:

> *Just as the relativity theory has taught us that the convenience of distinguishing sharply between space and time rests solely on the small-ness of the velocities ordinarily met with compared to the velocity of light, we learn from the quantum theory that*

> *the appropriateness of our usual causal space-time description depends entirely upon the small value of the quantum of action as compared to the actions involved in ordinary sense perceptions.*[11]

In fact, Bohr, as many physicists of the time, believed that there was a direct correspondence between classical and quantum physics, as he further notes,

> *The aim of regarding the quantum theory as a rational generalization of the classical theories led to the formulation of the so-called correspondence principle…… In pursuing further the correspondence of the quantum laws with classical mechanics, the stress placed on the statistical character of the quantum theoretical description, which is*
>
> *brought in by the quantum postulate, has been of fundamental importance.[11]*

This means, in general, when we are dealing with a large number of quanta (an ensemble), the quantum phenomenon should recover the classical values for these phenomena.

That changed in 1924, when Wolfgang Pauli proposed a new quantum rule of exclusion—no two electrons with exactly the same quantum properties can occupy the same quantum state, for example, in the same orbit around the atomic nucleus. This led to the proposal of a new quantum property for electrons, called *spin*. The reason one orbit around the nucleus can have two electrons, despite all the other properties being the same, is because their spins are different.

This new property, spin, has no classical analog.

This was a major blow to the efforts of those who were trying to keep the classical physics in correspondence with the quantum phenomena. It shocked most, if not all, including the people who helped shape the theory in the first place.

The last major effort to stick to the old picture of wave for the description of an electromagnetic field, came in the form of The Bohr-Kramers-Slater (BKS) theory. The proposal was to get rid of the two of the most sacred pillars on which our understanding of the world rested so far—the energy and momentum conservation, and the concept of causality.

As someone put it, desperate times call for desperate measures. But it was not meant to be.

The conservation of energy-momentum at the elementary level was experimentally confirmed by Arthur Compton and Alfred Simon the same year.[19]

Although these findings settled the argument partially—the main battle between Bohr and Einstein on the fundamental ideas of quantum mechanics was still to be fought.

1927 was an important year—two historically significant conferences were held that year.

The first one took place in Como, Italy. Here Bohr introduced his Complementarity principle for the first time to a larger audience. Again, staying within the classical description, he stressed,

> *... [the quantum of action] forces us to adopt a new mode of description designated as complementarity in the sense that any given application of classical concepts precludes the simultaneous use of other classical concepts which in a different connection are equally necessary for the elucidation of the phenomena.*

What are the implications of this principle?

We can never know everything about this world completely. We can only know a part of it at any given time. To know about the whole, we will need to do the experiment again, but by that time we would lose the information about the first part.

This new proposal by Bohr, renewed the debate on whether quantum mechanics is a complete theory or not.

The second memorable conference in 1927 was the Fifth Solvay meeting held in Brussels.

It was a physics red carpet event. Everyone who was anyone, was there. Einstein, Planck, Bohr, Heisenberg, Dirac, Schrodinger, Born, de Broglie, Ehrenfest, Pauli, and Lorentz to name a few.

In the meeting, Einstein voiced his criticism quite openly:[20]

> *I have objections to make ... If* $|\psi|^2$*, were simply regarded as the probability that at a certain point a given particle is found at a given time, it could happen that the same elementary process produces an action in two or several places on the screen. But the interpretation, according to which* $|\psi|^2$*, expresses the probability that this particle is found at a given point, assumes an entirely peculiar mechanism of action at a distance, which prevents the wave continuously distributed in space from producing an action in two places on the screen.*
>
> *In my opinion, one can remove this objection only in the following way, that one does not describe the process solely by the Shrödinger wave, but that at the same time*

> *one localizes the particle during the propagation. I think that Mr. de Broglie is right to search in this direction. If one works solely with the Shrödinger waves, interpretation ... of $|\psi|^2$ implies to my mind a contradiction with the postulate of relativity.*

That is, if a particle, which we think of as taking up a small volume in space, is represented by a wave, which we consider to be extended beyond its volume, then, upon observation, why this *wave* collapses at one single point?

And when that collapse happens how the information of that collapse is conveyed to all the other parts of the wave so that we don't see particle manifestations at the other points?

This information or message is transferred to all points instantaneously, defying basic principles of relativity.

After seeing its experimental success, Einstein became convinced that the theory was correct, but he maintained that the theory in its current form is incomplete. He proposed that the reason we cannot determine all the properties fully, at the same time, as is the case in classical mechanics, is not because of some fundamental limitation, as implied by the uncertainty principle and the complementarity argument. The reason we cannot determine all the properties of a system is because there are some *hidden-variables* that we are not accounting for.

Einstein believed once the theory includes those variables as well, everything will be deterministic again—just like in the classical physics. Just like we can tell where exactly the earth is around the moon, we will be able to tell where exactly an electron is around the nucleus at any given time.

To understand the concept of hidden-variables, consider the following example: when we throw a dice, the outcome is supposedly random—we cannot tell which way the dice will fall. All we can do is calculate the probability of getting a certain number, which, if the dice is not tampered with, would be 1/6.

But is it really random?

The answer is *no*.

If we know the exact initial position of the dice, the angle at which the dice is thrown, the speed, friction of air etc. etc., that is we know values of all the variables involved in the movement, we can tell, with hundred percent surety, which way the dice will fall.

The calculation is difficult but, in principle, can be done.**[**21**]** (Of course, you would not be allowed 50 miles around Vegas, if you could do that calculation easily.)

Similarly, according to Einstein, the hidden-variables are needed to define the full reality of a quantum situation—only we just don't know how to account for them—hence the limited knowledge.

In 1935, Einstein's rejection of these ideas was formally described in, now very famous and perhaps the most amazing attack on quantum mechanics to date. The Einstein-Rosen-Podolsky (EPR) paper,[22] or the *EPR paradox*, proposed a thought experiment to prove their point.

This is how the paper begins:

> *In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system.*
>
> *In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then*

> *either (1) the description of reality given by the wave function in Quantum Mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false.*
>
> *One is thus led to conclude that the description of reality as given by a wave function is not complete.*

Authors of EPR paradox further argue,

> *If without in any way disturbing a system we can predict with certainty...the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.*

In other words, in ideal conditions, act of experiment or observation, e.g. looking at the moon, only reveals the state in which the moon is in reality at that time, without disturbing or changing (and certainly creating) this reality.

The idea is something like the relationship between thermodynamics and statistical mechanics. Thermodynamics describes phenomenon involving observable quantities like pressure, temperature, and volume. Statistical mechanics, on the other hand, gives the description of the same phenomenon but at a deeper level that is hidden from our eyes—from motion of atoms and molecules.

A simpler example could be studies in genetics by using the apparent traits of pea crops compared to the results based on the study of genes.

One could argue that, similarly, quantum mechanics is incomplete, and there is some more fundamental theory which will predict everything with certainty, without any ambiguity.

The EPR paradox makes two main assumptions.

The first assumption is about the reality of our own world—the world is real, and this reality is objective. A system is in a definite state even before we make the observation, and the observation is not context dependent, just as in the classical theory.

The second assumption is about locality. The EPR thought experiment claims to measure two complementary properties simultaneously, to an arbitrarily high degree of accuracy—something that quantum mechanics prohibits at all.

Consider two particles produced such that their spins (the direction of the axis about which the particle is rotating) are produced in a process that demands that these spins are pointing in the opposite directions. Now let us assume both particles are sent to two detectors, one closer to home, and the other on some distant planet. Since we know that particles have been produced with opposite spins, if the detector on earth detects one particle with spin up, we instantly know that the other particle is spin down. Now the observation of the particle in the detector on earth can have influence on that particle, but it cannot possibly have influenced the particle far away (condition of locality). Once the detector on the far planet does make a measurement we will hear it was opposite to the particle spin found on earth, as we already guessed.

Conclusion: the other particle must have spin down even before we started the detection or observation process. Thus, reality already existed even before we made the measurement on the far planet—contrary to the tenets of quantum mechanics.

Bohr responded to EPR paper in a letter to the editor of Nature, titled *Quantum Mechanics and Physical Reality.* In his rebuttal, he again brought up the need to give up the ideas of causality and realty in the classical sense:

> *Indeed the finite interaction between object and measuring agencies conditioned by the — very existence of the quantum of action entails because of the impossibility of controlling the reaction of the object on the measuring instruments if these are to serve their purpose —the necessity of a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality.[23]*

Now compare this situation with a classical example. For Christmas your mother bought two, exactly same sweaters, but in different colors. She sent one to you and other to your sibling. Until you opened your box, you had no idea who got which color? But as soon as you open the box, not only you know exactly which color you have, but you also know instantly which color your sibling got.

No surprise there.

In the classical case, we know the reality already exists. The sweater did have a specific color all the time. Our ignorance is only because we didn't look at it. But our *looking* at it doesn't have any effect other than increasing our own knowledge. The reality did not change.

Quantum mechanics, in contrast, tells us that it is meaningless to talk about a particle's real state (color of the sweaters) until it is observed.

In quantum mechanics, it is impossible for you to know a particle's state before it has been observed (color of your brother's sweater). There is always a possibility that one observation can affect the other—but for that to happen, we will have to let the condition of locality go.

That is, accept that something can travel with a speed greater than the speed of light, forbidden by our beloved theory of relativity.

The conclusion of EPR paper was that the objective reality *does* exist, only quantum mechanics cannot tell us because in its current form it is incomplete.

What is missing?

The hidden-variables—needed to describe the reality. Once we know these hidden-variables, we would be able to predict every outcome with full certainty, that is, with 100% probability.

So, now either we can say that quantum mechanics is incomplete, which was the view of many, including Einstein, or the theory is not incomplete, but the term *objective reality* needs revisiting—a point of view maintained by the team Bohr.

Now that many experiments have confirmed this theory, it is not just about the nature or interpretation of one theory, but the nature and the reality of nature itself.

This discussion continued for 30 years. The two camps kept firing their arguments at one another, but it was not something more than a philosophical discussion. Until John Bell put a stop to it in 1964.

John Bell's famous paper, *Bertelsmann's socks and the nature of realty,* starts with the following statement:

> *The philosopher in the street, who has not suffered a course in quantum mechanics, is quite unimpressed by Einstein-Podolsky-Rosen [EPR] correlations. He can point to many examples of similar correlations in everyday life. The case of Bertlmann's socks is*

> *often cited. Dr. Bertlmann likes to wear two socks of different colours. Which colour he will have on a given foot on a given day is quite unpredictable. But when you see that the first sock is pink you can be already sure that the second sock will not be pink.*
>
> *Observation of the first, and experience of Bertlmann, gives immediate information about the second. There is no accounting for tastes, but apart from that there is no mystery here. And is not the EPR business [regarding quantum correlations] just the same?[24]*

Bell, very carefully, scrutinized logic behind the claims of hidden variables, and came up with his own arguments, now collectively known as Bell's theorem.

According to Bell's theorem, if certain predictions of quantum mechanics are correct, it means our world is non-local. That is, if quantum mechanics is the theory of nature, then it is possible, at least in some situations, for information or influence to travel at a speed that exceeds the speed of light.

Bells' theorem provided an extraordinary opportunity to test Einstein's claim of reality and locality.

Reinhold Bertlmann, whose socks are mentioned in Bell's paper, wrote few years ago,

> *John's profound discovery was that locality was incompatible with the statistical predictions of quantum mechanics.[25]*

The beauty of Bell's theorem is that it is completely general, and makes it possible to test and experimentally compare the theory of quantum mechanics to any other theory.

Such experiments have been proposed and performed. First of these experimental tests of this theorem took two decades, and were performed by Aspect et-al in 1982.

In these experiments entangled pairs of particles are used to test the Bell's in-equality, whether it is violated (quantum mechanical predictions) versus if it is not violated (local hidden variable theories).

Spoiler alert, the results agree with the predictions of quantum mechanics.

These experiments have settled the matter without any significant doubt. Theories with the classical concept of reality, and consistent with relativity, cannot explain experimental data. quantum mechanics on the other hand does.

This theorem, as you can imagine, has been under intense debate. The experiments that confirmed this theorem have been challenged, and the experimental setup and the assumptions made in these experiments have been under intense scrutiny. These experiments have been repeated many times. So far, no significant deviations from the original results (in the favor of quantum mechanics) have been reported.

Bell's theorem and its experimental confirmation has far reaching consequences, as was noted after another repeat of these experiments:

> *The results fulfill a long-standing goal, not so much to squelch any remaining doubts that quantum mechanics is real and complete, but to develop new capabilities in quantum information and security. A loophole-free Bell test demonstrates not only that particles can be entangled at all but also that a particular source of entangled particles is working as intended and hasn't been tampered with. Applications include perfectly secure quantum key distribution and unhackable sources of truly random numbers.[26]*

So, what is the end result?

Quantum mechanics does not provide us the full picture of reality as we are used to seeing in classical physics.

The question is, should we be expecting such an objective reality to begin with?

Bohr insisted that the complementarity principle does not mean that quantum mechanics is incomplete—it merely points to an inherent quality of nature itself.

What is the correct interpretation of quantum mechanics? It is unclear. From the mathematical formulation we have, we do understand that this is just a tool and cannot be interpreted literally to specify the state of a quantum system. It is only the final measurements, along with the context in which they have been measured, that make sense in the real world.

Although Copenhagen interpretation is by far the most famous interpretation of quantum mechanics, it is not the only one. What is the correct interpretation of quantum mechanics, is a hot topic even today.

These days, many of the particle physicists appear to be convinced that right interpretation of quantum mechanics involves *Many Worlds theories*.

That is, every possible outcome of an event is materialized, just in different universes. There is no uncertainty—everything is fully determinable again.

