Steven Weinberg : The Physicist and his Physics

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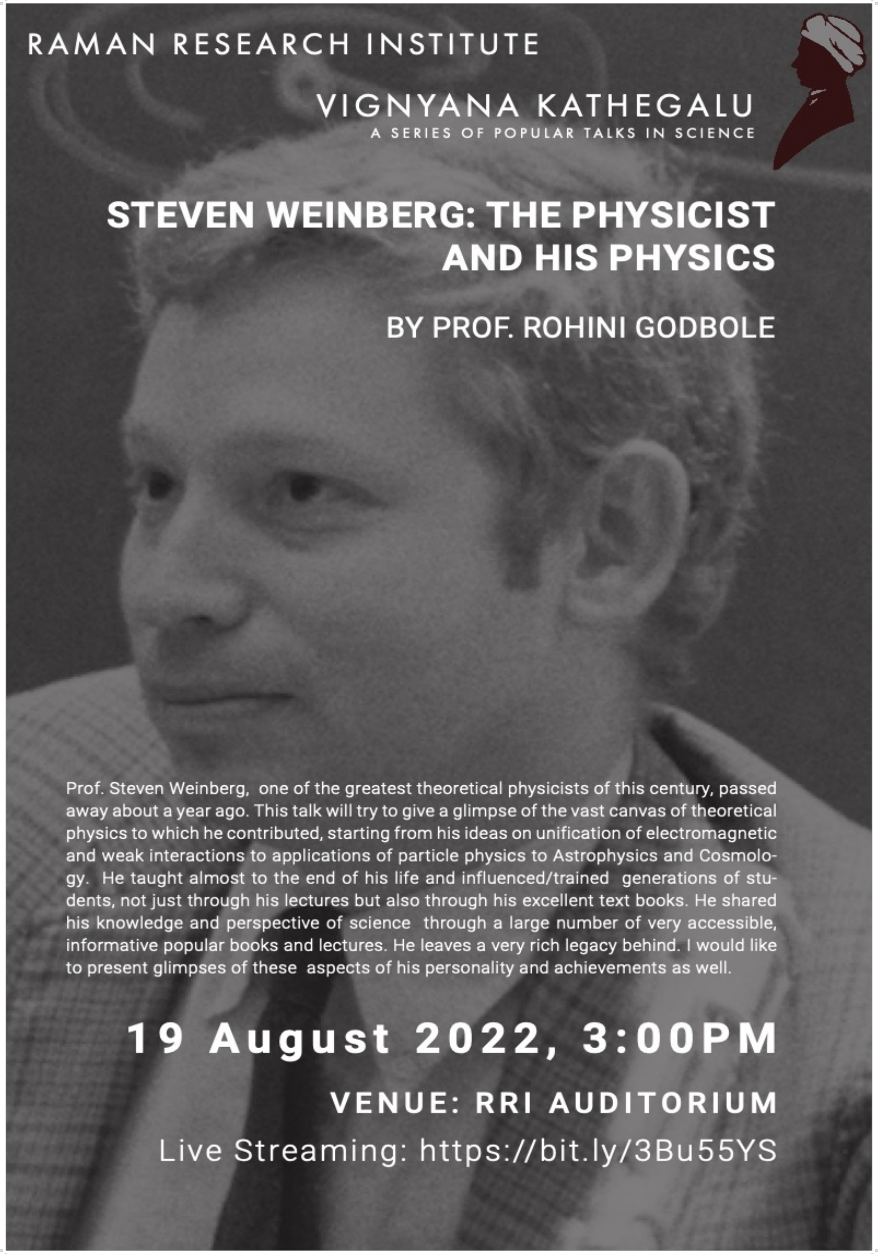
RAMAN RESEARCH INSTITUTE
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A SERIES OF POPULAR TALKS IN SCIENCE
STEVEN WEINBERG: THE PHYSICIST AND HIS PHYSICS
BY PROF. ROHINI GODBOLE
Prof. Steven Weinberg, one of the greatest theoretical physicists of this century, passed away about a year ago. This talk will try to give a glimpse of the vast canvas of theoretical physics to which he contributed, starting from his ideas on unification of electromagnetic and weak interactions to applications of particle physics to Astrophysics and Cosmology. He taught almost to the end of his life and influenced/trained generations of students, not just through his lectures but also through his excellent text books. He shared his knowledge and perspective of science through a large number of very accessible, informative popular books and lectures. He leaves a very rich legacy behind. I would like to present glimpses of these aspects of his personality and achievements as well.
19 August 2022, 3:00PM
VENUE: RRI AUDITORIUM
Live Streaming: https://bit.ly/3Bu55YS

Steven Weinberg: 1933-2021

Photo credit Matthew Valentine, University of Texas at Austin.

