R.P. Feynman

Janusz Gluza

BALATON2018 - Feynman Memorial Meeting

Balaton, Hungary, 18 September 2018

BACKUP SLIDES

My story, at the beginning was a word, "Feynman"

PHYSICAL REVIEW D VOLUME 45, NUMBER 5 1 MARCH 1992

Feynman rules for Majorana-neutrino interactions

J. Gluza and M. Zrałek*

Department of Field Theory and Particle Physics, Institute of Physics, University of Silesia, 40-007 Katowice, ul. Uniwersytecka 4, Poland

(Received 25 July 1991)

Simple Feynman rules for Majorana neutrinos and Dirac fermions interacting with spin-1 or spin-0 bosons are presented. Several examples using these rules are given.

PACS number(s): 13.15.−f, 11.15.Bt, 13.10.+q

A. Denner, H. Eck, O. Hahn and J. Kublbeck, "Compact Feynman rules for Majorana fermions", Phys. Lett. B **291** (1992) 278.

A. Denner, H. Eck, O. Hahn and J. Kublbeck, "Feynman rules for fermion number violating interactions", Nucl. Phys. B **387** (1992) 467.

"... he [Feynman] remembered thinking how amusing it would be if one day the Physical Review were full of them [diagrams]."

$N^C = N; \quad a, a^\dagger$

$$N_\alpha(x) = \sum_{\lambda=\pm 1/2} \int \frac{d^3k}{(2\pi)^3 2E} [u_\alpha(\mathbf{k},\lambda) a(\mathbf{k},\lambda) e^{-ikx} + v_\alpha(\mathbf{k},\lambda) a^\dagger(\mathbf{k},\lambda) e^{ikx}] , \quad (2.5)$$

$$N_\alpha^C(x) \equiv \mathbf{C} N_\alpha(x) \mathbf{C}^{-1} = C_{\alpha\beta}[\bar{N}^T(x)]_\beta = N_\alpha(x) ,$$

where $C_{\alpha\beta}$ is the 4×4 charge-conjugate matrix in Dirac space

$$C\gamma^\mu C^{-1} = -\gamma^{\mu^T}, \quad C^\dagger = C^{-1}, \quad C^T = -C . \quad (2.6)$$

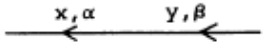
The Feynman vertices will be described by the $\Gamma^\mu_{(x)}$ or $\Gamma_{(x)}$ matrices and their charge-conjugate quantities

III. THE FEYNMAN RULES

We will present our Feynman rules for the Majorana fermion interactions given by (2.1)–(2.4). On Feynman diagrams the Dirac fermion will be depicted by a double continuous line (═══), the Majorana fermion by a single line (———) and other particles will be depicted traditionally.

The problems arising with the Feynman rules for Majorana neutrinos are connected with the fact that Majorana fields satisfy the self-conjugate condition (2.5). The basic propagator for Majorana neutrinos is the same as for Dirac fermions:

$$\langle 0|T[N_\alpha(x)\bar{N}_\beta(y)]|0\rangle \equiv iS_{\alpha\beta}(x-y) = \quad (3.1)$$



where

$$S(x-y) = i\int \frac{d^4x}{(2\pi)^4} e^{-i(x-y)k} \frac{\hat{k}+m}{k^2-m^2+i\epsilon} ,$$

and describe the fermion created at y and annihilated at x. Using the relations $N^T = \bar{N}C^T$ and $\bar{N}^T = C^{-1}N$ valid for Majorana particles (2.5) we can define the other three propagators,

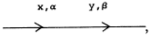
$$\langle 0|T[N_\alpha(x)N_\beta(y)]|0\rangle \equiv -i[S(x-y)C]_{\alpha\beta} = \quad , \quad (3.2)$$

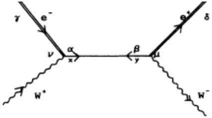
describing the Majorana neutrino annihilated at x and y,

$$\langle 0|T[\bar{N}_\alpha(x)\bar{N}_\beta(y)]|0\rangle \equiv i[C^{-1}S(x-y)]_{\alpha\beta} = \quad , \quad (3.3)$$