It means in the morning you get up and decide to wear a white T-shirt. But you could have equally decided to wear a red one. Well, the Many Worlds interpretation tells us that you *did* decide to wear the red T-shirt, just in another universe. There are infinite possibilities of an event happening, and each possibility does become reality, just in a different universe. That is, there are infinite universes.

I wonder if many world theories are any less mysterious or more explainable than quantum mechanics?

I also wonder whether Einstein would have liked this idea better than quantum mechanics?

The situation of entangled particles, particles whose fates are connected with one another no matter how far apart they are, raises some interesting thoughts. Do we have any way of knowing that we are not entangled with something else far away? Will our observations ever reveal that this is the case or not? Could it be that everything is somehow connected to everything else, in some way, we just don't know the connection?

Be it quantum mechanics with its uncertainty and randomness, or Many Worlds theories with their own quirks—these theories raise a lot of questions about the fundamental reality of our universe (or universes).

Sometimes questions about the reality of reality become overwhelming. People then find it easier to work with questions that can be answered in the known mathematical frameworks, and the results and predictions of those calculations can be experimentally tested. Without worrying about the correct interpretation of the underlying ideas. This attitude is expressed by a little phrase: *shut up and calculate*.

As an experimentalist, I can certainly admire the shut up and calculate approach. For us the reality is what we observe. If we can't calculate and measure something, the actual reality is basically irrelevant.

But is *shut up and calculate* the attitude founding fathers of these amazing theories followed themselves?

Of course not. Otherwise we wouldn't be where we are today.

As an aside, I have heard that the phrase was coined by none other than Feynman himself, and I always had hard time believing that. Given the diverse and the novel ideas he came up with, how could have Feynman promoted such an attitude towards research. Anyone familiar with Feynman's work would have hard time believing this.

Then I came across an article *Could Feynman Have Said This?* by N. Mermin, a professor of physics at Cornell University. Apparently, Feynman did not say that, and I am happy to know this.

I do agree, however, that sometimes, to make progress, one should move aside questions like *what is the reality of reality?* and stick to mathematical models that can provide us better understanding, even if not deep enough, for the moment. May be that is what Feynman meant as well.

Talking about the reality of reality, here is another idea: may be the concept that the only way to achieve knowledge is through calculations and measurements is to be abandoned. But then the question arises, what other do tools we have? Einstein believed there was a better, complete theory out there, but it might be completely different from our current, most successful theory. In exactly the same way as quantum mechanics was conceptually completely different from the theories of its time.

But in order to continue our story, let us shut up and calculate, for the time being.

★★★

Quantum mechanics was a risky idea, but even with all the bold and puzzling concepts, it has stood the test of time.

The debate about the reality of reality is on, even today. In the early decades of the development of quantum mechanics, this debate was at its height among the best brains we have ever seen in science.

Niels Bohr expressed his feelings about the theory:

> *Those who are not shocked when they first come across quantum theory cannot possibly have understood it.*

Richard Feynman said,

> *I can safely say that nobody understands quantum mechanics.*

And Murray Gell-Mann echoed similar feelings:

> *Nobody feels perfectly comfortable with it.*

The mystery of the nature of reality doesn't just keep physicists awake. Kant noted,

> *..... not only are the drops of rain mere appearances, but that even their round*
>
> *shape, nay even the space in which they fall, are nothing in themselves, but merely modifications of fundamental forms of*
>
> *our sensible intuition, and that the transcendental object remains unknown to us.*

So, if you didn't get it, rest assured you are in good company.

By the way, if you are having trouble sleeping, and you already know about *Schrodinger's Cat*, have a look at the *Quantum Violation of the Pigeonhole Principle.*[27]

☆☆☆

Theory Of Everything

> REVOLUTION IN SCIENCE
>
> NEW THEORY OF THE UNIVERSE
>
> NEWTONIAN IDEAS OVERTHROWN

This is the sensational headline The Times ran on 7 Nov. 1919. The accompanying headline from The New York Times read:

> LIGHTS ALL ASKEW IN THE HEAVENS;
>
> Men Of Science More Or Less Agog Over Results Of Eclipse Observations.
>
> Einstein Theory Triumphs.
>
> Stars Not Where They Seemed Or Were Calculated To Be, But Nobody Need Worry.

The Time magazine elected Einstein the Person of the Century.

The theory of relativity, despite all its complexity, won popularity with the public, making Einstein one of the very few scientists who enjoyed the status of a rock star.

Quantum mechanics, on the other hand, and the people involved in its development, did not enjoy such quick stardom.

One reason perhaps is that compared to heavenly bodies, which everyone can see, or at least imagine, quantum mechanics talks about the spooky quantum action, and objects the size of billions of times smaller than the width of human hair. (Reminds me of Whoville, a whole city inside a snowflake.)

Another reason is, of course, quantum mechanics does not feature a single rock star, but a whole band of them, who refined details of this theory over decades.

It is sad that most people have not heard many of the names that were essential in bringing to life the ***theory of (almost) everything*** that is ***visible*** to us in this universe.

I think the only time quantum mechanics came close to the above 1919 heading on relativity, was the discovery of the Higgs boson. And the Higgs boson perhaps owes its popularity to the famous (or notorious) nickname, the God Particle.

The development of quantum mechanics was a beautiful and intense tango between theory and experiment.

It is clear that we couldn't explain everything using the classical picture of matter and waves.

But why did we choose something that just gives us probabilities, and tells us that there is uncertainty attached to every measurement we make?

Answer is that we were forced by nature—quantum mechanics explained puzzles of the time.

It is the best tool we have to describe the workings of our universe. The only theoretical concept and the mathematical formulation that could explain the observed phenomena like the black body radiation, photoelectric effect, or the atomic spectra, was the one that came with these inherent properties of probability and randomness.

We have learned that the formulation of quantum mechanics, combined with the theory of relativity, and the theory of fields, describes most of the observed world around us.

Note that I used the word *describes* and not the word *explains*.

Today, we are very comfortable, at least in terms of the mathematical formulation and its experimental validation. So much so that we use the inherent uncertainty in quantum mechanics to predict new particles—through their effects in virtual production of particle pairs, only allowed to exist for a very short time, through the uncertainty principle.

Continuing our story from the last chapter, successful as it was, the quantum mechanics of Bohr and Schrodinger did not solve all the problems. There were still observations that could not be explained by this theory. Also, by the 1920s, the theory of special relativity was already established as the correct theory of space and time. But Schrodinger's formulation of quantum mechanics did not take special relativity into account.

Paul Dirac was the first one to come up with a theory of quantum mechanics, which was compatible with special relativity. He published his revolutionary paper on the subject, *The Quantum Theory of the Electron,* in 1928.[28]

His new theory predicted anti-electron.

Wait, what? You ask.

Well, a mathematical theory is exactly that—mathematics. To make a new theory, you start from already established rules and facts and then try to mix in new ideas.

The rest is just addition, subtraction, and division of numbers (OK, it can be little more complicated, but still these are standard mathematical ideas, mostly).

A good theory should have two properties:

- It should be able to explain phenomenon already observed.
- It should predict new phenomena that are experimentally testable.

Once you have a mathematically sound theory, you can't pick and choose.

That is, if your theory predicts ten different phenomena, but only five of those can be experimentally verified, you can't just throw other five, non-existent predictions out.

If a theory predicts something and this prediction is not prohibited by some specific rule, it *must* exist.

This is a very tight requirement—one that has put many new theories in trouble, which predict a large number of exotic spaceships along with your trusty GM and Honda. People invent mathematical concepts and theories all the time, but only those remain on the scene that fulfil above two rules.

In Dirac's case, his theory was predicting the presence of another particle, just like the electron, but with opposite charge (negative energy, to be precise).

The problem was, no such particle was known at the time.

Dirac tried very hard to give some explanation or to get rid of this part of the theory, but none of the solutions was satisfying.

Until 1932, when C.D. Anderson discovered exactly such a particle in the laboratory.

Today we know this particle as Positron, and this was the first but not the last particle discovered that was predicted by a theory first.

Of course, this was a great triumph for quantum mechanics and theoretical physics. Dirac and Anderson were awarded Nobel Prize for the prediction and discovery of anti-electron.

Max Born, after learning of the Dirac equation, reportedly said,

> *Physics as we know it will be over in six months.*

We now know Born was correct. This was the beginning of a new era in physics and our current, successful quantum theories are all essentially built on Dirac's theory.

Let us add another rule to the game, that every theory must obey:

> Everything that is possible will happen. Unless something is explicitly prohibited, it is not only allowed but *should* exist.

If a theory claims to explain nature, then every phenomenon that is possible in that theory, and is not prohibited explicitly by some rule, will be part of nature and should be experimentally verifiable.

In the context of anti-electron, it means that all other particles should also have their anti-particles. And if every particle has an anti-particle, we should expect to see those and anti-atoms and anti-molecules.

And why stop there, we might even have anti-you and anti-me, and, even an anti-earth, so on and so forth.

But this is not what we see. A fact, I am very thankful for, because if there was as much anti-matter as matter there wouldn't be anyone or anything left (except for the light resulting from matter-anti-matter annihilation).

A particle and an anti-particle are identical, except for a few properties. One of the things that would be different, for example, is electric charge. If a particle has an electric charge Q, then the anti-particle has the opposite charge of $-Q$.

In the case of the proton, its positive charge distinguishes it from the negatively charged anti-proton. The neutron, although electrically neutral, has another property called magnetic moment, which is opposite to that of the anti-neutron.

As far as our models of the universe are concerned, the physics processes are, for the most part, exactly the same for particles and their anti-particles. Modern theories of particle physics and of the evolution of the universe suggest that anti-matter and matter were equally common in the earliest stages of the formation of the universe.

Then where is all that anti-matter?

We know it is not nearby, or we would have been annihilated by now. So far, we haven't found any evidence of some far away regions of anti-matter in the universe either.

The anti-particles we have are produced in the particle production and decay processes. If not actively contained, they will quickly annihilate with their particle counterparts.

No matter what the Sci-Fi thrillers tell you, it is not at all easy to create, accumulate and store anti-matter.

Take an example of production of anti-protons. In our current scientific facilities like CERN and Fermilab we can produce anti-particles every day—millions of them every second.

But the number of atoms we need to make up a single gram of anti-protons is about 10^{23}. Given our current rate of production, it will take billions of years to produce even this amount. It is extremely difficult to store this amount in a fully equipped laboratory, let alone pouring it in a handy flask, and taking on a plane ride above Rome.

By the 1930s, we had an almost understood picture of atom. quantum mechanics and special relativity were also well established by then and, with Dirac's equation, we had a formalism to describe the motion of a free quantum particle.

One of the mysteries, however, was the emittance of electrons from the atomic nucleus (also known as beta decay). These electrons had a continuous energy distribution contrary to the expected discrete values for energy.

Wolfgang Pauli suggested that this continuous spectrum of energy for electrons could be explained if another invisible, massless particle was emitted along with the visible (detectable), massive electron in the decay. Pauli called this particle neutrino (little neutral one). The direct detection of this new, invisible particle took another two decades, however.

So far so good.

The atomic model seems in place. We have discovered protons, neutrons, electrons that make up the atom, and, in turn, our material universe. Beta decay is not a puzzle anymore, and we have an equation of motion (Dirac's equation) for quantum particles, compatible with the theory of relativity.

These tools led to the first, and perhaps the most successful theory in the world, the theory of *Quantum Electro-Dynamics* or QED for short.

Starting from Dirac's equation, QED is essentially quantum version of Maxwell's classical theory of Electrodynamics. This theory describes processes that involve electric and magnetic interactions.

With the successful formulation of the theory of Quantum ElectroDynamics, we had the recipe of making theories about interactions involving other known forces. This recipe includes quantum mechanics, relativity and fields, and we call it *Relativistic Quantum Field Theory*.

Initially the thinking was that there are still questions, but perhaps the tools we already have in the box would eventually find the answers.

By the mid-1960's, developments in the experimental techniques resulted in the discovery of a number of new particles. No one had any idea why all these particles are part of nature, given that the whole visible and stable universe (made up of atoms) can be reconstructed using just protons, neutrons, and electrons, and of course, photons (light).

Turns out, this onion had another layer.

Nature has an elegant plan.

Physicists realized that nature was not producing these particles randomly, but that they were being produced following specific patterns or *symmetries*.

This was a breakthrough.

As soon as the concept of symmetry was included in the recipe of theory making, things started to fall in place.

Based on the concept of symmetry, in 1964, Murray Gell-Mann and George Zweig put forward a new idea—the building blocks that make up our atomic nucleus, namely neutron and proton, are made up of even smaller particles themselves.

Different combinations (following specific symmetry) of these smaller particles could result in the composite particles we were observing, but didn't know where they were coming from.

This was it.

Except, there were a couple of problems.

If these smaller particles really exist, where are they? Because we have not observed anything that fits the description.

Also, if there were three of them making up a proton, how could three matter quantum particles occupy the same state, which is forbidden by the Pauli's exclusion principle?

The same year O.W. Greenberg came up with the idea that quarks perhaps have a new quantum property, termed *color charge*. It is this property that makes three quarks exist inside the proton. Soon after, M.Y. Han, and Y. Nambu proposed the underlying symmetry corresponding to this new quantum property.

Every quark, for example the *up* quark, comes in three *colors*, *red*, *blue,* and *green*.

Just to clarify, we have never observed a single quark up close to see its color—this *color*, is just another way of differentiating particles with different properties.

This new property of *color* explains why individual quarks cannot be observed because all observed particles are color neutral.

What is *color neutral*?

If we combine particles with these three colors, the resulting particle would be color neutral. For example, a proton. Or we can also make particles with combinations of a certain color and its anti-color, for example another particle called *pion*.

The reason we don't see single quarks like single electrons or protons, is because it is impossible for us to provide enough energy to separate a quark-anti-quark pair. If a quark and an anti-quark start moving away from one another, the energy between the two quarks increases. And, in accordance with Einstein's equation $E=mc^2$, this energy converts into additional pairs of quarks, such that the total color is always neutral. These additional color-less combinations form *jets* of particles that can be observed in the particle detectors.