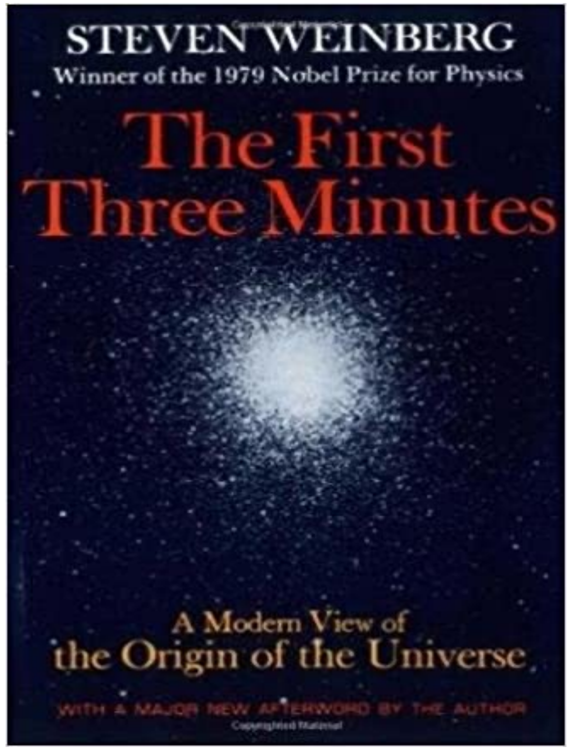
Steven Weinberg was awarded Nobel Prize in 1979
"jointly with Sheldon Lee Glashow, Abdus Salam "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current." (work done in 1967).

First steps towards the Standard Model of Particle Physics which kept this world busy for 50-60 years. Became well known to all only after Higgs boson was discovered (2012).

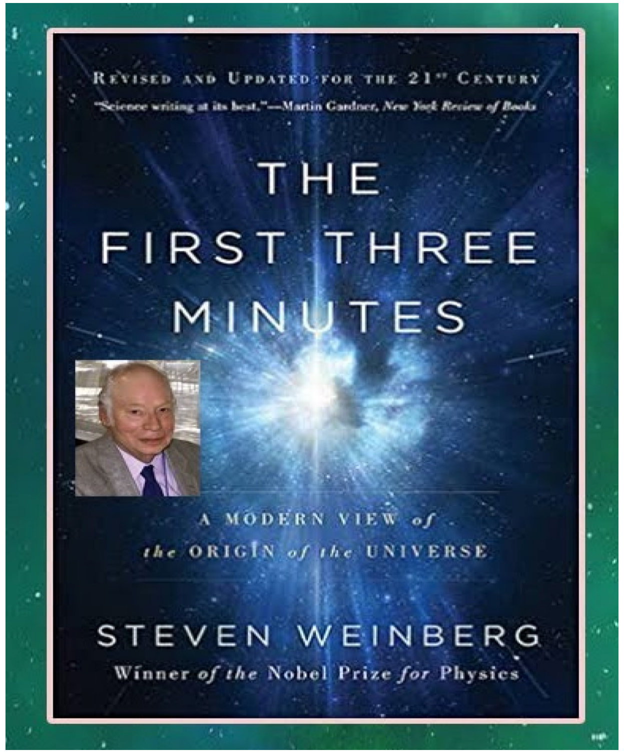
This work is only a part of his legacy for theoretical physics in general and particle physics particular!

To many a lay people he was already very well known through his book on Cosmology: 'The First Three Minutes' !

It has even been translated in Indian languages



My personal copy
1977



Revised and expanded
1992

Steven Weinberg: the physicist

1) Steven Weinberg was one of the most influential theoretical physicist of the 20 th Century.

2) His work and contributions comparable to Rutherford, Bohr, Paul Dirac and Enrico Fermi.

3) The paths in theoretical (particle) physics he chartered became the Highways for the world of particle physics for the past 60 years and were also important for other branches.

4) In some sense unification : of interactions, of ideas and disciplines was his passion!

Plan

A very brief description of the legacy by Steven Weinberg from 'The Unified theory of Electromagnetic and Weak Interactions' to the 'Theory of Everything'.

His legacy as a teacher not just for the University students but for all in general !

Weinberg's opinions and advise on practice of Science : Weinberg the advocate of Science, Weinberg on History of Science,……….

There is a lot more to the man and his science.

Obituaries of Steven Weinberg , (R.M. Godbole and Urjit Yajnik), Physics News(July-Sep, 2021), Current Science 10 September 2021.

Steven Weinberg

Steven Weinberg passed away on 23rd July 2021 at the age of 88 . He held the Josey Regental chair at the University of Texas (UT) at Austin at the time.

The world of physics truly mourned his passing away. He was a brilliant theoretical physicist who dominated the world of particle physics from the 60's to late 80's. There is hardly an area in the development of particle physics where he did not leave his footprint.

He continued doing so till the end. His latest book `Foundations of Modern Physics ' was published in April 2021.

He uploaded a paper on the High Energy Physics ArXives as late as January 2021!

Steven Weinberg

He said in an interview

"I plan to retire shortly after I die"!

This prediction of his also came to be true.
He continued to teach actively at the UT till the end

I remember listening to an online lecture by him in April 2020 which kicked off an International lecture program, when he called his secretary to tell the students to wait for ten minutes so that he could answer our questions! Not once did he look at his notes while giving that lecture at the age of 87! (Quote the experience of students)

Worldline

Born in New York to immigrant parents in 1933. First one from the family to have a college education.

Went to the Bronx High School for Science which boasts of at least seven Nobel Laurates among its alumni, Steven Weinberg and Sheldon Glashow being two of them! They were in the same class!

Melvin Schwarz : μ neutrino; D.Politzer : QCD (Theory of Strong Interactions); Roy Glauber : Quantum Optics, ------

1954: Graduated from Cornell University.
(I was born in 1952, so this puts it in perspective for me!)