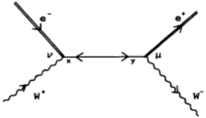
where the particle is created at x and y, and finally

$$\langle 0|T[\bar{N}_\alpha(x)N_\beta(y)]|0\rangle \equiv -i[C^{-1}S(x-y)C]_{\alpha\beta} = \quad , \quad (3.4)$$

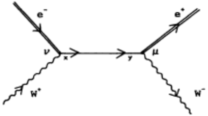




$$=[i\Gamma^{\nu}]_{\alpha\gamma}[iC^{-1}S(x-y)]_{\alpha\beta}[i\Gamma^{\mu}]_{\beta\delta}$$
$$=[i\Gamma^{\nu}]^{T}[iC^{-1}S(x-y)][i\Gamma^{\mu}]\ , \tag{3.10}$$

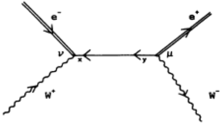


$$=[-iC^{-1}\Gamma^{\nu}]^{T}[-iS(x-y)C][-iC^{-1}\Gamma^{\mu}]\ , \tag{3.11}$$



$$=[i\Gamma^{\nu}]^{T}[-iC^{-1}S(x-y)C][-iC^{-1}\Gamma^{\mu}]\ , \tag{3.12}$$

and



$$=-[iC^{-1}\Gamma^{\nu}]^{T}[iS(x-y)][i\Gamma^{\mu}]\ . \tag{3.13}$$

We may see that in all four cases we end up with the same amplitude ($C^{T}=-C$):

$$T_{e^{-}W^{+}\to e^{+}W^{-}}\sim -iC^{-1}[\Gamma_{C}^{\nu}]S(x-y)[\Gamma^{\mu}]\ . \tag{3.14}$$

Drawing apart...

THE UNIVERSITY OF CHICAGO PRESS BOOKS

ABOUT | C

{ BOOKS } | JOURNALS | CHICAGO DISTRIBUTION CENTER | INFO & SERVICES

Browse by: SUBJECT | SERIES

BUY THIS BOOK

Paper $46.00
ISBN: 9780226422671
Published June 2005

E-book $10.00 to $46.00
About E-books
ISBN: 9780226422657
Published November 2009
Also Available From

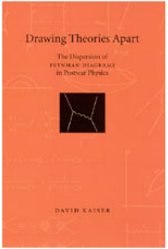
Instructors
Get Exam Copy or Adopt this Text

Librarians
Information and E-books

Rights, Permissions & Translations
Licensing from a Book

Drawing Theories Apart

THE DISPERSION OF FEYNMAN DIAGRAMS IN POSTWAR PHYSICS



Google Preview

DAVID KAISER

376 pages | 15 halftones, 73 line drawings, 2 tables | 6 x 9 | © 2005

Winner of the 2007 Pfizer Prize from the History of Science Society.

Feynman diagrams have revolutionized nearly every aspect of theoretical physics since the middle of the twentieth century. Introduced by the American physicist Richard Feynman (1918-88) soon after World War II as a means of... ***Read More***

Drawing apart...

Feynman first introduced his novel diagrams at a special, by-invitation-only meeting at the Pocono Manor Inn in rural Pennsylvania during the spring of 1948.

"**And yet, by all indications, his inaugural presentation of the diagrams was a flop. The odds were stacked against him:** Feynman's presentation followed a virtuoso lecture by his young rival, Julian Schwinger, that stretched into an all-day affair, punctuated only by a break for lunch. Schwinger's magnetic-moment calculation had already brought widespread acclaim just a few months earlier. At the Pocono meeting, Schwinger demonstrated his new methods with a dazzling display of austere mathematical sprezzatura-a display that likely reminded several of his listeners of Oppenheimer's famous grandiloquence. Though few in the room could follow Schwinger's derivation line by line, all could appreciate that it took the form of a derivation: the performance in itself signaled to most that the problem of renormalization was in good hands.

Drawing apart...

Schwinger had spent the war working on radar. Collaborating closely with electrical engineers, he had learned that many electrical calculations became tractable only if one "blackboxed" various circuit components, calculating in terms of effective input-output variables instead of the "fundamental" variables that appeared in the original equations.

Drawing apart...