A good analogy perhaps would be the example of a broken magnet. If you try to isolate a magnetic pole by stretching a dipole, the magnet breaks down and two new poles appear at the breaking point.

Initially it was thought that all new particles are made of three quarks, named *up*, *down* and *strange*. (I have no idea why the first two are named what they are, but the third one has a good reason to be called strange.)

In the absence of the direct measurements, the properties of these new particles were postulated such that their proper combinations could explain properties of particles observed in nature.

For example, a proton is made up of the two *up* and one *down* quark. Since we have already given proton one unit of charge, 1*e*, each of the three quarks will have to have charge in the units of one third, or $^1/_3\ e$.

How many particles we have talked about so far, that our universe seems to be made of?

As of now, we have two kinds of fundamental building blocks of matter—*Leptons* and *Quarks*. The quarks are the *up (u), down (d), strange (s),* we just talked about, and Leptons are the electrons, muons, etc.

Soon after, these categories of elementary particles were established, people realized that there were uncanny similarities between the types of quarks and the types of leptons. By that time, we already knew about four types of leptons, electron *(e)*, muon (μ), and their corresponding neutrinos $(\nu_e$ and $\nu_\mu)$. Several physicists proposed a 4th quark and the formal theory was presented by Glashow, Iliopoulos, and Maiani. Along with proposing a new quark, they also noted the symmetry between quarks and leptons:

> *We wish to propose a simple model ………. Our model is founded in a quark model, but one involving four, not three, fundamental fermions;……..thereby revealing suggestive lepton-quark symmetry. The extra quark is the simplest modification of the usual model…[29]*

This fourth quark was named *charm (c)*.

The behavior of quarks was formulated in a quantum field theory of strong interaction. This theory of quarks and gluons was similar in structure to quantum electrodynamics (QED). Since the strong interaction deals with the color charge, this theory is called Quantum Chromo Dynamics, or QCD.

Quarks are determined to be real particles, carrying a color charge. Gluons are massless quanta of the strong-interaction field, like the photon is quanta of the electromagnetic force. This strong interaction theory was first suggested by Harald Fritzsch and Murray Gell-Mann.

In 1968-69 new experiments were performed at the Stanford Linear Accelerator. These experiments were similar to Rutherford's experiment of alpha particles bombarded on a gold foil. Instead of alpha particles scattering from a gold foil, a beam of electrons was scattered off protons.

Just like in the Rutherford's experiment scattering of alpha particles at large angles meant atoms within the gold foil had hard centers (atomic nucleus), the electrons appeared to be bouncing off small hard cores inside the proton. This was the first experimental evidence of quarks.

We talked about particles and anti-particles. For the most part laws of physics do not distinguish between them. However, a difference was observed experimentally—symmetry between particle and anti-particle was broken or violated.

Now the question was how to explain this effect?

While trying to find a formulation to explain the observed behavior, following the work of Nicola Cabibbo, Makoto Kobayashi, and T. Maskawa extended the quark model to three families of six quarks. It turns out that 3 is the minimum number of pairs of quarks that could provide a mechanism to produce this asymmetry. These new particles were named the ***top (t)*** quark and the ***bottom (b)*** quark.

The *b* quark was discovered soon after the prediction. At the same time, another, 5th, lepton was also discovered, called *tau (τ)* lepton. Given the pattern so far, it wasn't hard to predict that there should be a corresponding neutrino. However, it took about two decades to discover the last lepton and the quark.

At this point things look pretty good. The ideas about these particles were somewhat scattered, but the picture was becoming clear. There was this one issue, however—theories that used symmetries so beautifully to explain the plethora of particles we were observing in our detectors, needed all the particles to be massless if the symmetries were to stay unbroken.

That was the case until Steven Weinberg and Abdus Salam proposed a new theory that used an idea Sheldon Glashow had already proposed—a mechanism to combine electromagnetic and weak interactions, unifying interactions of two of the four known forces, into a single, *electroweak*, interaction.

According to the new theory, at lower energies this bigger symmetry, the electroweak symmetry, breaks, giving rise to two separate symmetries. These new symmetries correspond to the familiar electromagnetic and weak interactions.

The mechanism of symmetry breaking requires introduction of a new field and an accompanying particle—the field is called the Higgs field and the particle is known as the Higgs boson.

This Higgs field is very special. The whole universe is sort of immersed in this field. Every particle that interacts with the quanta of this field, the Higgs boson, gets mass—stronger the interaction, heavier the mass.

Within the next few years, the predicted quanta of the electroweak interactions, the charged *W* bosons and the neutral *Z* boson, were observed.

The mediator of the strong force, gluon, was not seen directly (being massless and colored). But the indirect evidence was strong enough for it to be considered a real particle.

A beautiful, intricate yet simple picture of the universe was forming as the pieces of this puzzle came together, and were discovered experimentally one by one. By the end of 1970s, most particles predicted by the theory were discovered, and their interactions were found to agree dramatically with the predictions of the theory.

BY 1995, only two of the major pieces of this picture were left to discover. Namely the *top* quark, the heaviest of all the quarks, and the Higgs boson, the giver of mass to other particles, the infamous God Particle.

In 1995, the CDF and D0 experiments at Fermilab, finally, discovered the *top* quark. Turns out the reason it took so long to discover is the unexpectedly heavy mass. The *top* quark, like all the other five quarks, is considered a fundamental particle. But its mass is as much as a gold atom, which is about 200 times heavier than a single *proton*. Why the *top* quark is so heavy compared to the other quarks (about 100,000 times heavier than the *up* quark)? We have no idea.

Going back to our particle count, we now have 6 leptons and 6 quarks, moreover, both kinds of particles make three pairs each. This repeated pattern is termed as the three *generations* of matter.

$$\binom{u}{d} \quad \binom{c}{s} \quad \binom{t}{b}$$

$$\binom{e}{\upsilon_e} \quad \binom{\mu}{\upsilon_\mu} \quad \binom{\tau}{\upsilon_\tau}$$

The first generation includes *up*, *down* quarks and electron and electron-neutrino. The most of our visible universe is made up of the first generation as *up* and *down* quarks make protons and neutrons, which in turn make up the nucleus of atom.

The second and the third generation, interestingly, are very similar in properties to the first generation, but with heavier masses.

Leptons and quarks are the matter particles.

The list of the fundamental particles also includes the force particles or the force carriers. These are photon, W^+,

W^-, and Z^0 boson for the electroweak force, and the eight types of gluons for the strong force.

And, added to this list now, is also the Higgs boson.

As far as we know, quarks, leptons, force carriers and the Higgs boson, are all fundamental particles, and do not have any smaller constituents. All of these particles have corresponding anti-particles, except photon, Z^0 and Higgs boson.

We have successfully combined Electromagnetic and Weak forces. The Electroweak theory together with Quantum ChromoDynamics, the theory for Strong interactions, explains most of the world around us.

We call this magnificent theory the Standard Model of particle physics.

To kill my own buzz, the great Standard Model of particle physics, the mesmerizing theory of relativity, and the fascinating models of cosmology that are such success in describing the universe we see around us, describe phenomena concerning only a small part of the universe.

Using our current theories, we can describe phenomenon for only about 5% of the whole universe we know exists around us.

We have an *almost* theory of everything *visible*, but getting to a full theory of really everything, visible or not, will need more time and effort.

✯✯✯

Recall the tale of two worlds—the smallest and the largest. The three forces that are connected to the smallest of the fundamental building blocks of matter, and the interactions responsible for binding these blocks into the particles that make up the visible universe around, is described by the theory called the Standard Model. When these particles combine to form planets, stars, and galaxies, the fourth force, gravity, becomes the dominant one.

Quantum mechanics and the theory of relativity are two of the most, if not the most, precisely tested theories in the whole history of all the sciences.

For example, take one of the properties of electron, called the magnetic moment. Because electron has charge and spin, it behaves like a tiny magnet. When such a particle is placed in a magnetic field, it behaves exactly how a magnet would—like a compass needle moving in the earth's magnetic field.

Recall the inherent spin of a point particle, like an electron or a muon, is a quantum mechanical concept, without any classical analog. The effects resulting from this and other quantum properties are predicted by the theory of quantum mechanics (Quantum ElectroDynamics to be precise.)

For electron's magnetic moment, the associated quantity measured in the experiments is the gyromagnetic ratio, *g*. The lowest order value of *g* predicted by the quantum theory is 2. When the higher-level quantum effects are taken into account, this prediction differs a little from this value, and is predicted to be (with uncertainties in parentheses):

$$g/2_{Theory} = 1.001\ 159\ 652\ 182\ 8(77)$$

Experimentally measured value of this property is:

$$g/2_{Experimental} = 1.001\ 159\ 652\ 180\ 73(28)$$

Incredible!

We know exactly what the value of this property is in our universe—to one part in a trillion (with a T).

Even more incredible, the measured value matches with the theory prediction to a breathtaking *eleven* decimal places.

I am speechless!

☆☆☆

Part III

The Bang

Our Latest Time Machine

The *other* proton-anti-proton beam collider detector at Fermilab, called CDF, was open for scheduled improvements. Looking at it from a high terrace, the complexity and the beauty of that gigantic machine overwhelmed me with joy and pride.

Joy at being fortunate enough to be there.

Pride at being the part of a community, a race, no matter how different we all are, no matter what our race, color, religion, we can still come together, and build something so complex, so delicate, and so beautiful.

This was the first time I looked at a particle collider, many years ago. Even before I started working at the D0 (D-Zero) experiment at Fermilab, as a graduate student.

The CDF and D0 experiments discovered the *top* quark in 1995.

These feelings of joy and pride were many folds enhanced when I visited the CMS and ATLAS detectors at the Large Hadron Collider, many years later.

These two are the experiments that discovered the Higgs boson in 2012, which led to the 2013 Nobel Prize in Physics.

These, and the other experiments like these, are an indispensable part of developing a credible theory about how our universe works.

Unless proven correct experimentally, all theories are just beautiful toys. We can play with them, pretend to be heroes in them, fly, even move around in *other* dimensions, but that's about it.

The discoveries like the *W*, *Z* and Higgs bosons and the *top* quark that proved the theory of Standard Model correct, require three main elements:

- A *time machine* that takes you back to the hot environment right after the Big Bang.
- A *camera* to see and record what is happening in that environment.
- A *family* of scientists that builds and maintains these tools and makes sense of the recorded data.

To see a particle like the Higgs boson, we will need to travel back in time. The time when this universe began. The time very close to the Big Bang itself. That is when the universe was *hot* enough, or energetic enough, to create such particles.

While we are still working out how to make a time machine that can take the human beings to the past or the future, for now, the methods we use to *see* Higgs and the other sub-atomic particles involve producing the conditions of that past—close to the time of the Big Bang, and create these particles in a controlled environment.

This requires an unprecedented amount of energy. In fact, the smaller the particle you want to probe, the more energy you need.

You ask why?

And I ask, how do we see?

To see something, you need two things: one, the thing itself that you want to look at and, two, something to look at it with.

Let us suppose you want to look at your hand—obviously you need light in the room. The reason you can see anything around you is because the light (photons, to be precise) scatters from the objects and reaches your eye.

As a rule, the wavelength of the light must be smaller than the size of the object you want to probe with it.

The smaller the wavelength of photon the more energetic is the photon.

Consider a wave in the water in a pond. It is made up of hills and valleys (crest and trough). One hill and one valley makes up one wavelength. The number of wavelengths that pass through a point in a second is called frequency of that wave. The more wavelengths pass in a second, the more energy that wave has. Thus, larger the frequency, larger the energy. Smaller the wavelength, larger the energy.

That is why the blue flame is hotter than the red flame—the blue light has a higher frequency and a smaller wavelength than the red light.

You don't necessarily have to use photons to probe a structure. In fact, other small particles with very high energy can be even more efficient in probing very small things.

For example, the electron microscope that uses electrons to probe small structures is thousands of times better in resolution than the optical microscope where we use light (photons) to probe various structures.

But to look at an atom such that its structure is clear to us, is not possible even with the best microscopes available today. Looking at a proton or its constituents (quarks), or the electrons revolving around the nucleus of an atom is of course out of the question.

So then, when we claim that we have found a sub-atomic particle, how do we know it is what we think it is? If it is not possible to look at an atom or sub-atomic particles like quarks, then how do we know they are there? How big they are? How heavy they are?

What tool do we use to *look* at such small objects?

And equally more important—where do you find such particles anyway?

For example, if I have a powerful enough tool, would I be able to look at a Higgs boson inside the atoms of my hand?

The simple answer is, no.

To study such particles, we must create them in a controlled environment.

As Einstein discovered, energy and mass are two sides of the same coin. Mass can transform into energy and vice versa, in accordance with the famous equation $E=mc^2$, where m is the mass of the object, and c is the speed of light.

If we make highly energetic particles collide with one another, like the two high speed cars crashing into one another, their energy can convert into mass, creating new particles.

Most of the time these particles are the ones we already know, but sometimes some new particles are created that we have not seen so far, and can only be produced at certain high energies.

The Higgs boson is one such particle.

These are strange crashes. In a normal car crash the only things that come out flying are the small parts of the car itself. Collisions of two very high energy particles are like car crashes, where, along with all the little screws, tires, and the other familiar metal parts, two battle ships could also come flying out of the collision. In fact, in these collisions, we hope to see some exotic spaceships, that is, very heavy particles predicted by many theories but never seen before.

For various technical reasons, the particles used to produce this near Big Bang environment at the LHC, are the very protons that make up the positive center of every atom in the visible universe.

To energize particles like protons, we need to accelerate them to very, very high speeds, and higher the speed, higher the energy. As per our current knowledge, nothing can move faster than the speed of light (about 300,000,000 meters per sec). For a proton, accelerated to the energy of 7 TeV (10^{12} electron volts), this speed is 99.9999991 percent of the speed of light.