Worldline (con.)

1957: Finished his Ph.D. in Princeton and settled in Berkeley as a faculty after spending time in Columbia and Berkeley as a PDF.

1966: Moved to the east coast first to MIT/Boston University and then to Harvard where his wife (now Law prof.) Louise Weinberg wanted to pursue a degree in law.

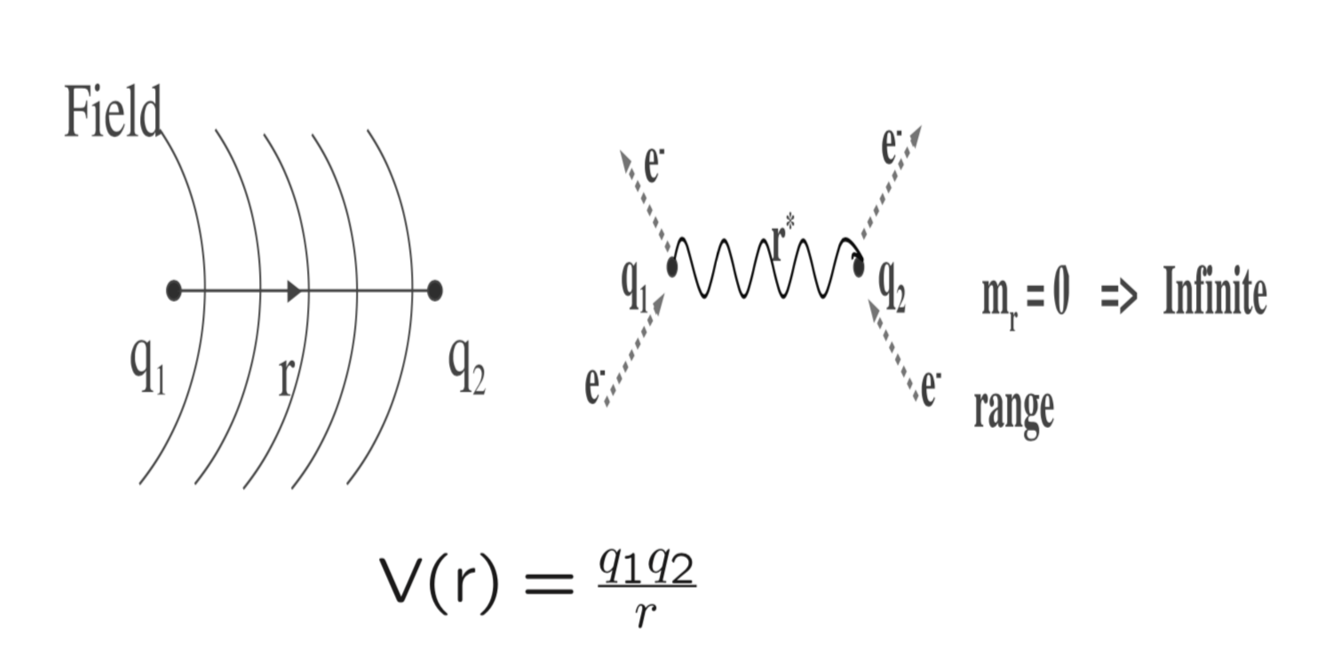
I found this very endearing:
"a lot of my thinking was done while sitting on the park benches and watching my daughter play"

1979: He and his wife made a move to UT (Austin) where Prof. Louise continues to be a professor.

Situation circa 1960

Quantum Field theory had been developed. A framework constructed on the principles of the Special theory of Relativity and Quantum Mechanics.

First step in understanding interactions in terms of the exchange of a force carrier was complete. Feynman, Tomanaga and Schwinger had finished the formulation of Quantum Electrodynamics



Situation circa 1960 (con.)

For the strong and weak interactions situation was very confusing. Experiments were far ahead of the theory.

Strong:
Gell-Mann and Zweig had made some sense of the Particle Zoo in terms of the Quark Model. But no free quarks were seen. Not all believed in them (including Weinberg)

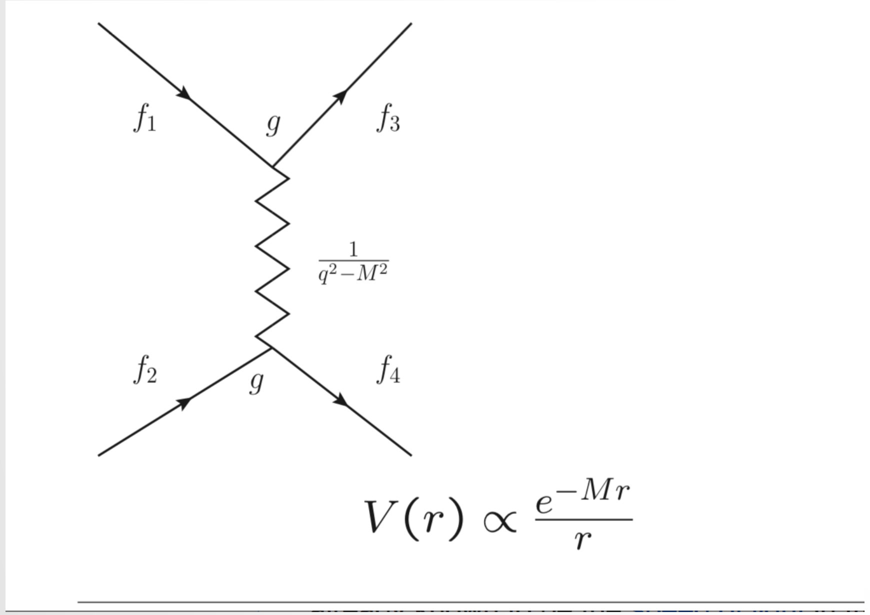
Yukawa's theory qualitatively explained nuclear force in terms of pion exchange. (exactly like photon exchange in the last slide!)