Coming late in the day, in contrast, Feynman's blackboard presentation was rushed and often interrupted.
Niels Bohr raised repeated objections to the very notion that spacetime diagrams could be of any help for studying what Bohr insisted were inherently unvisualizable quantum phenomena.
Dirac pressed Feynman on the question of "unitarity,"
"Most important, Feynman's weary auditors repeatedly wondered aloud what rules-if any-governed the diagrams' use. The official notes from the meeting dedicated relatively little attention to Feynman's presentation (certainly as compared to the lengthy review of Schwinger's work), and Feynman left the meeting disappointed, even depressed"
Goldberger: [Feynman] "talked very fast, and drew lots of diagrams which I didn't understand or significantly comprehend."

Next months...

Marshak we are indebted to Professor Feynman for performing the calculation at our request.

Dyson "I have done nothing in the last two months that you could call very clever or difficult; nothing one tenth as hard as my [Trinity] fellowship thesis; but because the problems I am now dealing with are public problems and all the theoretical physicists have been racking their brains over them for ten years with such negligible results, even the most modest contributions are at once publicised and applauded."
Dyson "Feynman and Schwinger talk such completely different languages, that neither of them is able to understand properly what the other is doing."

It was thus Dyson, and not Feynman, who first codified the rules for the diagrams' use-precisely what Feynman's frustrated audience had hoped to hear at the Pocono meeting a few months earlier.

Dyson: Feynman+Schwinger

The correspondence between diagrams and S-matrix elements in momentum space

Component of Diagram	Factor in S-Matrix Element	
Internal photon line	$g_{\nu\lambda}\frac{1}{k^2 - i\mu}$	photon propagation function
Internal electron line	$\frac{i\not{p} - m}{p^2 + m^2 - i\mu}$	electron propagation function
Corner	$\gamma^\nu\delta(p - p' - k)$	
External photon lines	$\frac{1}{\sqrt{2\omega}}e_\mu(\mathbf{k}),\ \frac{1}{\sqrt{2\omega}}e_\mu(\mathbf{k})$	ingoing and outgoing photons
External negaton lines	$\sqrt{\frac{m}{\epsilon}}\,u(\mathbf{p}),\ \sqrt{\frac{m}{\epsilon}}\,\bar{u}(\mathbf{p})$	ingoing and outgoing negatons
External positon lines	$\sqrt{\frac{m}{\epsilon}}\,\bar{v}(\mathbf{p}),\ \sqrt{\frac{m}{\epsilon}}\,v(\mathbf{p})$	ingoing and outgoing positons

Figure 3.2. The “Feynman rules” in the momentum-space representation, following Dyson’s prescriptions. (Source: Jauch and Rohrlich, *Theory of Photons and Electrons* [1955], 154.)

Dyson: Feynman+Schwinger

January 1949 meeting of the American Physical Society in NewYork: "On the first day the real fun began; I was sitting in the middle of the hall and in the front, with Feynman beside me, and there rose to the platform to speak a young man from Columbia whom I know dimly. The young man had done some calculations using methods of Feynman and me, and he did not confine himself to stating this fact, but referred again and again to **'the beautiful theory of Feynman-Dyson,'** in gushing tones. After he said this the first time, **Feynman turned to me and remarked in a loud voice, 'Well, Doc, you're in.'**"

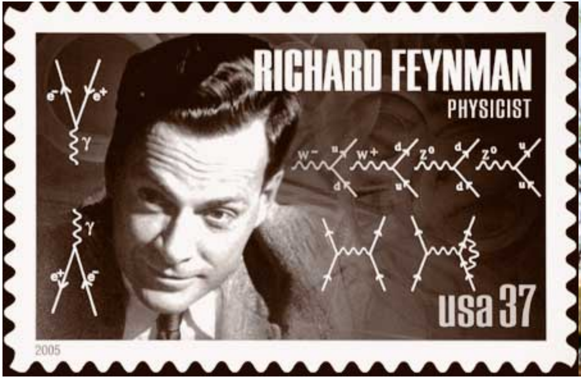
Path integrals $\propto e^{iS/h}$

Диаграммы Фейнмана. Ричард Фейнман водил знаменитый фургончик, разрисованный диаграммами. Эта артистичная демонстрация сделала диаграммы широко обсуждаемыми. Хотя Фейнман умер в 1988, фургончик всё еще хранится около Калтека в Южной Калифорнии.