The Large Hadron Collider produces two energetic beams of protons by accelerating them to these extreme velocities. The experimental apparatus needed to accelerate protons to such ultra-high energies makes the LHC one of the largest and the most complex machines ever built by the human race.

These ultra-high energy beams of protons are circulated in a 27 kilometers underground tunnel, one in clockwise and the other in the anti-clockwise direction. Once reached to their maximum energy, these beams are made to collide inside the detectors, which, like cameras, record whatever happens in these collisions.

Interestingly, this energy is not at all impressive if you compare it to, for example, the energy we could get from a doughnut. The amount of energy equivalent to 1 TeV is about the same energy in the motion of a flying mosquito.

What makes this energy so extraordinary, and enough to takes us back to the temperatures only seen near the Big Bang? The fact that in proton collisions this energy is squeezed into a space about a million, billion times smaller than a mosquito.

This is as much energy as in clapping, but now try hitting one palm with a needle, instead of the other palm? What would happen to your hand if the pin was million, billion times sharper, but strikes your hand with the same energy? Now replace both hands with these ultra-sharp pins.

The result of such focused collision is breaking of the proton itself, creating new, massive, particles according to $E=mc^2$.

Why we talk about travelling to the time of the Big Bang in this scenario? Because such collisions, where a lot of energy is packed in a very small space, create a density of energy that only existed less than a second after the Big Bang. LHC collisions are the first time such energies have been created by a man-made apparatus.

The LHC is currently the world's largest and the most powerful particle collider. It is truly a unique machine in many respects.[30]

It took more than 30 years to design and build the LHC, by the European Organization for Nuclear Research(CERN), starting in 1984.

It consists of 27 kilometer circular tunnel, about 200 meters under the French-Swiss border near Geneva, Switzerland.

The proton beams, made up of bunches of billions of protons each, collide millions of times every single second.

To make sure that protons collide with protons only and not any other particles present in the air, the beam pipe needs to be free of all such particles, or *vacuumed.* This ultrahigh vacuum (10^{-13} atm) makes the LHC tunnel 100 times emptier than the outer space.

The superconducting magnets at the LHC use superfluid helium at a temperature of 1.9K, colder than the temperature in the outer space (2.7K).

The magnetic field produced by these magnets is 100,000 times more powerful than the Earth's magnetic field (that moves the compass needle).

The LHC magnets are made by wounding electric cable, which is made up of strands about 7 times smaller in diameter compared to a human hair, and as long as to circle the whole earth six times.

ATLAS [31] and CMS [32] are the detectors that discovered the Higgs boson by examining the LHC collisions. These are also the biggest of the seven LHC experiments.

The CMS detector is 21m long, 15m high, 15m wide, and weighs 12500 tons. The ATLAS detector is 46m long, 25m high, 25m wide, and weighs 7000 tons. For comparison, the navy destroyer, USS Fitzgerald, weighs 9,000 tons.

Both ATLAS and CMS are general-purpose detectors designed to detect a broad range of processes. Our goal is to be able to detect charged, neutral, and invisible particles produced in every collision of proton beams. Here *invisible* means particles that do not interact much with the detector. Detection of these different kinds of particles requires a combination of different detectors. This combination is termed a *general-purpose detector*.

A general-purpose detector is essentially a Russian nested doll made of many sub-detectors—one inside the other, all centered around a few inches round pipe containing the colliding beams. In the case of Fermilab's Tevatron accelerator, these particle beams were protons and anti-protons. At the LHC, both beams are made of protons.

By design, the LHC and the Tevatron both have two similar general-purpose detectors each. These detectors do the same thing, but completely independently. They differ in technical details of how they work, and collect and analyze the accelerator data, completely independent of the other experiment. This redundancy is imperative for the verification of the results from the both experiments.

These detectors work like sophisticated cameras. But their pictures are not like those of a usual camera, where you can identify a group of people just by looking at it. In case of these detectors, it is a bit more complicated. What the detectors record are the electrical and light signals, millions, and millions of them, coming from each and every part of the extremely finely segmented detectors.

A lot of work goes into connecting these millions of *dots*.

First, energies and tracks of particles are measured and matched. Then physical objects are reconstructed from this information, and by comparing the collected signals in the detector with the expected patterns a sub-atomic particle of certain energy would create when passing through the detector.

In the end, we reconstruct all long-lived particles that traverse a path while passing through some parts of the detector, and deposit their energy in some other parts.

The presence of particles that do not interact much with the detector, is inferred from the physical laws of energy and momentum conservation, expected to hold in every collision. These particles include neutrinos and many kinds of predicted exotic particles, depending on which physics process we are searching for.

The detectors at the LHC have extremely fine resolution, and chances of reconstructing a fake particle or misidentifying a particle (like a quark or gluon signal reconstructed by the algorithm as an electron instead) are very small.

The amount of data produced by the LHC collisions, and the simulations of the physical processes that could produce those data, is tens of petabytes per year at this point. These data need to be made available to thousands of scientists all around the world.

The handling sharing, archiving, and analyzing of such big and complex data, requires the cutting edge high performance computing, complex mathematical analysis algorithms, and a grid of computing hubs spread all over the world.

The Worldwide LHC Computing Grid (WLCG) is the world's largest scientific computing grid. It is a global network of thousands of computer centers connecting more than 40 countries, and serving thousands of physicists.

One of the major parts of the system needed to analyze the LHC data is the Open Science Grid in the US, which serves the scientific community in general along with the High Energy Physics at the LHC.

The construction and the maintenance of LHC is truly an international effort. Thousands of scientists from hundreds of institutions, from over 70 countries are part of this endeavor.

The CMS collaboration alone has over two thousand Ph.D. physicists, about a thousand engineers, and about two thousand doctoral and undergraduate students, all actively working on the experiment.

Before LHC started operating, there were many theories predicting black holes or other strange exotic particles predicted to be produced in the LHC collisions. There were also (conspiracy) theories that these particles, if produced, could start the destruction of LHC and eventually the world, and perhaps the universe.

The LHC and its experiments, remarkable though they are, are no match to what nature can do. Anything that can be created in the LHC collisions, is already happening in the cosmic rays. These are rays from outer space that produce particle showers upon entering the earth's environment. Their energies can exceed, by billions of times than the energy we can produce in LHC collisions.

This means Higgs bosons and anything else, including the small black holes (if they exist) are being produced on the earth constantly.

The reason we only discovered the Higgs boson just now is because it is only now that we can produce these particles in a controlled environment, and study its remnants in the detector.

The only negative side effect of a facility like the LHC can be the harmful radiation produced in the collisions. Cosmic rays also cause radioactivity which is a part of our environment. Since LHC is more than hundred meters underground, the amount of radiation above the ground is much, much lower than the amount naturally experienced by the human beings. Also, there are several layers of security systems to make sure that LHC and the people around the facility are safe in the case of an unstable beam. These systems make sure that in the case of a failure, beam is directed towards and dumped in a special place that can withstand and absorb this amount of energy. All of this happens within a tiny fraction of a second.

Even before the discovery of the Higgs boson, the LHC and the Higgs boson received an unusual amount of attention in the popular media. Including mention in the newspapers, magazines, blogs, twitter, facebook, novels, movies, and TV programs. The Large Hadron Collider has now become a part of the popular culture. The news media reports regularly on its progress and fiction writers are using LHC and the corresponding physics in their work.

The novel Angels & Demons (by Dan Brown), involves antimatter created at the LHC to be used as a weapon against the Vatican. This was perhaps one of the most debated pieces of fiction about what LHC does, and how lethal its products could be? But none of the fiction has come close to the fears that this experiment could create black holes that could swallow the whole earth.

The fact is the other way around.

This machine is so sensitive that the beam energy can be influenced by the moon. The earth-tides caused by the full moon, cause noticeable variations in the beam energy. The same is true for the earthquakes. The Large Hadron Collider Beam Operation Committee reported the effect of New Zealand earthquake in 2016.[33] Given that the collision area for the two beams is less than the width of a human hair, even tiny changes to the beam need to be corrected for successful collisions.

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The Large Hadron Collider is extraordinary in many ways. It is the largest human effort to answer the most fundamental questions about the nature and makeup of our universe. It is also one of the largest and the most complex experiment built ever.

So far, LHC has broken its own highest energy records many times over. The proton-proton collisions have been recorded at the collision energies of 2, 7, 8, and now 13TeV.

Since the first collisions, LHC has discovered the Higgs boson, created quark–gluon plasma, achieved observations of many new particles and processes predicted by the Standard Model, as well as, along the way, blown a lot of theoretical models out of the water.

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Higgs Discovery—Doom Or Dawn?

Progress leads to confusion, confusion leads to progress, and on and on...

Abraham Pais

The production of the Higgs bosons at the LHC have not destroyed the universe—not yet any way.

When, after a long search, the Higgs boson was not discovered, one of the ideas floated at the time (out of desperation?) was that God does not want us to discover this particle. Any machine that tries to observe this particle will be destroyed. One of the examples in the support of this idea was the Superconducting Super Collider in Texas—the project was canceled by the U.S. Congress in the middle of the construction. These statements followed by a train wreck in the LHC tunnel.

Of course, the physicists working at the Large Hadron Collider made fun of these statements, especially when a particle just like the Higgs boson was discovered soon after.

However, now that we have found the Higgs boson, it seems universe, after all, *is* doomed—or quasi-doomed, to be precise.

The Scientific American quoted a prominent physicist, Joseph Lykken:[34]

> *If you use all the physics that we know now and you do what you think is a straightforward calculation, it is bad news. It may be that the universe we live in is inherently unstable.*

It turns out that the mass of the Higgs boson (125 GeV), has interesting implications for the lowest energy that our universe exists in—this, in fact, might not be the lowest value of the energy that our universe *can* exist in.

What we have learned so far, about the things in the universe, is that everything likes to be in the state of the lowest possible energy, including the universe itself. This means our universe is currently in a quasi-stable state, and someday might spontaneously *fall* to its lowest energy state.

The *doom* in this case refers to the fact that the properties of this universe, and the composition that ended up giving birth to a carbon-based life like us, will be completely different, and the universe we know will no longer exist.

But that might not happen in our life time, so, let's talk about what is next, now that we have discovered this long-sought particle.

First thing first, have we really discovered the so-called God Particle or something that just looks like it?

In the early 2013, LHC presented results after the analysis of two and a half times more data than what was available for the discovery in July 2012. The new particle looked increasingly like a Higgs boson. Since then, more data, at even higher energies have been analyzed, and results have not changed.

The properties measured so far, are close to what is expected for the Standard Model Higgs boson. But it is still not definite whether this is *the* Higgs boson—the single spin zero particle, linked to the mechanism that gives mass to the elementary particles, or *a* Higgs boson, possibly the lightest of several bosons predicted by some theory other than the Standard Model. We need more data and time to analyze these data, before we can get a conclusive answer to these questions.

Results indicate that particle discovered at CERN is very much like a Higgs boson. But there is still a possibility that other Higgses or Higgs-like particles exists.

In fact, we eagerly hope and wish that we find such new particles.

Naturally you ask: what does it mean to say that the discovered particle *looks* like the one predicted by the Standard Model?

Well, this is determined by comparing the measured properties of the newly discovered particle with the theoretical predictions. For example, Standard Model predicts the strength of the interactions of the Higgs boson with other Standard Model particles. These predictions can be simulated. When the data from the collisions is compared to simulated data, these interactions are found to follow the pattern predicted by the Standard Model. There are other predictions about the properties that can be tested, for example spin. The data seem to match the predictions of the Standard Model.

The measurements so far, strongly suggest that this is *the* Higgs boson predicted by the Standard Model.

So, what is next?

While it is true that we might have found the *physicist's stone*, in no way this discovery is capstone of our knowledge about this universe. Even if the question of the existence of the Higgs boson is resolved, there are a lot of questions that remain unanswered.

Even though interaction with the Higgs boson is the reason particles get mass, the mass of the particles our visible universe comes, mainly, from the fact that small quarks are confined in the form of a proton or a neutron, as the free quarks cannot exist by themselves.

For example, the *up* and *down* quarks make up a proton or a neutron—particles about a 1000 times heavier than these quarks. Because most of the mass arises from the binding energy of the quarks constituents.

This might seem to suggest that quark masses, and the role of the Higgs boson in this process, is no big deal—Higgs or no Higgs, our visible universe would look similar either way.

Not quite.

I have not seen Feynman's office, but I am told he kept in the corner of his blackboard the question

Why does the muon weigh?

Not *what* but *why*.

If the Higgs boson is the particle described in the Standard Model, and all its properties and couplings to other particles are exactly as predicted by the theory, which so far seems to be the case, then we are finally in a position to answer Feynman's question.

But the other fundamental question, that naturally arises next, *why these particles have the masses they do?* remains unanswered.

You can also phrase this question even more generally: *why the universe is the way it is?*

Why it is an important question for us, the special, carbon based life in this universe? Because, apparently, a tiny change in the properties of the constituents of this universe can be the difference between a universe with or without life.

Recall, an atom is a building block of the universe we observe around us with the properties we experience every day.

Also recall, an atom comes into existence when we have a negative electron revolving around a positive nucleus made up of positively charged protons and neutral neutrons.

A neutron, being electrically neutral, while part of the nucleus for almost all elements observed in the universe, would not be able to make an atom by itself.

A neutron is a tiny bit heavier than a proton. Thus, a neutron can easily decay into a proton, but a proton cannot do that and remains stable. In fact, fortunately for us, proton is an extremely stable particle. Its lifetime is much longer than the lifetime of the universe.

This tiny mass difference is due to even a tinier mass difference between *up* and *down* quarks.

If this difference was other way around than what it is now, proton would become heavier than the neutron. As a result, all the protons would have decayed into charge-less neutrons long, long time ago—essentially destroying any chances of having a universe we see around us today.