But strength of the coupling being large known methods of computations did not work. Worse there were many different models!

Situation circa 1960 (con.)

Weak Interactions:

Thanks to E.C.G. Sudarshan and Marshak as well as Feynman and Gell-Mann, and Schwinger some understanding existed. The general idea was that like the 'photon' there is a 'weak anologue of the photon' .



BUT:

Short range of the weak interactions meant that the 'mediators' were super heavy.

The photon on the other hand had zero mass!

Further, predictions of the theory made no sense in higher order in perturbation theory or for high energies!

Confusion is an opportunity for creativeness

Crisis: Is Field Theory the correct framework?

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Precisely such mess is what he loved. His advise to young students

"My advice is to go for the messes — that's where the action is."

"Particle physics…really was a mess in the 1960s, but since that time the work of many theoretical and experimental physicists has been able to sort it out, and put everything (well, almost everything) together in a beautiful theory known as the standard model. "

"to continue using my oceanographic metaphor, is that while you are swimming and not sinking you should aim for rough water. "

He, of course, was preaching what he practiced!

Situation circa 1960 (con.)

In fact, Weinberg's work produced order in the chaos for both these subjects.

1) Formulation of Effective Field Theories:
Once again relevant today

2) Electroweak Unification:
The unified description of Electromagnetic and Weak Interactions that was theoretically well founded and made sense of the chaos.

This work was work done in 1966/1967.

I should emphasize he had already done enormously important work of very technical nature and was a very well recognized authority in 'Field Theory' and 'Renormalisation'. Will not mention/discuss that work here!

(1966) Order out of Chaos: Strong Interactions

He showed that while one could not do calculations using perturbation theory because the coupling was very strong he proposed a new framework to do calculations: an expansion in inverse powers of energy! Indeed, he was then able to make predictions in this formalism for the 'pion-nucleon' cross-sections in terms of a parameter or two which were determined independently in other experiments.

As he himself said:

My style is .... to interpret in a broad way what is going on and make very general remarks, like the development of the point of view associated with Effective Field Theory .

As it happens it also made a very good prediction!

1966: Effective Field Theory

In fact soon after this, particle physicists discovered that the strong interactions could be described in using 'Quantum Chromodynamics', in terms of quarks and gluons. (Politzer from the Bronx High School got the Nobel Prize for work in this theory)

But framework introduced by Weinberg remained effectively the only one to handle strong interactions among composite objects : pions and nucleons.

Not just that, later the ideas offered a possible theoretical understanding of why the 'neutrinos' are so incredibly light ($\frac{m_\nu}{m_{top}} \simeq 10^{-13}$ at least). And today the framework is used even in condensed matter theory.

1966: Effective Field Theory

In spite of the success, the SM is incomplete in many ways and many problems are not yet fully resolved in its framework!

Dark Matter, Matter-Antimatter Asymmetry in the Universe….

This means that the Beyond Standard Model Physics (BSM), particles and interactions outside the SM, lie at high energy, like the W-boson was in 1966, and hence an effective theory description is the best way to proceed now to make sense of the current **mess**.

So, the methods invented by him are the best tools for now!

1967 : Weak Interactions

'A model of Leptons': a three-page paper. As far as the leptons are concerned not a line has to be changed in the paper today if it has to be put in a textbook (and is indeed in many a textbooks!)

Basic message was that the electromagnetic and weak interactions are actually the same when the energies are very high with respect to the masses of the W/Z bosons. He showed how the nonzero masses of leptons and quarks were also compatible with gauge principle : the basis of the Standard Model now!

A result obtained by Peter Higgs (Englert and Brout as well) made this possible! In fact, along with Salam and Goldstone he had written an influential paper, Higgs et al had found a loop-hole there!

A model of Leptons

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

and on a right-handed singlet

$$R \equiv [\tfrac{1}{2}(1-\gamma_5)]e. \tag{2}$$

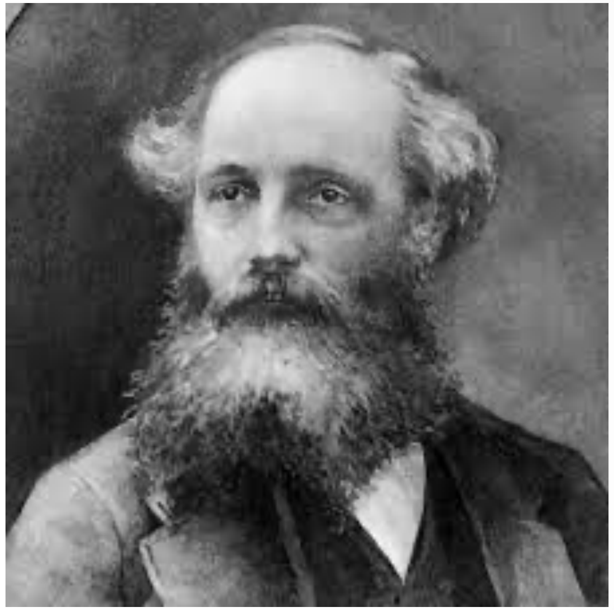
The largest group that leaves invariant the kinematic terms $-\bar{L}\gamma^\mu\partial_\mu L - \bar{R}\gamma^\mu\partial_\mu R$ of the Lagrangian consists of the electronic isospin $\vec{T}$ acting on L, plus the numbers N_L, N_R of left- and right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q = T_3 - N_R - \tfrac{1}{2}N_L$, and the electron number $N = N_R + N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y \equiv N_R + \tfrac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero dou-