Path integrals $\propto e^{iS/h}$

Feynman Diagrams Richard Feynman drove a famous van with Feynman diagrams painted on it. This artist's depiction was made to show the diagrams discussed above. Though Feynman died in 1988, the van is still around—in storage near Caltech in Southern California.

30 PhDs thesis



Gravity, Warsaw/Jablonna 1962

114 participants: P. A. M. Dirac, R. Feynman, J. A. Wheeler, P. G. Bergmann, H. Bondi, S. Chandrasekhar, B. DeWitt, V. Ginzburg, L. Rosenfeld, J. Weber, R. Penrose, ...

Letter to his wife

"**I am not getting anything out of the meeting. I am learning nothing.** Because there are no experiments this field is not an active one, so few of the best men are doing work in it. The result is that there are hosts of dopes here and it is not good for my blood pressure: such inane things are said and seriously discussed that I get into arguments outside the formal sessions (say, at lunch) whenever anyone asks me a question or starts to tell me about his "work". The "work" is always: (1) completely un-understandable, (2) vague and indefinite, (3) something correct that is obvious and self-evident, but worked out by a long and difficult analysis, and presented as an important discovery, or (4) a claim based on the stupidity of the author that some obvious and correct fact, accepted and checked for years, is, in fact, false (these are the worst: no argument will convince the idiot), (5) an attempt to do something probably impossible, but certainly of no utility, which, it is finally revealed at the end, fails, or (6) just plain wrong. There is a great deal of "activity in the field" these days, but this "activity" is mainly in showing that the previous "activity" of somebody else resulted in an error or in nothing useful or in something promising. It is like a lot of worms trying to get out of a bottle by crawling all over each other. It is not that the subject is hard; it is that the good men are occupied elsewhere. **Remind me not to come to any more gravity conferences!**"

Feynaman, Summary of the coference (proceedings): "At each meeting it always seems to me that very little progress is made. Nevertheless, if you look ever any reasonable length of time, a few years say, you find a fantastic progress and it is hard to understand how that can happen at the same time that nothing is happening in anyone moment (zeno's paradox)."

"You know, the most amazing thing happened to me tonight... I saw a car with the license plate ARW 357. Can you imagine? Of all the millions of license plates in the state, what was the chance that I would see that particular one tonight? Amazing!"

841

Vol. XXIV (1963) *ACTA PHYSICA POLONICA* Fasc. 6 (12)

QUANTUM THEORY OF GRAVITATION*

By R. P. Feynman

(Received July 3, 1963)

My subject is the quantum theory of gravitation. My interest in it is primarily in the relation of one part of nature to another. There's a certain irrationality to any work in gravitation, so it's hard to explain why you do any of it; for example, as far as quantum effects are concerned let us consider the effect of the gravitational attraction between an electron and a proton in a hydrogen atom; it changes the energy a little bit. Changing the energy of a quantum system means that the phase of the wave function is slowly shifted relative to what it would have been were no perturbation present. The effect of gravitation on the hydrogen atom is to shift the phase by 43 seconds of phase in every hundred times the lifetime of the universe! An atom made purely by gravitation, let us say two neutrons held together by gravitation, has a Bohr orbit of 10^8 light years. The energy of this system is 10^{-70} rydbergs. I wish to discuss here the possibility of calculating the Lamb correction to this thing, an energy, of the order 10^{-120}. This irrationality is shown also in the strange gadgets of Prof. Weber, in the absurd creations of Prof. Wheeler and other such things, because the dimensions are so peculiar. It is therefore clear that the problem we are working on is not the correct problem; the correct problem is what determines the size of gravitation? But since I am among equally irrational men I won't be criticized I hope for the fact that there is no possible, practical reason for making these calculations.