Another example—consider the scenario where electron did not have the mass it does now. A slightly lighter or heavier mass than what it actually is, would render the whole atomic model useless. Either the electrons will fall into the charged nucleus, or it will drift away like a rogue satellite in empty space.

So, now the question has changed from, *why particles have mass?* to, *Why they have the mass they do?*

And this is not a small question, as answer to this question might be key to answering the reason of our own existence.

And talking about mass, the Standard Model does not account for the observed neutrino masses.

Then there is still the question of where is all the anti-matter? From our current theories, we know the universe prefers matter over anti-matter. But this difference is very small, and cannot explain the large disparity between the two species of the matter we observe.

Oh, and why we have three generations of matter?

So far, we have talked about a theory of almost everything visible.

Our observations so far, tell us that there is much more to this universe than meets the eye—literally.

Gravity is very different from the other forces. It is extremely week compared to the other three forces, and the theory that describes it, is also very different in composition than the theories for all the other forces. As of now, it is unclear how to combine theories based on quantum mechanics and the ones based on the theory of general relativity.

Then there are the dark sides of our universe—the Dark Matter and the Dark Energy.

As per our current knowledge of this universe, about

25% of the universe is made up of Dark Matter, and about 70% is Dark Energy, leaving only about 5% made up of the matter we can interact with and see around us.

As of today, we understand that the universe started with the Big Bang. But we don't understand how exactly it came to be the universe we see around us today.

This is why the LHC is so important. The energies explored by the LHC were only present a very tiny fraction of a second after the Big Bang. Thus, providing a unique opportunity to understand our universe at that critical time.

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Doom or Dawn?

The *doom* could be taken in two ways:

A literal doom: well, not to freak you out or anything, but now that we know we live in a quantum mechanical universe, anything that is possible, could happen any moment. Quantum mechanics clarified Seneca's quote, at last:

Whatever can happen at any time can happen today.

But, since we can't control it, let us not worry about this kind of doom.

A metaphorical doom: what started with beautiful and ingenious insights of people like Planck and Einstein, and culminated into the most precise theory the humankind has ever seen, ends with the Higgs discovery?

Certainly not.

The dawn, it certainly is—Higgs discovery is a quantum leap, in every sense of the word.

The 18th and 19th century brought us revolutions in the way we look at our universe including our own existence. With the Higgs discovery at the Large Hadron Collider and the other experiments searching for answers to the deeper questions, it is clearly the beginning of a new era in science. This might be the beginning of another revolution with even deeper revelations about the nature of nature itself.

☆☆☆

Part IV

The Buck

Good Bang For your Buck?

SENATOR PASTORE: When you consider priorities, I know exactly what you mean, provided we have the money.

After all, when you have people who are hungry, the big question here is: Is it more important to put a man on the moon, or to fill the stomachs of our starving children?

DR. WILSON: It is most important to fill the stomachs of our starving children.

SENATOR PASTORE: You would put that as the first priority, would you not?

DR. WILSON: Yes, sir.

SENATOR PASTORE: Of course.

DR. WILSON: But it is also important to get on with the things that make life worth living, and, fortunately, it is possible to do these things in a manner which also contributes to the feeding of hungry children. .….

SENATOR PASTORE:

Essentially, the major purpose of this bevatron is for fundamental high-energy physics *research, which is an educational and academic process, is it not?*

DR. WILSON: And a cultural process, yes, but with the firm expectation that technological developments will come. Directly, but after a very long time; from the results of the research will come new technology. However, there will be a bonus that will come indirectly but very soon, through the technological inventions, that is "Spin-off," that results whenever such work is done.

Thus, because we are doing extremely difficult technical things, and because we are working in a strange kind of research, we know from past experience that new techniques inevitably develop, techniques which have paid, more than paid, for the cost of the basic research that was not pointed to such developments.

The klystron of the linac at Stanford, the vacuum pumps for the early cyclotron research, and the high-frequency oscillator tubes which were so valuable during the war, computer techniques, all these resulted from work on accelerators.

Above is part of the dialogue between Senator John Pastor, member of the Congress' Joint Committee on Atomic Energy, and Robert R. Wilson who testified in front of the committee on April 17, 1969.

Robert Wilson was one of the US physicists who participated in the Manhattan Project, and was awarded the National Medal of Science. He was also the first director of the Fermi National Accelerator Laboratory (Fermilab). The same laboratory for which he is making this argument in front of the Congressional committee.

Fermilab was approved for construction by President Lyndon B. Johnson in 1967. The laboratory, about 30 miles west of Chicago, was renamed Fermi National Accelerator Laboratory, or Fermilab, in 1974, after Enrico Fermi. Fermi was Nobel Prize winning physicist, most renowned for producing the world's first controlled, self-sustaining nuclear chain reaction.

Fermilab housed the world's largest accelerator, Tevatron, until even larger accelerator, the Large Hadron Collider, produced even higher energy particles in 2009. Tevatron also has the honor of being the world's first superconducting synchrotron.

Leaving the cultural part of his answer out for now, Robert Wilson very eloquently made the point that investing in the technology used for research in the basic science pays off, many times over, sooner or later.

Fermilab is one of the 17 national labs under the Department of Energy (DOE), and the only facility exclusively dedicated for the research of fundamental particles and forces using accelerator technology. The DOE's budget is around $30 billion, out of which around $400 million went to Fermilab in 2012.

In 2011, the University of Chicago commissioned a report to estimate economic impact of Fermilab.[35] The study was mainly for the impact in Chicago and the state of Illinois.

According to this report Fermilab is responsible for 4500 jobs in IL, and contributed $643 million in net earnings in IL, in FY2010 alone. Same year, 2300 scientists from 42 countries visited Fermilab to collaborate on worldwide research, including the development of the accelerator technology.

Today, after more than 40 years, with what Fermilab has accomplished and has contributed to the society, Robert Wilson's argument is even easier to make for the investments made in this facility, which the U.S. taxpayers paid for.

Even without considering the future impact of such a facility and the research done here.

But this is not the argument I want to make.

The amount of $400 million, or $600 million is not even peanuts compared to today's world economy. One could even argue that investing this amount of money in some other business might have generated lot more than $600 million that Fermilab gave back to the community.

Instead, let us dig a little deeper.

I will stick to the accelerator and the particle detector technology, since this is the basic apparatus on which the most of the money was spent. Also, because it is directly related to the cost of discovering the Higgs boson.

The accelerator technology was developed by the physicists to explore nature for the sake of understanding it, rather than any practical applications. Today, however, out of above 30,000 accelerators in use worldwide, only a few are used in the physics research itself.

Accelerators, like any other invention and technology, did not come into existence suddenly one day. A convenient place to start this story perhaps could be in the mid 19th century. The vacuum tubes were then developed by physicists Heinrich Geissler, William Crookes, and Ferdinand Braun. This technology was later used by a number of physicists to study the phenomenon of rays ejected from the cathode (negative electrode), and accelerated as a beam from the cathode to the positive electrode (anode), or onto a fluorescent screen.

J.J. Thomson, in 1897, used these cathode ray tubes (CRT) to make the discovery that cathode rays are in fact negatively charged particles. Today we know these particles as electrons. Thomson won the 1906 Physics Nobel Prize for this discovery.

Around the same time, Wilhelm Röntgen, another physicist, and a Nobel Laureate, discovered the X-rays using similar tubes.

Ever saw those fat-screen (not-*flat*-screen) TVs? CRTs were used for TV, monitors, as well as other appliances like the microwave ovens, until very recently. Today these tubes are mostly used for special applications.

Let me pause for a moment here:

I haven't gotten to the accelerators we use today yet. But we have already talked about the discovery of the electrons, the *X*-rays, and the CRT.

I don't think I need to emphasize the discovery of electron, and the importance of the efforts made to understand their properties and their behavior in electric and magnetic fields.

I am also sure that most people appreciate the importance of word -elect- in electronics and electricity in our daily lives.

The cathode ray tubes have wide ranging applications. CRT monitors are still widely used in instruments including the medical diagnostics. An electron gun, a spin-off of CRT to get a collimated beam of electrons with a uniform energy, is commonly used in the industry today.

Since the mid 20th century, we have been used to taking advantage of the solid-state devices. But before the invention of semiconductors, CRTs were used to accomplish the same task.

And, talking about the solid-state devices, semiconducting material was noticed first by Alessandro Volta in 1782—the same physicist who invented the first electric battery, and the commonly used word *volt* is named after. Later, another physicists Michael Faraday, made the first observation of semiconductor effect.

Finally, the significance of X-rays in medical diagnostics and homeland security needs no underscoring.

The most important thing to note in these examples is the fact that all of this was a result of sheer curiosity and basic, fundamental research—scientists were simply trying to understand natural phenomena.

Today electronics industry makes up a very large chunk of global economy. Would this be possible without the discovery of electron, or understanding the nature of electricity, or the nature of semiconductors, whose behavior, by the way, is described by quantum mechanics.

The effect a discovery like the X-rays has in uncovering the problems inside a living body in the medical field and in homeland security, for example, is hard to sum up in a dollar amount.

Röntgen had already seen that his newly discovered rays could pass through the soft stuff like the human flesh, but not through the dense matter like bones. He used these rays to photograph the image of his wife's hand. It is easy to understand why the X-ray machines were shown in theatrical shows to entertain people as a medical wonder. For the first time, the medical industry had the technology to see inside the human body without cutting it up first. Within a short time after the discovery, doctors were producing images like kidney stones, or a penny in the throat of a child. Today X-rays have become a part of our daily routines.

Modern accelerators at Fermilab or the LHC with a 27 kilometer long tunnel to accelerate the beams of particles, still use the same principle that Thomson used to discover the electron. And so do thousands of accelerators used in medicine or other fields of science and industry.

Since the 1950s, the accelerator technology is being used for medical diagnostic and treatment, including the treatment for cancer. This technology has not only turned into billions dollar market, but has saved millions of lives.

By the way, the use of protons for cancer treatment was first proposed in 1946 by the same Robert Wilson who participated in the congressional hearing in 1969 about the funding of a laboratory to research fundamental particles and forces.[36]

The physicists and engineers at the Fermilab built the very first proton accelerator for cancer therapy in the U.S. in 1990 for the Loma Linda University Medical Center. More than 10,000 cancer patients have been treated by this center so far. The Neutron Therapy Facility at Fermilab itself has treated thousands of patients.

The Positron Emission Tomography, commonly known as the PET scan, uses the technology developed at facilities like CERN for the particle physics experiments. CERN is also contributing to the research that uses carbon ions instead of protons, as they can be managed as precisely as protons with even higher energies.

These few examples are enough to illustrate how the technology developed for the pure, fundamental science, is directly benefitting the humanity.

Another important aspect of the scientific facilities like Fermilab and LHC is pushing the limits of the technology needed. These experiments are always built ahead of time. The physics research is not done by considering what is already available in terms of technology. Scientists make their goals in terms of what they want to explore, and then demand the technology to match their needs. In many cases this technology does not even exist. So, they go ahead and either invent it themselves, or help the industry come up with the solution, thus driving innovation as well as technology.

An example of the research in fundamental science inventing and developing technology is superconductivity, a phenomenon that causes certain materials to lose all electrical resistance.

Superconductivity makes it possible to conduct much larger current through a wire without losing the energy in the form of heat. To accelerate particles to high velocities, as is done at Fermilab or LHC, the conventional electromagnets, which direct the beam of particles, are not practicable. This can only be accomplished using the superconducting coils.

Superconductivity was first observed in 1911 in mercury by the Dutch physicist Heike Onnes. He was looking at the changing properties of mercury with temperature. To his utter surprise, the element lost it resistance completely, and became a *superconductor* when he cooled it to an extremely cold temperature, about 4 degrees above the absolute zero. (zero degrees Kelvin, which is the coldest, possible temperature), which is about −450°F, −268°C). In comparison, the natural coldest temperature on earth, as measured by NASA in Antarctica (South Pole) is −94.7°C (−135.8°F).

The discovery of superconductivity is regarded as one of the greatest scientific discoveries of the 20th century. In 1913, Heike Onnes won the Nobel Prize in physics for this work.

Tevatron at Fermilab was the first facility to use superconducting magnets on a large, industrial scale, significantly accelerating the development of this technology. For its efforts and contributions towards this field, Fermilab was given the *Superconducting Magnets National Medal of Technology* (1989). And for developing the accompanying Cryogenic Cooling System, Tevatron was designated an *International Historic Engineering Landmark* by the American Society of Mechanical Engineers in 1993, stating,

> *Many innovations are included in the system, which has been a model for similar systems worldwide.*

Of course, physicists and the latest particle physics facilities are not the only ones to use superconducting magnets.

According to a report by Global Industry Analysts,[37] in 2012 the yearly value of superconducting magnet industry was estimated at $1.5 billions, and the global superconducting magnets market was estimated to reach about $3 billion by 2017.

The amount of power lost along the transmission lines, by moving it along long distances, could power 14 cities the size of New York, according to a 2010 National Geographic report. Recently materials have been developed, which can exhibit the superconducting properties at relatively warmer temperatures. Cables made of such superconducting material can carry far more electricity than conventional cables with minimal power losses. Given that copper transmission lines and power cables are already near their capacity in densely populated areas, superconducting cables might end up becoming a need than just a better alternative.

The magnetically levitating trains are considered to be the future mode of transportation where electromagnets are used to suspend and propel. The high speed of such trains depends on the power of electromagnets used, making this technology another area that benefits from superconducting magnets.

The promise of (hopefully cheap) electricity without any transmission loss, levitating vehicles, and environmentally friendly solutions to many current problems are part of any futuristic vision of our world. Thus, the monetary worth of the industry of superconducting magnets is expected only to increase.

The Global Magnetic Resonance Imaging equipment market is expected to reach $8.2 billion by 2017, according to a report by Global Industry Analysts.[38]

The MRI is another medical diagnostic technology that born out of the basic physics research, and now benefits from further developments in the field.