Did we know of such unification before?

Earlier Unification

We know of one more unification of two different phenomena: Electricity and Magnetism.



Velocity of light 'c' was 'predicted' in terms of the electric and magnetic permeability of vacuum: ϵ_0 and μ_0 measured in completely independent ways:

$$\frac{1}{c^2} = \epsilon_0 \, \mu_0$$

Predictions of the Lepton Model:

1) Existence of a heavy counterpart of the photon which would mediate new weak interactions, the so called 'neutral current interactions'

2) Predictions of the masses for the W and Z and also of couplings of leptons with the Z boson in terms of the electron charge e and a parameter θ_W.

The Nobel prize was given when this was confirmed! (W/Z were not seen. Experiments did not have enough energy to produce them!)

The Standard Model (SM) is nothing but the model of leptons extended to include the quarks and strong interactions.

This indeed kept the particle physics community busy for 60 years!

A model of Leptons

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What did Weinberg himself felt about this work?

In an interview to CERN courier on the occasion of his winning the 'breakthrough prize in fundamental physics' he said, *"But it was rather untypical of me. My style is usually not to propose specific models that will lead to specific experimental predictions…"*

On being introduced as a "model builder' he said he "**had proposed only 'a' model.**"

And what a model it was. It went on to become the 'theory'!

A model of Leptons

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He himself felt that the model *"has too many arbitrary features…"*. The most arbitrary of them all were the parameters corresponding to the masses of the quarks and leptons.

Trying to address this mass problem without the arbitrary parameters occupied him for quite some time!

He wrote a paper 'A model for Quark and Lepton masses' in January 2020. He said it was not a realistic model but an idea! So far it has not found followers! But the 'A model of Leptons' also did not get any attention in the first few years. (😁)

Unification Further

Unification of all the interactions is a dream many shared beginning from Einstein!

Georgi and Glashow proposed the idea of unification and suggested proton could decay to a π (made of a quark and antiquark) and an electron.

Weinberg, Quinn and Georgi predicted the proton decay lifetime to be 10^{30} years using the measurements of these couplings at low energies and rules of Quantum Field Theory!

More importantly gave a prediction for existence of particles with very large masses. Opened a new vista!

Just to give an idea the masses we are talking about are $\mathbf{10^{16}}$ GeV

Unification further

In lectures given in a school at Brandeis University Weinberg conjectured that the ideas of grand unification and the observation of CP violation means that particle physics ideas might have relevance to what happened in the early universe.

These contained the seeds of an explanation of the matter antimatter asymmetry in the Universe. This is indeed one of the most active areas of research at present and is an important part of a subject called 'Astroparticle Physics' . Unification of different fields: Particle physics, Cosmology and Astrophysics.

In the 60's Weinberg was one of the few going on this path! (He was following the likes of Bethe and Gammow here!). Today Astroparticle Physics is indeed the forefront of scientific explorations, now including gravitation as well!

Gravity and Cosmology

Gravity, Quantum Field Theory and massless particles were his abiding interests.

In his early work he gave clarity to the formulation of Quantum Field Theory and proved 'inter alia' that Special theory of relativity and quantum mechanics tells us that a massless spin 2 particle has to be a graviton! This opened up the doors for Quantum Gravity theories in a way!

His interest in gravity drove him to understand the subject of 'Observational Cosmology'. His pursuits in Cosmology yielded an understanding of the 'cosmological constant problem'.

Gravity and Cosmology

General theory of relativity allows possible existence of a constant in its equations called the cosmological constant Λ. It has units of energy per unit volume, with dimensions of $(energy)^4$. Observed Universe is flat and large. The energy density of our large and flat Universe was known to be small:

$\boldsymbol{\rho_v \sim 10^{-26}\ kg/cm^3}$ or equivalently $\boldsymbol{\Lambda_{obs} \sim (10^{-10})\,(eV)^4}$

Naive classical predictions of were $\mathbf{10^{120}}$ times the observed energy density. Quantum theory predicted it to be $\boldsymbol{(100\ GeV)^4}$ which is $\mathbf{10^{55}}$ times bigger than the observation.

Gravity and Cosmology

The question was why is it so small?
Anthropic principle: It is as small as it is because otherwise, we will not be here to ask this question.

But Weinberg wanted to make this answer more meaningful and quantitative.

Weinberg gave an explanation based on the 'Anthropic Criterion' that the size of this constant be such that it allowed formation of galaxies and hence our presence. He, with Shapiro and Martel predicted a value for it .