I am limiting myself to not discussing the questions of quantum geometry nor what happens when the fields are of very short wave length. I am not trying to discuss any problems which we don't already have in present quantum field theory of other fields, not that I believe that gravitation is incapable of solving the problems that we have in the present theory, but because I wish to limit my subject. I suppose that no wave lengths are shorter than one-millionth of the Compton wave length of a proton, and therefore it is legitimate to analyze everything in perturbation approximation; and I will carry out the perturbation approximation as far as I can in every direction, so that we can have as many terms as we want, which means that we can go to ten to the minus two-hundred and something ryd-

and a proton in a hydrogen atom; it changes the energy a little bit. Changing the energy of a quantum system means that the phase of the wave function is slowly shifted relative to what it would have been were no perturbation present. The effect of gravitation on the hydrogen atom is to shift the phase by 43 seconds of phase in every hundred times the lifetime of the universe! An atom made purely by gravitation, let us say two neutrons held together by gravitation, has a Bohr orbit of 10^8 light years. The energy of this system is 10^{-70} rydbergs. I wish to discuss here the possibility of calculating the Lamb correction to this thing, an energy, of the order 10^{-120}. This irrationality is shown also in the strange gadgets of Prof. Weber, in the absurd creations of Prof. Wheeler and other such things, because the dimensions are so peculiar. It is therefore clear that the problem we are working on is not the correct problem; the correct problem is what determines the size of gravitation? But since I am among equally irrational men I won't be criticized I hope for the fact that there is no possible, practical reason for making these calculations.

I am limiting myself to not discussing the questions of quantum geometry nor what happens when the fields are of very short wave length. I am not trying to discuss any problems which we don't already have in present quantum field theory of other fields, not that I believe that gravitation is incapable of solving the problems that we have in the present theory, but because I wish to limit my subject. I suppose that no wave lengths are shorter than one-millionth of the Compton wave length of a proton, and therefore it is legitimate to analyze everything in perturbation approximation; and I will carry out the perturbation approximation as far as I can in every direction, so that we can have as many terms as we want, which means that we can go to ten to the minus two-hundred and something ryd-
bergs.

I am investigating this subject despite the real difficulty that there are no experiments. Therefore there is so real challenge to compute true, physical situations. And so I made

* Based on a tape-recording of Professor Feynman's lecture at the *Conference on Relativistic Theories of Gravitation*, Jablonna, July, 1962. — Ed.

Conclusions of the conference by R.P. Feynman [not much on gravity]

(i) "The high priests of Babylon used to predict things by looking at the liver of a sheep. And why? Because in the complexity of the arrangement of the veins, interpreted correctly, they could tell what the future would be. **It is that complexity, and the possibility of reinterpreting later the arrangement of the veins, that permits the power of the priests to be maintained. The diagrams which go with my name appear to me like the veins of a liver of a sheep. It is always possible to follow the right lines after the events."**

(ii) "I have always suspected that, one day, working far way from theorists, close to their [JG: experimental physicists] big machines, they will get the idea of a new experiment ; an experiment which will test the oracle. **They would like to see what would happen, just for the fun of it, if they falsly report that there exists a certain bump, or an oscillation in a certain curve, and see how the theorists predict it. I know these men so well that the moment I thought of that possibility I have honestly always been concerned that some day they will do just that. Then you can imagine how absurd the theoretical physicists would sound, making all these complicated calculations to demonstrate the existence of such a bump, while these fellows are laughing up their sleeves."**

From Dyson's letter

He said he had given his copy of my paper to a graduate student to read, then asked the student if he himself ought to read it. The student said no, and Feynman accordingly wasted no time on it and continued chasing his own ideas. **Feynman and I really understand each other; I know that he is the one person in the world who has nothing to learn from what I have written, and he doesn't mind telling me so. That afternoon Feynman produced more brilliant ideas per square minute than I have ever seen anywhere before or since.** In the evening I mentioned that there were just two problems for which the finiteness of the theory remained to be established; both problems are well-known and feared by physicists, since many long and difficult papers running to fifty pages and more have been written about them, trying unsuccessfully to make the older theories give sensible answers to them. When I mentioned this fact, Feynman said, "We'll see about this," and proceeded to sit down and in two hours, before our eyes, obtain finite and sensible answers to both problems. It was the most amazing piece of lightning calculation I have ever witnessed, and the results prove, apart from some unforeseen complication, the consistency of the whole theory. The two problems were the scattering of light by an electric field, and the scattering of light by light.