The MRI technique itself is based on the work of another physicist, I. I. Rabi, who developed techniques for using nuclear magnetic resonance to understand the magnetic moment and nuclear spin.

This work not only led to his Nobel Prize in Physics in 1944, but also became the beginning of the MRI technique. Today, this technology is used in the medical diagnosis of a range of problems from broken bones to cancer, all around the world.

MRI uses a large magnet and radio waves to look at organs and structures inside the body. The quality of images is proportional to the strength of the magnetic field used in the imaging process. That is why MRI industry directly benefits immensely and directly from any developments in the superconducting magnet technology.

Another important use for the cathode-ray research, or particle beams, has been the electron-microscope. Hans

Busch, a physicist, published the principle in 1928. Ernst Ruska, another physicist, used Busch's insight, and invented the electron-microscope. The use of the electron-microscope increases the magnification power to the order of millions of times, compared to the conventional microscope (with magnification of the order of thousand times). As a result, many materials (e.g. virus) that are invisible under the conventional microscope (that uses light or photons to see objects), become visible under the electron-microscope. Today the use of this technology ranges from medical sciences and electronic industry to mining and forensic research.

The use of the accelerated electron beams to process materials for enhanced durability, or even to get desired arrangement of atoms and ions in a material has become common. Such beams are being used widely, from the manufacturing of wires and cables for electronic instruments to the synthesis of nanomaterials. Accelerators are being used at almost every step of the process of drug manufacturing. Beams of particles are used to create the 3D images of molecules, for example of protein, helping to understand the structure and, in turn, in developing corresponding drugs.

The technologies developed to detect particles are helping in the study of the turbulence phenomenon in fluids, improving the efficiency of engines, and the understanding of the changes in the climate. These technologies are also used in monitoring the nuclear waste proliferation and testing reliability of the nuclear weapons.

These applications will of course benefit from the developing and new particle detection technologies in the experimental facilities like the Fermilab and the LHC. And let us not forget these facilities were built for fundamental research.

The point of citing this never-ending array of applications is to give you an idea about how far, wide, and deep in our society the discoveries in basic, fundamental science penetrate, and benefit in countless ways.

Yes, it might have taken some time to get here, but without these discoveries it is hard to imagine the life, the civilization, and the society we are used to today.

Looking forward, building upon what we have learned about and from the accelerator technology, hubs like the Illinois Accelerator Research Center (IARC),[39] at Fermilab, are going to bring the scientists from the national laboratories, educational institutions, and the private industry, together. This alliance will help develop the accelerator technology further, and will eventually translate into applications for our nation's health, wealth, and security. This will be a gift that will keep on giving to the nation and the world.

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Was the Higgs boson discovery a good bang for your buck?

Is it worth spending billions of dollars on Tevatron, or the Large Hadron Collider, or any other experiment like that, in the hope to be able to find out what the building blocks of matter are? Is it worth more than just a glorious feeling that we, as a race, have done something so spectacular?

At first glance, the answer is probably no.

As our knowledge stands right now, the Higgs boson can’t be marketed for technological purposes. Neither can we make a bomb out of it, as some spy novels might claim. It cannot be used to solve the immediate energy crisis in the world, or to eradicate poverty.

So, then what is it good for?

We could ask the same question when another particle called electron was discovered, or when the electromagnetic waves were discovered.

What were they good for at the time?

I have only followed one thread in the history of the scientific fields, and, even that, picked at scattered moments, and very briefly.

But the lesson of the story is already quite clear. Take these few insights into the workings of nature out of the picture, and see what sort of world we end up with? And then, remind yourself that it was all done in the name of basic science, just to satisfy curious minds.

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How I Met My Soul Mate?
You've Got Mail

The summer of 2012 reminds me of another summer many years ago—when, in another gathering of scientists, I met the love of my life and now my husband for about two decades.

I met my husband at a conference. We kept in touch via email for the next year or so. The second time we met in person, we were already engaged.

That summer was also hot in more than one way.

The *top* quark was discovered few years ago, but in the absence of any other discoveries, the buzz was still in the air. Anwar gave a presentation on the latest *top* quark results from Tevatron, the proton-antiproton beam collider at the Fermi National Accelerator Laboratory, near Chicago.

I still vividly remember the opening day of the conference, when I saw him for the first time—standing at the conference reception desk, looking very casual in his black shirt and blue jeans, with his signature rolled-up sleeves. The way that scene is etched in my mind, after all these years, tells me that, somehow, I knew in that moment that I was looking at someone who was very important to me. Just like when I looked at my son for the first time some years later lying down on an operation table in a New York hospital.

In those days, email was common in academia, but had not become part of everyday life as it is now. Our letters are perhaps still on one of the servers in the university. They will perhaps be found in some future archives of medieval technology.

Email has played a big role in our lives since then. The only thing I hate in domestic life is fighting—we usually don't fight, but when it happens, it happens in emails.

I think my life would have turned out very differently if it were not for the email.

May be my husband and I would have met anyway, but then considering how far in space we were, we might not have. I might be spending my life with someone else, not even knowing that my soul mate does exist.

I am sure there are estimates on how much email market is worth. But I wonder if there is an estimate of the effect this technology has on the human society, and the way we interact with one another.

Can we even put a price on something like that?

Of course, email is not the first or the last technology to change our social lives and relationships. Twitter, facebook, instagram, radio and TV with thousands of channels, are among the many forms of communication and information dissemination available today. They play an important and consequential role in our lives socially, culturally, and politically.

The history of using electric signals to send messages around the world is about two hundred years old. We all know about electricity and magnets. Most of us have played with magnets, and most of us have been asked not to play with electricity.

The way to wire-less communication was paved with the discovery of electromagnetic waves and understanding their potential. Insights of physicists like Oersted, Sturgeon and Faraday started this revolution in the early 1800s.

Hans Oersted discovered that a current carrying wire affects a compass as if there was a magnetic field around it. That was the beginning of electromagnetism. A few years later, William Sturgeon, a lecturer in science at the Royal Military College, Surrey, exhibited first electro-magnet that could lift 20 times of its own weight. This revolutionary invention along with many other contributions after that, became the foundation of technological revolutions of the 19^{th} and 20^{th} century, especially in electronic communications.

It took an American, Joseph Henry, only a few years to use Sturgeon's electromagnet for long distance communication by sending an electronic current over one mile of wire. At the end of the wire another electromagnet was activated causing a bell to strike. Later, British physicists, William Cooke, and Charles Wheatstone, patented the Cooke and Wheatstone Telegraph, using the same principle of electromagnetism.

Finally, a professor of painting and sculpture at New York University, Samuel Morse, invented the commercializable telegraph system.

A big breakthrough in our understanding of the electromagnetic phenomena came from one of the greatest scientists ever. Michael Faraday discovered that he can produce electric current in a conducting wire by simply changing the magnetic field close to that wire. This is the fundamental principle behind the operation of electric motors and generators.

This discovery became the focal point for James Clerk Maxwell. He took this and other ideas, and formulated a full theory in less than a decade. His progress can be seen in the series of papers he published during this time. Everything came together in his historic paper titled *A dynamical theory of the electromagnetic field,*[40] in 1865.

In this theory, Maxwell postulated that travel of light, and the whole field of optics as a result, could be described in terms of electromagnetism. In fact, light itself is an electromagnetic field propagating in space. This theory was confirmed experimentally in the late 1887s, by another physicist, Heinrich Hertz.

Not long after, all this information was picked up by a young man experimenting in his villa, with the help of his butler.

No, not Batman.

It was Guglielmo Marconi (1894), a young Italian amateur experimentalist, who sent the first signal of radio waves from an oscillating circuit connected to one antenna, and received the signal by another antenna far away. It took Marconi only a few more years to get the commercial radio transmission started.

The importance of wireless communication in every aspect of our lives needs no explanation.

This was not just a technological revolution, but a social one as well. Among other things, the radio transmission found a wide use in the first world war. By the second world war, radio had become a necessity not only in the war zone, but at home as well. Since then radio has weathered some fancy transmission and communication tools. Even in the age of TV and internet, rsadio has remained one of the top mediums that most people in the world get their news from.

Note that all of this took place only little more than a century ago.

The next revolution in communication perhaps started with *e-mail,* and now this and many other activities like *facebook* and *twitter* bind our lives together.

This revolution, of course, would not have been possible without computers, internet, and the World Wide Web.

In the early 19th century, Charles Babbage, a mathematician, inventor, and engineer, was sitting in his office looking at a table of astronomical data full of errors. He asked the question: is it possible to calculate these tables with least human interaction?

He answered his own question by devising the first mechanical computer that could perform such calculations.

Babbage won the Gold Medal of the Royal Astronomical Society for this invention.

As an aside: Babbage had wide interests. In his book *Passages from the life of a philosopher,* he writes about his activities with his friends, when he was an undergraduate at Cambridge:

> *At one time we resolved ourselves into a Ghost Club, and proceeded to collect evidence, and entered into a considerable correspondence upon the subject. Some of this was both interesting and instructive.*

> *At another time we resolved ourselves into a Club which we called The Extractors. Its rules were as follows,*
>
> *1st. Every member shall communicate his address to the Secretary once in six months.*
>
> *2nd. If this communication is delayed beyond twelve months, it shall be taken for granted that his relatives had shut him up as insane. 3rd. Every effort legal and illegal shall be made to get him out of the madhouse. Hence the name of the club — The Extractors.*

At a very early age he developed life threatening fever. Later when he was sent to school, among other things, his parents instructions were that his *brain was not to be taxed too much*.

Today, half of Charles Babbage's brain is on display in the Science Museum, London. This is the same museum that displays the world's first complete Difference Engine built in 1991 from Charles Babbage's drawings.

In 1912, two years after the death of Charles Babbage, another man, Alan Turing, was born in UK. Turing was a mathematician and philosopher, trying to understand, among other things, logical foundations of quantum mechanics.

Today we know Alan Turing as the father of computer science and artificial intelligence.

Today, calling computers, a necessity seems like an understatement these days. But even though by mid-20th century we had working computers, they were still in the development mode, and expensive enough to be mostly owned by large universities and the defense department.

This was the time when, in the 60s, *Time-sharing* was developed to eliminate the computer downtime. This was the beginning of the user interaction on computers.

I am sure not a single person at that time had any idea that decades later, two people, 6000 miles apart, would come together just because of this technology.

Similarly, our history would have been very different without the World Wide Web.

In 1989, Tim Berbers-Lee, a computer scientist at CERN invented a new technology. He wanted the scientists working on answering the deepest, the most fundamental questions in physics, to be able to communicate and share the scientific information in a better way, all around the world. The people sitting in CERN at that time could not have any idea what it would mean in the near future.

For things like the internet, web, e-mail, it is very difficult, if not impossible, to measure their monetary worth or their full impact on the society. The UK government hosted an international conference on Cyberspace in London in 2011.[41] The message from the Foreign Secretory on the need of this conference is worth quoting here:

> *I am inviting governments, international organisations, NGOs and businesses from across the world to a conference in London in November. We have a shared responsibility to address the challenges presented by the networked world including cyber crime that threatens individuals, companies, and governments. It is vital that cyberspace remains a safe and trusted environment in which to operate. This can only be done effectively through international cooperation, engaging both the public and private sectors.*

> *Together I hope that we can begin to build the broadest possible international consensus on how to realise the enormous economic and social benefits the Internet offers. It is crucial that we start a focused dialogue now.*

According to a report prepared by McKinsey Global Institute, for this conference:

> *The Internet is changing the way we work, socialize, create and share information, and organize the flow of people, ideas, and things around the globe. Yet the magnitude of this transformation is still underappreciated.*
>
> *The Internet accounted for 21 percent of the GDP growth in mature economies over the past 5 years. In that time, we went from a few thousand students accessing Facebook to more than 800 million users around the world, including many leading firms, who regularly update their pages and share content. While large enterprises and national economies have reaped major benefits from this technological revolution, individual consumers and small, upstart entrepreneurs have been some of the greatest beneficiaries from the Internet's empowering influence. If Internet were a sector, it would have a greater weight in GDP than agriculture or utilities.*
>
> *And yet we are still in the early stages of the transformations the Internet will unleash and the opportunities it will foster. Many more technological innovations and enabling capabilities such as payments platforms are likely to emerge, while the ability to connect many more people and things and engage them more deeply will continue to expand exponentially.[42]*

This is in 2011, only two decades after the invention of the *world wide web*.

As of 2016, close to 90% Americans are using internet. And a large fraction out of those is connected to communication and social applications like facebook, twitter and instagram.

Less well known, but equally taking hold in our lives, directly or indirectly, are the *Grid* and the *Cloud*. Physicists pioneered these technologies decades ago. Industries such as medicine and finance are examples of other fields that also generate large amounts of data, and benefit from an advanced computing technology.

A 2009 article in Computer Weekly notes,[43]

> *CERN's IT department head, Frédéric Hemmer is helping to drive an ambitious project to develop huge grid computing networks that would support the LHC and many other important research initiatives throughout Europe and rest of the world.*
>
> *Frédéric Hemmer's former colleague, Tim Berners-Lee, of course invented the web. Now his and CERN's work on grids is itself leading to powerful and interesting innovations leading to major changes in computing and communications; most notably the move towards the cloud.*

In the entertainment industry, movies are a big business—*Avatar* and *Titanic* made more than 2 billion dollars each, with a long line of titles grossing close to or more than a billion dollars.

I can talk about how the camera and the other relevant technology developed, and how the basic science played a crucial role, before this technology became commercial. But let me stay with the thread of accelerator technology, and talk about a relatively recent addition to the entertainment industry—the video games.

At one point, *The World of War Craft* was my son's most favorite video game. We paid around $60 to get the initial, basic product and then paid monthly subscription for about a couple of years, until he grew out of it.

That was 2011.