The observation of an expanding, accelerating Universe yielded a small value for $\boldsymbol{\rho_v}$ consistent with the prediction. This is what we call Dark Energy.

The current problem is why the observed $\boldsymbol{\rho_v}$ is of same order as mass destiny $\boldsymbol{\rho_{\mathrm{m}}}$!

VOLUME 59, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1987

Anthropic Bound on the Cosmological Constant

Steven Weinberg
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(Received 5 August 1987)

In recent cosmological models, there is an "anthropic" upper bound on the cosmological constant Λ. It is argued here that in universes that do not recollapse, the only such bound on Λ is that it should not be so large as to prevent the formation of gravitationally bound states. It turns out that the bound is quite large. A cosmological constant that is within 1 or 2 orders of magnitude of its upper bound would help with the missing-mass and age problems, but may be ruled out by galaxy number counts. If so, we may conclude that anthropic considerations do not explain the smallness of the cosmological constant.

PACS numbers: 98.80.Dr, 04.20.Cv

Reviews of Modern Physics, 1989

The cosmological constant problem*

Steven Weinberg
Theory Group, Department of Physics, University of Texas, Austin, Texas 78712

Astronomical observations indicate that the cosmological constant is many orders of magnitude smaller than estimated in modern theories of elementary particles. After a brief review of the history of this problem, five different approaches to its solution are described.

Textbooks

Weinberg was a great and consummate teacher.

"As is natural for an academic, when I want to learn about something, I volunteer to teach a course on the subject."

Almost every time then it led to a book.

It began with two volumes on Quantum Field Theory

His scholarly monograph "Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity" published in 1972 heralded the cross-fertilisation between the two disciplines of Elementary Particle Physics and Cosmology.

Many a particle physicists trained on these books!

Textbooks (con.)

From the preface to Gravitation and Cosmology.

"I found that in most textbooks the geometric ideas were given a starring role … so that a student would come away with the impression that this had to do with space-time being a Riemannian manifold."

Later in the same book, he said

"The important thing is to be able to make predictions about the images on the astronomers' photographic plates … and it simply doesn't matter whether we ascribe these predictions to the physical effects of gravitational field …. ..or curvature of space time"

An approach which attracted many a particle physicists to the book and then to the field

Textbooks (con.)

His almost compulsive need to clarify and elucidate led him to pen a series of monographs and books!

Early 2000's he wrote a modern sequel to 'Gravitation and Cosmology' , called "Cosmology", informed by the latest experimental data giving an analytic understanding of the phenomena occurring in the early Universe. Then he started writing books on 'Quantum Mechanics, Modern Physics'…

The books "talk" to the reader, avoid scholarly rubric, and yet make a lasting impact as the most enduring scientific monographs.
His books are always accessible to the students with great clarity but also an uncompromising rigour. These textbooks are an important part of his legacy.

I personally have all of them except the : 'Foundations of Modern Physics!

Popular Writings

His book on 'Cosmology and Gravitation' led to his first popular science book 'The First Three Minutes' in 1977. Many were to follow. 'The discovery of subatomic particles (2003) and 'Dreams of a final theory (1994)' are two which we can mention here.

His touchstone for popular science was that the arguments must remain true to science, yet accessible to an intelligent non-scientist reader.

"I think it's very important not to write down to the public. You have to keep in mind that you're writing for people who may not be mathematically trained but are just as smart as you are."

Advise to young scientists

He had spent one year in Niels Bohr Institute on a Fellowship before joining Princeton. He did his first piece of research there and it was about theoretical issues with the 'Lee Model' of strong interactions!

It is this experience that was behind his advice to young people, given much later at the graduation address at McGill University: "*You don't have to know everything because I didn't when I got my PhD.*"

He advised young people to learn things on the job as it were, as one goes along working on the subject!

He used this 'swimmer' analogy to describe pursuit of Science often!

Thoughts on Science and Society

He wrote extensively on science, history of science, science and religion....They have been published as articles and books!

He was aware of the dangers of rising anti-science sentiment from religious, political and philosopher lobbies

In a talk at a graduation ceremony, he called upon the students at a college to become his "*allies in a movement … known as the Enlightenment*", because *"the ethos of the Age of Enlightenment has made the world a freer and gentler place"* and urged them "*to guard against the dilution of its values*".

Age of Enlightenment: Time from Newton's Principia

Thoughts on Science and Society

He told students:

"As you will learn rich history of Science, you will come to see how time and time again - from Galileo through Newton and Darwin to Einstein - science has weakened the hold of religious dogmatism".

Dreams of a Final Theory

He told Graham Farmelo in an interview:

"I could only be happy as a theorist if experimenters were giving me regular feedback from nature about my speculations. "

To me it really examplifies what drove his scientific pursuits.

But he was fully supportive of practitioners of String Theory! He believed that we might be in for a long haul or for a change of paradigm in our search for an understanding of nature!

Dreams of a Final Theory (con.)

This book takes us to the future, the promise of superstring theory at the turn of the twenty-first century. He also said in an interview that this future seems further away than we had hoped it to be.

An interesting point he makes is that if the promise of string theory as a "final theory" is borne out, the endeavour of Physics as a "Mathematical Philosophy of Nature" started by Newton will be finished.

Summary

I will direct you to obituaries in PN and CS, for some personal stories by Urjit Yajnik

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In summary I hope you would agree with me that this was a life of science lived with the single-minded pursuits about the truths of nature. He had said in interviews that science strives to understand why things are the way they are!

He felt that pursuit of science brings solace to one's mind. He said in 'The First Three Minutes':
"The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce and gives it some of the grace of tragedy".

Indeed, he has done that for all of us who are interested in Science! We are all his students!

Personal Connections

I did not have any direct personal connection, but I can quote examples how his work had 'directly' affected what I did.

I am a child of the days when the 'Standard Model' became 'Theory of fundamental particles and interactions among them'! So clearly that is an obvious influence! A major part of my research was on suggesting methods to 'test' the SM and probe physics beyond it.

Apart from this very generic statements there has been very direct influences also.

Let me give a few examples.

Lower Bound on the mass of the Higgs boson!

Mass of the Higgs Boson*

Steven Weinberg
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(Received 15 December 1975)

The stability of the vacuum sets a lower bound of order $\alpha G_F^{-1/2}$ on the Higgs-boson mass. For the simplest $SU(2) \otimes U(1)$ model, this lower bound is $1.738\alpha G_F^{-1/2}$, or 3.72 GeV.

If the light Higgs boson has a mass of order 5–10 GeV, the best place to produce it may be in a neutrino reaction.[8] For a center-of-mass energy E between M_H and μ_W, the light Higgs boson would tend to be emitted from the exchanged intermediate vector boson line. Aside from numerical phase-space factors, the probability of producing the Higgs boson would be of order $G_F E^2$.

Physical Review Letters 36 (1976) 294

My second single author paper

PHYSICAL REVIEW D VOLUME 18, NUMBER 1 1 JULY 1978

Trimuon events due to neutrino- and antineutrino-induced production of vector mesons and Higgs bosons

Rohini M. Godbole
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(Received 30 November 1977)

We calculate the charged-current neutrino production of the vector bosons ρ, J/ψ, Υ via their electromagnetic couplings. We also consider the production of a Higgs boson H. We add the decay of these particles into $\mu^+\mu^-$ pairs and calculate the event rates and distributions for these trimuon events. We also discuss the antineutrino production of these particles and their decays resulting in $\mu^+\mu^+\mu^-$ events.

(b)