The *World of War Craft* had already become the highest grossing video game in 2004 by making more than $10 billion in gross revenue. The games like *Call of Duty*, *Mario*, *Grand Theft Auto,* need no introduction either.

Making billions of dollars every year, this industry has come close to any other form of entertainment in sharing the market. Passing quarter of a trillion-dollar mark already in 2010, it is not far behind movies and TV.

How and where did it all start?

South Carolina, 1948.

Thomas Goldsmith, a professor of physics at the Furman University South Carolina, with Estle R. Mann, was granted a patent for co-inventing a *Cathode ray tube Amusement Device*. They were working on the development of Cathode Ray Tubes at the DuMont Laboratories. The game featured simulation of a missile being fired at targets. This is the same Cathode Ray Tube (CRT) invented and developed by physicists, and was used in TV's to display the picture since the 1930s.

Around 1960, Brookhaven National Laboratory and MIT created interactive electronic games like *Maze*, *Tic-Tac-Toe*, *Spacewar* and *Tennis for Two*.

It was not until about a decade later that the first successful commercial video games like *Computer Space* and *Pong* were released

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Today, life as we know it, without computers, e-mail, facebook, twitter, instagram ……would not exist.

This is just another small example of things that started as steps in understanding the nature of nature, done in the name of pure science. These insights into the fundamental nature of our universe have affected life for the masses, and in a manner that is beyond anyone's imagination.

Certainly, Babbage, Maxwell, Hertz, Faraday, and all the other important people I have not mentioned, did not work with these results of their research in mind that we see around us today, decades and centuries later.

The fruits of the basic science are now a significant part of the world's economy. We can put a price on the worth of a technology in terms of its economic impact, but its effect on humanity, directly or indirectly, is impossible to factor in. In my opinion, this impact is as large, if not larger, than the economic impact.

When the radio waves or the internet were discovered, no one thought that one day they would be used to communicate from behind the virtual walls, against oppression. This aspect of technology cannot be measured in terms of dollar amount.

A most recent example of such impact—the citizens of the democracies of the world, and their intelligence agencies, are still trying to understand the full impact of dissemination of information, or, more accurately, dis-information, on social media in the last few years.

☆☆☆

Revolution Vs Reform

Applied science leads to reforms,
pure science leads to revolutions,
and revolutions,
political or scientific,
are powerful things if you are on the winning side.

J.J. Thomson

When Thomson remarked on the difference in pure and applied science in 1916, he could not have any idea of the revolution that his and others' discoveries would bring within a few decades.

Thomson discovered electron in 1897.

Thomson in his speech talked about the difference in fundamental and applied science, as quoted in a beautifully written article by the former Director-General of CERN, C.H. Llewellyn Smith, on the benefits of basic science:[44]

By research in pure science I mean research

> *made without any idea of application to industrial matters but solely with the view of extending our knowledge of the Laws of Nature. I will give just one example of the 'utility' of this kind of research, one that has been brought into great prominence by the War - I mean the use of X-rays in surgery...*
>
> *Now how was this method discovered? It was not the result of a research in applied science starting to find an improved method of locating bullet wounds. This might have led to improved probes, but we cannot imagine it leading to the discovery of the X-rays. No, this method is due to an investigation in pure science, made with the object of discovering what is the nature of Electricity.*

Llewellyn Smith further quotes Hendrik Casimir, a theoretical physicist. At the time of these remarks, Casimir was a member of the Advisory Council for Science Policy of the Dutch Ministry of Education and Sciences, and the Director of Research Laboratories for the Philips Industries of Holland. Casimir delivered these remarks in a discussion on the topic of, *Technology: Its Influence on the Character Of World Trade and Investment,* in Technology and World Trade Symposium, 1966.[45]

> *I have heard statements that the role of academic research in innovation is slight. It is about the most blatant piece of nonsense it has been my fortune to stumble upon.*

Casimir went on to elaborate,

> *Certainly, one might speculate idly whether transistors might have been discovered by people who had not been trained in and had not contributed to wave mechanics or the quantum theory of solids. It so happened that the inventors of transistors were versed in*

and contributed to the quantum theory of solids.

One might ask whether basic circuits in computers might have been found by people who wanted to build computers. As it happens, they were discovered in the thirties by physicists dealing with the counting of nuclear particles because they were interested in nuclear physics.

One might ask whether there would be nuclear power because people wanted new power sources or whether the urge to have new power would have led to the discovery of the nucleus. Perhaps - only it didn't happen that way.

One might ask whether an electronic industry could exist without the previous discovery of electrons by people like Thomson and H.A. Lorentz. Again it didn't happen that way.

One might ask even whether induction coils in motor cars might have been made by enterprises which wanted to make motor transport and whether then they would have stumbled on the laws of induction. But the laws of induction had been found by Faraday many decades before that.

Or whether, in an urge to provide better communication, one might have found electromagnetic waves. They weren't found that way. They were found by Hertz who emphasised the beauty of physics and who based his work on the theoretical considerations of Maxwell. I think there is hardly any example of twentieth century innovation which is not indebted in this way to basic scientific thought."

Or whether, in an urge to provide better *communication, one might have found electromagnetic waves. They weren't found that way. They were found by Hertz who emphasised the beauty of physics and who based his work on the theoretical considerations of Maxwell.*

I think there is hardly any example of twentieth century innovation which is not indebted in this way to basic scientific thought.

Two monumental achievements in the field of fundamental science are the theories of quantum mechanics and relativity. These theories provide us with all the ingredients we need to describe the everyday world around us.

The underlying technology in most of the electronics we use today, owes to quantum mechanics, the branch of physics that describes the properties of the semiconductor materials. As we know by now, quantum mechanics was not invented to explain the semiconductor devices.

Einstein was a theorist, and he was certainly not looking to make money through the GPS (Global Positioning System) technology, which would not work without his theory.

Everyone knows how to subtract or add. If we know how to subtract add and divide we know how to look at the changes in different quantities, in a simple case, for example speed of a car. But as soon as the situation gets a little bit more complicated than that, which, in fact, is the case most of the time in the real world, we need calculus.

But, Newton and Liebniz, did not invent calculus with all these applications in mind. Newton invented calculus to solve his problems in physics while trying to understand the motion of planets. Today calculus is one of the most basic branches in science. What is the estimate of monetary value of this science?

The finance market is benefitting from the skilled work-force trained by the fundamental fields of science. And many basic concepts, for example, in theoretical physics, are used in modeling the financial market behavior more accurately.

On another front, who knew that the branches of pure mathematics will be used for homeland security?

It is worth asking whether developments in the industrial sector prompted these fundamental discoveries? Whether these developments in the applied science and industry could even be possible without the fundamental discoveries and an understanding of nature?

In most cases, the products and ideas in applied science get to these fields after they have been shaped, sometimes over the course of centuries, by the people doing the fundamental research.

For example, the heat engine was developed in many steps over many centuries, and includes the work of people like da Vinci, Taqi al-Din, Robert Boyle, Edward Somerset, and many others. These people were not just driven by the desire to invent an engine—they had a variety of interests in many different fields from science to philosophy and theology. They were driven by their desire to understand and harness natural phenomena. They were merely trying to answer their own curiosity. In most cases they didn't even see or realize the full potential of their discoveries in their lifetime.

Margaret Thatcher, a staunch proponent of small government, understood that progress in basic science cannot be judged by its immediate benefits: [46]

> *First, although basic science can have colossal economic rewards, they are totally unpredictable. And therefore the rewards cannot be judged by immediate results. Nevertheless the value of Faraday's work today must be higher than the capitalisation of all the shares on the Stock Exchange!*
>
> *Indeed it is astonishing how quickly the benefits of curiosity driven research sometimes appear. During the Great War, our then President J. J. Thompson, cited the use of X-rays in locating and assessing the damage of bullet wounds. The value of the saving of life and limb was beyond calculation yet X-rays had only been accidentally discovered in 1895!*

One of the important aspects of basic science is the research facility itself, which provides a place to train the next generation of great scientific minds, and a highly skilled workforce.

As Joseph Henry put it,

> *The seeds of great discoveries are constantly floating around us, but they only take root in minds well-prepared to receive them.[47]*

The investment in Tevatron at Fermilab is about $4 billion over couple of decades. The number of Ph.D. and the post-doctoral researchers trained at this facility, about 80% of whom are contributing in diverse sectors of the national economy, alone is enough to compensate this investment in Tevatron.

Yet another facet of these institutions are their public outreach programs like the Saturday Morning Physics at Fermilab. The cultural impact of such events in the area in general is un-calculable. Especially the thousands of students, including K-12, the inspiration and the knowledge that the laboratory and its scientists impart, is unmeasurable, invaluable and irreplaceable. At Fermilab, this program has offered this unique opportunity to about 300 students per year, for the past 30 years.

The general outreach programs, lectures, and other events at such places, reach even a larger number of citizens.

On an even bigger scale, the scientific collaborations, where no immediate economic gains are involved, help create better relationships among nations, even the ones that would not talk to one another in any other setting. For example, after the world war II, CERN played an important role in bringing the European nations together, and had a role in making the European Union. Likewise, Fermilab played an important role in establishing similar international relationships.

Today the corporate giants are making the courts decide whether the human genes, or the shape of their device should be patented? I wonder how much royalty Newton, Röntgen, Sturgeon, Einstein, and countless others received for their contributions?

This is exactly what the difference is between industry and the pure science.

Businesses, and the science driven by businesses, have always immediate material benefits in mind.

The fundamental science and scientists, on the other hand, primarily think about broadening the horizons of the human knowledge. Their efforts inevitably translate into benefits for the whole society. (Ok they do dream about getting Nobel Prize, but that's about as far as the material benefits go.)

So why society supports basic science?

They do it, and they should do it, because the basic science of today drives the technological developments of tomorrow.

Any new phenomena observed inevitably makes it to the mainstream. In most cases, a breakthrough happens only when people try to understand nature, and push the limits of the human knowledge just by being curious.

In the end, no matter which science we are talking about, it will not advance unless we understand that long term progress is always driven by a genuine desire to understand the nature of any given phenomenon, rather than an immediate, commercial goal.

★★★

The 2012 Nobel Prize in Physics went to Serge Haroche and David Wineland. According to the press release,

> *Perhaps the quantum computer will change our everyday lives in this century in the same radical way as the classical computer did in the last century.[48]*

What were they working on? The release states their work in these words:

> *Serge Haroche has designed ingenious experiments to study quantum phenomena when matter and light interact.*
>
> *Using electric fields, David Wineland has*

> *successfully captured electrically charged atoms, or ions, in a kind of trap and studied them with the help of small packets of light, or photons.*

Do the *study quantum phenomena when matter and light interact* sound like something we should spend taxpayers' money on?

If your answer is yes, then discovery of the Higgs boson is also a good bang for your buck.

If history is any guide, every such discovery, sooner or later, finds an important role to play in our everyday life.

☆☆☆

Part V

The Crux

The Human Gene

> *SENATOR PASTORE: Here we are. We have these Senators going all over the District of Columbia. It has been on the front pages. They are going all over the country showing how many people are starving, how many people are hungry, how many people live in rat-ridden houses.*
>
> *Here we are, asking for $250 million to build a machine that is an experimental machine, in fundamental high energy physics, and we cannot be told exactly what we are trying to find out through that machine.*
>
> *DR. WILSON: Senator Pastore, I and my colleagues will be spending a good part of our lives building and using this machine. We have a deep and very personal commitment to it. May I try to explain what it is we are trying to find out.*

Above is a part of the dialogue between Senator John Pastor and Robert R. Wilson, who testified in front of the Congressional Committee, in 1969.

The machine under discussion is the Fermi National Accelerator Laboratory that discovered many fundamental particles, including the top quark in 1995, and the evidence for the Higgs boson in 2012.

Senator Pastore's argument is not new, but Robert Wilson's answer poses some new questions:

Why some of the most brilliant, technically educated minds of the time, would have a deep and personal commitment to a project that, apparently, has no direct benefit for the humanity?

Why would they spend a big part of their lives in endeavors where success is often less likely than failure?

Why they could not think of a better use of their time and energy?

What is it that has more importance to them than the pressing matters facing the rest of the world?

Certainly, they are not doing it for the money, or the fame. Money and fame are not the words that come to mind when one thinks about a physicist.

That reminds me of a statement from Uhlenbeck, one of the two discoverers of electron spin:

> *For me the only trouble was that, to earn money, I accepted a job in my fourth year. I taught mathematics, ten hours a week, at the high school in Leiden. I did not mind the teaching, but I had trouble keeping order in my classes, and I begrudged the time it took. I did not get much sympathy from my father, who pointed out that, as I knew, even with a doctor's degree all I could expect was a job as a high-school or gymnasium teacher in some Dutch town. As he said, "Tu l'as voulu,*

George Dandin"! ("You wanted it, George Dandin.")[49]

Some of these same scientists that Dr. Wilson was talking about, are sometimes recruited by different governments to work on some top-secret projects (like building bombs).

But once this work is over, they go back to their *useless* pursuits.

Why?

Looking around myself, all the people I know, all the people I have read about, heard about, given examples of—asking *why they are so determined to figure out mysteries of nature*, seems like asking why parents try to protect their kids? Why we breath? Eat? Have sex?

The only answer I can think of is—because we need to—this need relates to our life and our survival. Wondering about the mysteries of nature, and then striving to find their answers, is part of the same set of the inherent traits that make us protect our kids, breath, eat, have sex.

Homo sapiens are not the only specie that breaths, eats, procreates, or even cares for its weak. Physically, human beings share a large fraction of their DNA with other animals. There is a reason we test drugs made for humans on animals. Chimpanzees are our closest relatives, as our DNA blueprints are a 99% match. We have been observing these cohabitants of earth with us for thousands of years. How much these other, genetically very similar species, learn from the universe around them? And how much of this acquired knowledge is used to harness the available resources for the benefit of their kind?

Apparently, we are the only specie that not just appreciates the beauty of this universe, but also wonders about its mysteries—and in doing so, can, and do tap into the unknown resources it has to offer.

This is what has made us the civilization we are today.

What is in human beings that makes them think about these issues. Why they are fascinated by the *travel to moon* or the *Big Bang* or *how this universe works?*

There is something in me, and a large number of other people I know, who share the same *mental problem*.

What is more, it is not just those men and women that have spent decades learning about and solving the mysteries of this universe.

How many of us out there would say that they are not interested in the *moon landing* or the *mission to mars*? We may not know why exactly these events and efforts are important, but there is something about them that we can only feel.

I can't resist quoting the memory of one Christopher Flournoy that he shared with BBC on the moon landing in 1969:

> *Although I had only recently celebrated my fifth birthday, I have a very vivid memory of that day.*
>
> *We were all glued to the television at our kitchen table. My brothers and sister and I were gathered around our parents. I was the smallest boy, so I got the privilege of sitting on Dad's lap.*
>
> *I remember, my father being very quiet and mindful of what was being described on TV. Then when Neil Armstrong started down the ladder, I felt a tremor run through my Dad.*
>
> *When he made his famous speech, I felt something wet drop onto the top of my head—I turned to see profuse tears streaming from*

> *my father's eyes and rolling over his cheeks.*
>
> *My father would later say, "Even serving in the war (WWII) paled in comparison." He was never more proud of being an American than on the day our flag flew on the moon.*

The feelings conveyed in this memory are not stranger to me. And I am sure many other people watching that event, and the scientists directly involved in this mission, felt exactly the same in that moment.

This feeling is shared by everyone, scientist or not.

But I have no explanation why we feel the way we do about such things.

The way I felt when I saw the Higgs bump for the first time, reminded me of the moment I saw my son for the first time. I can still vividly see his big black eyes, looking at me intently, all bundled up in the hospital blue blanket, cradled in the arms of one of the nurses. The feeling when I looked at the little bump in the data on top of the smooth background was not as intense, but it is still one of the most memorable moments in my life. I knew in that moment that I was witnessing something incredible and precious.

As a human being, I can explain why I felt the way I do about my son, or my other family members, or why I love food in any shape and form, and same for other human needs.

But I have no explanation, whatsoever, why I felt the way I did about that, apparently good for nothing, bump.

I can still vividly picture myself sitting on the floor in one of the conference rooms, packed with people, trying to control my tears.

And I was not alone.

I know there are thousands of people in the world who have spent sleepless nights, trying to make part of one experiment or another work, or trying to solve a mathematical equation that might lead us to new clues about our mysterious universe.

I also know that they don't do it for the money, or the fame.

In recent times, another small example was seen when, in Sep. 2012, the Endeavor shuttle flew to its retirement destination in LA. Later, the shuttle took a road trip to the museum.

Scientific American noted,

> *.... tens of thousands of residents and visitors are expected turn out to witness Endeavour's slow trek to its new home.[50]*

The Fox News mentioned kids in pajamas waiting for the shuttle [51], CNN reported some of the spectators' feelings:

> *.... I want to be able to share this with my kids, my grandkids, my great-grandkids ... and the children of our school...[52]*

The city of Los Angeles was out on the streets that day. A TV commentator noted how awesome it was that motorways were closed because people just stopped to see the shuttle. He went on to add that there are only five porta potties and long lines, but people are being *so nice to one another*. Not that LA people are usually not nice to one another, but there is no doubt that some things do bring out the best in all of us.

There are some things that connect us not only to nature, but also to one another, and this was one of those things.

But the question remains—why?

Was the Higgs discovery, the shuttle, the moon landing, or the recent discovery of the gravitational waves, good for our economy?

Do such endeavors and discoveries promise to help erase hunger and poverty from earth, or may be help with cure of deadly diseases?

If not, then what instincts make these events important for all of us? And make the underlying science important for many of us, to the point that we are willing to spend our lives trying to discover it.

I wonder how much money would it amount to if a nickel is charged every time someone uses a concept of pure mathematics or physics, discoveries of Newton, or Einstein, or discovery of electron, or of x-rays, ……. and the list goes on.

But we already know that the financial gain was not what drove these efforts.

In the end, it comes down to the human nature—we want to know how this universe works—we have, and we will follow our curiosity.

Asking questions and seeking answers, is the habit that has made us the civilization we are today.

The discovery of the Higgs particle is another giant step in our understanding of this universe. That is why this discovery, and the pride on this accomplishment, belongs to all of us.

The whole world gets excited at such discoveries. Not because they are going to solve the issue of gas prices, but because the curiosity about the universe is common among all of us, no matter who we are or what we do.

Like children, scientists, almost always, very selfishly, pursuit their own curiosity. But to answer their own questions, along the way, they almost always end up benefitting the society.

This, however, remains a bi-product—after all Einstein did not develop the theory of quanta so he could create multi-billion-dollar laser industry.

The era of small, cheap science is over. The time, when a priest could pioneer a scientific revolution by growing peas in his backyard, is gone. Today, the elected members have a responsibility to figure out what resources should be used where? There will always be bridges that need to be built. There will always be presidents who would like to spend millions on weekly trips to their properties. While the facilities like Fermilab will see the cuts in funding.

We have to decide whether we want to spend some portion of today's resources on our future or not? As CERN DG, Rolf Heuer, put it at the time, if you have a sack of corn, you can't use it all, no matter how hungry you are. You must use some of it to get the next crop going.

We need to realize, if history is any guide, this universe is more than eager to share its secrets, and the power that comes with it. But only with those who are willing to try. Leave it to others, and you essentially hand over the ultimate power to others as well.

☆☆☆

The argument here is not that we could not have made *any* progress at all with just applied science.

The argument is not that we could not have survived without these discoveries. After all, we have survived thousands of years without most of the things we can't imagine living without today.

The argument is not how much skilled workforce the funding provides, or how much economic impact the pure research has?

The argument is that the way of life, and the progress we *have* made as human beings, would not have been possible if we have not tried to understand the nature of nature, and in the process, unlocked the full potential of humanity.

The argument comes down to recognizing this *quirk* of pure curiosity, and the courage and the capacity to make use of it, as the most important trait that sets humans apart from all other living beings.

The argument comes down to saving and using this *human gene*, whatever it is, it is what has made us what we are today, by bringing the most out of mankind. This *human gene* should be protected and nurtured at every cost.

As a proud member of a race that wants to explore all that this mysterious universe has to offer for the benefit of its inhabitants, I eagerly await new theories on how this universe works, from the largest to the smallest scale, and the experimental discoveries, giving us better insight into the nature of nature itself.

Let Einstein's beautiful words be a guide to us all:

> *The most beautiful experience we can have is the mysterious. It is the fundamental emotion that stands at the cradle of true art and true science. Whoever does not know it and can no*

longer wonder, no longer marvel, is as good as dead, and his eyes are dimmed. It was the experience of mystery—even if mixed with fear—that engendered religion. A knowledge of the existence of something we cannot penetrate, our perceptions of the profoundest reason and the most radiant beauty, which only in their most primitive forms are accessible to our minds: it is this knowledge and this emotion that constitute true religiosity. In this sense, and only this sense, I am a deeply religious man... I am satisfied with the mystery of life's eternity and with a knowledge, a sense, of the marvelous structure of existence—as well as the humble attempt to understand even a tiny portion of the Reason that manifests itself in nature.[53]

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References

[1]. Holger B. Nielsen, Masao Ninomiya, *Search for Effect of Influence from Future in Large Hadron Collider*, Int. J. Mod. Phys., 2008.

[2]. Holger B. Nielsen, Masao Ninomiya, *Card game restriction in LHC can only be successful!* arXiv:0910.0359 [physics.gen-ph], 2009.

[3]. New Scientist, *Time-travelling Higgs sabotages the LHC. No, really*, 13 October 2009.

[4]. The New York Times, *The Collider, the Particle and a Theory About Fate,* 2009.

[5]. Leon Lederman and Dick Teresi, *The God Particle If The Universe Is The Answer, What Is The Question?*, 1993.

[6]. Albert A. Michelson, University of Chicago Catalogue, 1898.

[7]. A. Einstein, *On a Heuristic Point of View about the Creation and Conversion of Light?* Ann. Physik 17, 132, 1905.

[8]. N. Bohr*, On the Constitution of Atoms and Molecules*, Philos. Mag. 26, 476, 1913.

[9]. Arthur H. Compton, *A Quantum Theory of the Scattering of X-rays by Light Elements*, Phys. Rev. 21, 483, 1923.

[10]. George E. Uhlenbeck, *Fifty Years Of Spin: Personal*

reminiscences, Physics Today, 29, 6, 43, 1976.

[11]. N. Bohr, *The Quantum Postulate and the recent Development of Atomic Theory*, Nature, 121, 580-590, 1928.

[12]. W. Heisenberg, *Physics and Beyond*, 1971.

[13]. Abraham Pais, *Niels Bohr's Times: In Physics, Philosophy, and Polity*. 1993.

[14]. C Moller, Special issue of Fysisk Tidsskrift, 60,1962.

[15]. The New York Times, *Here They Are, Science's 10 Most Beautiful Experiments*, Sep. 24, 2002.

[16]. Physics World, *The most beautiful experiment*, Volume 15, Number 9, 2002.

[17]. The Born - Einstein Letters, The correspondence between Max & Hedwig Born And Albert Einstein, 1916/1955.

[18]. R. A. Bertlmann and A. Zeilinger (eds.), *Quantum [Un]speakables: From Bell to Quantum Information*, 2002.

[19]. Arthur H. Compton and Alfred W. Simon, *Directed Quanta of Scattered X-Rays*, Phys. Rev. 26, 289, 1925.

[20]. Guido Baiagaluppi and Antony Valentini, *Quantum Theory at the Crossroads Reconsidering the 1927 Solvay Conference*, 2009.

[21]. M. Kapitaniak, J. Strzalko1, J. Grabski1, *The three-dimensional dynamics of the die throw*, Chaos 22, 047504, 2012.

[22]. A. Einstein, B. Podolsky and N. Rosen, *Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?* Phys. Rev. 47, 777, 1935.

[23]. N. Bohr, *Quantum Mechanics and Physical Reality*, Nature 136, 65-65, 1935.

[24]. J. S. Bell, *Bertlmann's Socks And The Nature Of Reality*, Invited address to meeting of philosophers and physicists, Paris, 17 June 1980.

[25]. Reinhold Bertlmann, *Magic moments with John Bell*, Physics Today 68, 7, 40, 2015.

[26]. Johanna L. Miller, *Three groups close the loopholes in tests of Bell's theorem*, Physics Today 69, 1, 14, 2016.

[27]. Y. Aharonova, F. Colombod, S. Popescuc, I. Sabadinid, D. Struppab, and J. Tollaksenb, *Quantum violation of the pigeonhole principle and the nature of quantum correlations*, 2015; doi: 10.1073/pnas.1522411112.

[28]. P. A. M. Dirac, *The Quantum Theory of the Electron*, Proceedings of The Royal Society A; doi:10.1098/rspa.1928.0023.

[29]. S. L. Glashow, J. Iliopoulos, and L. Maiani, *Weak Interactions with Lepton-Hadron Symmetry*, Phys. Rev. D 2, 1285, 1970.

[30]. The Large Hadron Collider. http://home.cern/topics/large-hadron-collider

[31]. The ATLAS detector. https://home.cern/about/experiments/atlas

[32]. The CMS detector. https://home.cern/about/experiments/cms

[33].https://lhc-beam-operation-committee.web.cern.ch/lhc-beam-operation-committee/LBOC-Documents.html

[34]. Scientific American, *How the Higgs Boson Might Spell Doom for the Universe,* Mar. 26, 2013.

[35]. The economic Impact of Fermi National Laboratory, http://www.andersoneconomicgroup.com, 2011.

[36]. Robert R Wilson, *Radiological Use of Fast Protons*, Radiology, Volume 47, Issue 5, Nov. 1946.

[37]. Superconducting Magnets—A Global Strategic Business Report. Global industry Analytics, Inc., Annual estimates and forecast 2009-2017.

[38]. Magnetic Resonance Imaging (MRI) Equipment—A Global Strategic business report Global Industry Analytics, Inc., Annual estimates and forecast 2009-2017.

[39]. Illinois Accelerator Research Center. http://iarc.fnal.gov.

[40]. James Clerk Maxwell, *A dynamical theory of the electromagnetic field*, Phil. Trans. R. Soc. Lond. 155, 459-512, 1865.

[41]. www.gov.uk, 2011.

[42]. J. Manyika and C. Roxburgh, *The great transformer: The impact of the Internet on economic growth and prosperity*, Report McKinsey Global Institute, 2011.

[43]. *CERN's LHC pioneers quantum leap in cloud computing*, Computer Weekly, November 2009.

[44]. C.H. Llewellyn Smith, *The use of basic science.* https://public-archive.web.cern.ch/public-archive/en/About/BasicScience1-en.html

[45]. *Technology and World Trade*, Proceedings of A Symposium, U.S. Department Of Commerce / National Bureau of Standards Miscellaneous Publication 284, 1967.

[46]. Margaret Thatcher, 1988, Speech to the Royal Society.

[47]. Presidential Address to the Philosophical Society of Washington, 24 Nov 1877.

[48]. https://www.nobelprize.org.

[49]. George E. Uhlenbeck, *Fifty Years Of Spin: Personal reminiscences*, Physics Today, 1976.

[50]. Scientific American, *Space Shuttle Endeavour to Leave on L.A. Road Trip This Week*, 9 Oct. 2012.

[51]. Fox News, *Space shuttle Endeavour making 12-mile trip to LA museum*, AP, 12 Oct. 2012.

[52]. CNN, *Space shuttle Endeavour rolls into new home as crowds cheer,* 15 Oct. 2012.

[53]. Einstein's 1931 essay, *The World as I see it.*

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