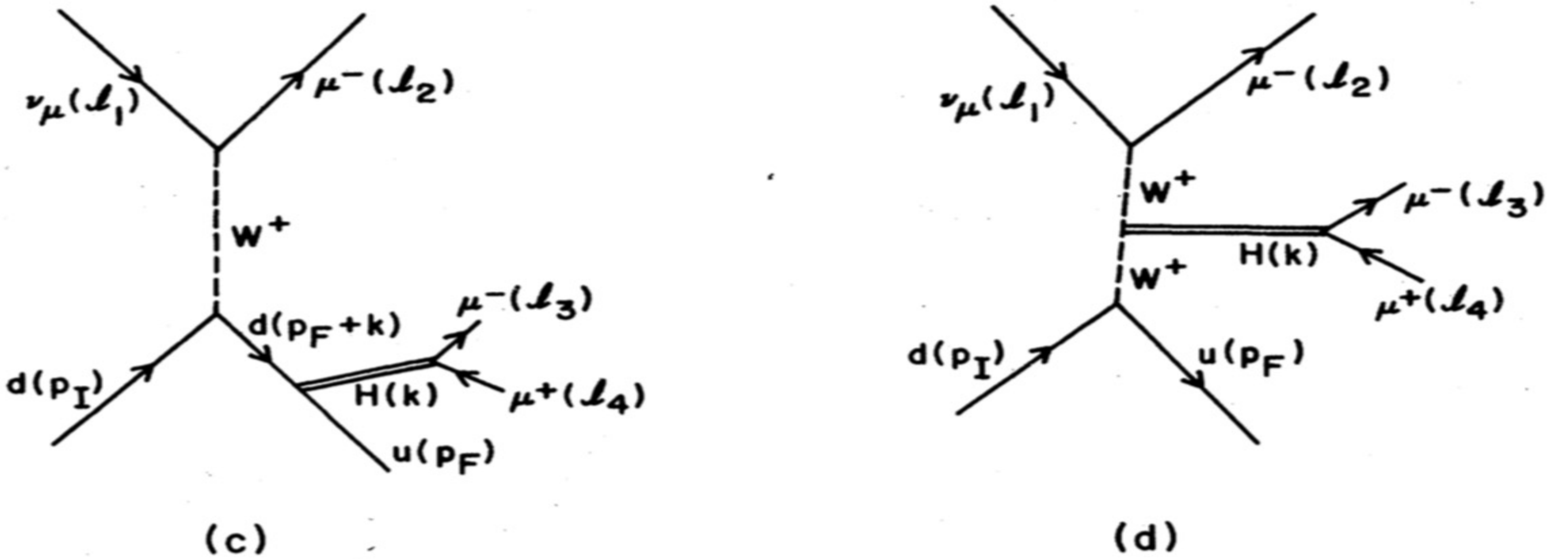


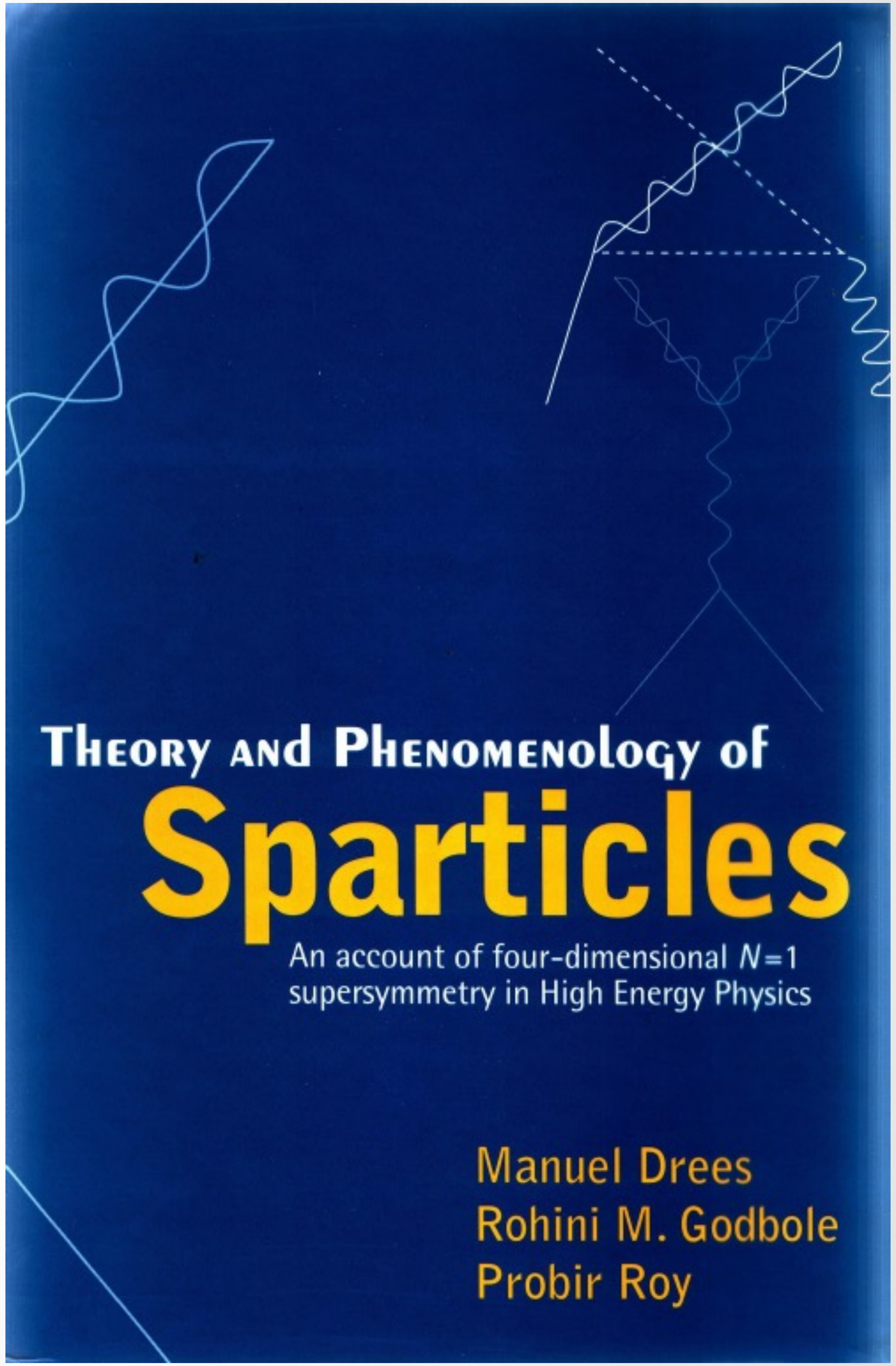
FIG. 3. Feynman diagrams for the production and decay of the Higgs boson.

My entry into Supersymmetry

I 'grew' in the home of formal studies of a subject called Supergravity in Stony Brook University till 1979, but it never caught my attention!

It was a paper by Weinberg written in 1983 which got me 'directly' interested in Supersymmetry Phenomenology!

Not just that I learnt 'Supersymmetry' from his 'lecture notes' of a course given at UT, Austin, Texas. I ended up writing a textbook on Supersymmetry!



VOLUME 50, NUMBER 6 PHYSICAL REVIEW LETTERS 7 FEBRUARY 1983

Upper Bound on Gauge-Fermion Masses

Steven Weinberg
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(Received 22 November 1982)

A large class of broken supersymmetry theories is shown to imply the existence of fermions $\lambda^{\pm}$ and λ^0, lighter than or nearly degenerate with the $W^{\pm}$ and Z^0 gauge bosons, and with vanishing baryon and lepton number. If the $\lambda^{\pm}$ is appreciably lighter than the $W^{\pm}$ it can be readily produced in $W^{\pm}$ decay, as well as in e^+-e^- collisions.

PACS numbers: 11.30.Pb, 14.80.Er, 14.80. Pb

quark mass matrices. Furthermore, we find that the simultaneous existence of a light photino and a chargino with mass below $M_Z/2$ is strongly disfavored. We finally discuss the possible effects of new physics on the bounds on the top-quark mass and the number of light neutrino species that can be derived from the experimental upper bound on R.

PHYSICAL REVIEW D VOLUME 37, NUMBER 7 1 APRIL 1988

Do data on *W* and *Z* decays already constrain nonstandard physics?

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