1950's

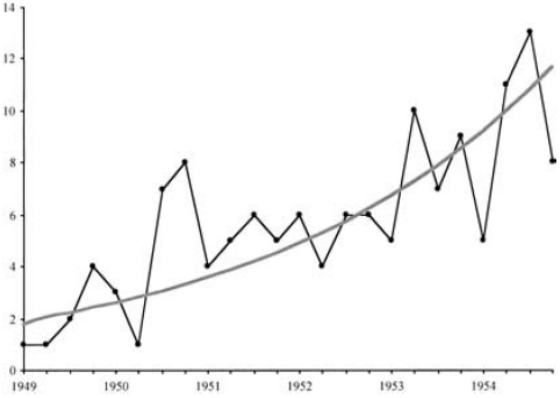


Figure 2.7. Number of articles using Feynman diagrams in the *Physical Review* during three-month intervals, based on the entries in appendix A. The solid gray line gives the best-fit curve, demonstrating that the number of articles rose exponentially during this

Table 2.1. Acknowledgments and authorship for articles in the *Physical Review* that used Feynman diagrams, 1949–54

Name	No. of Times Acknowledged by Other Authors	No. of Articles Contributed
Freeman Dyson	13	7
Hans Bethe	12	4
Norman Kroll	8	4
Richard Feynman	8	3
Abraham Klein	6	7
Abdus Salam	6	6
Abraham Pais	6	2
Paul Matthews	4	6
Fritz Rohrlich	4	4
Murray Gell-Mann	3	4
Robert Karplus	3	4
Francis Low	3	3
Kenneth Watson	3	3
Keith Brueckner	2	5
Malvin Ruderman	2	5
Marvin Goldberger	2	3
John Ward	1	4

1950's

Table 4.1. Citations and publications of diagrammatic articles, 1949–54

	No. of Citations to Dyson [A.1], [A.2], and Feynman [A.4]	No. of Diagrammatic Articles	No. of Authors
United States (*PR*)	241	139	114
Japan (*PTP*)	100	97	92
Great Britain (*PRSA*)	35	23	26
Italy (*Il Nuovo Cimento*)	42	18	18
W. Germany (*Zeitschrift für Naturforschung*)	33	11	12
Soviet Union (*ZhETF*)	24	12	11
France (*Journal de Physique et le Radium*)	14	3	5

Tomonaga Sin-Itiro

Tomonaga Sin-Itiro

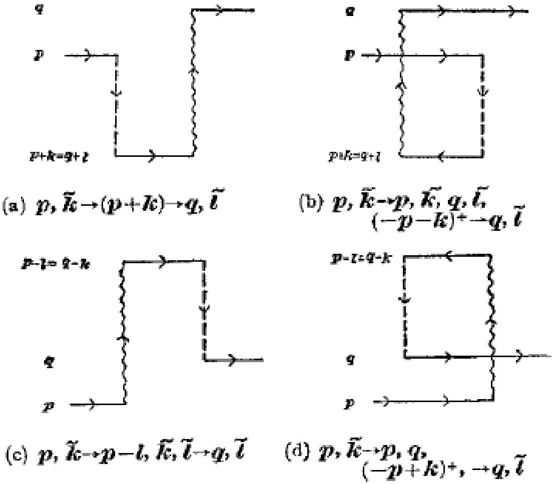


Figure 4.6. Compton scattering, as illustrated by transition diagrams. (Source: Koba and Takeda, "Radiation reaction, III," pt. 2 [1949], 64.)

Tomonaga Sin-Itiro

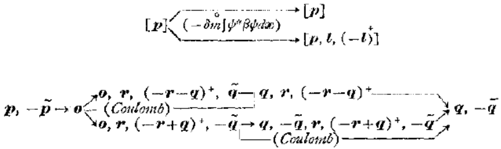


Figure 4.4. Arrow notation for perturbative calculations. (Sources: *top*, Koba and Tomonaga, “On radiation reactions, I” [1948], 294; *bottom:* Koba and Takeda, “Radiation reaction, II” [1948], 414.)

All sorts of Art

The traditional subdivision of the Arts: Architecture, Sculpture, Painting, Music, Poetry, Dance, Performing.

Poetry science

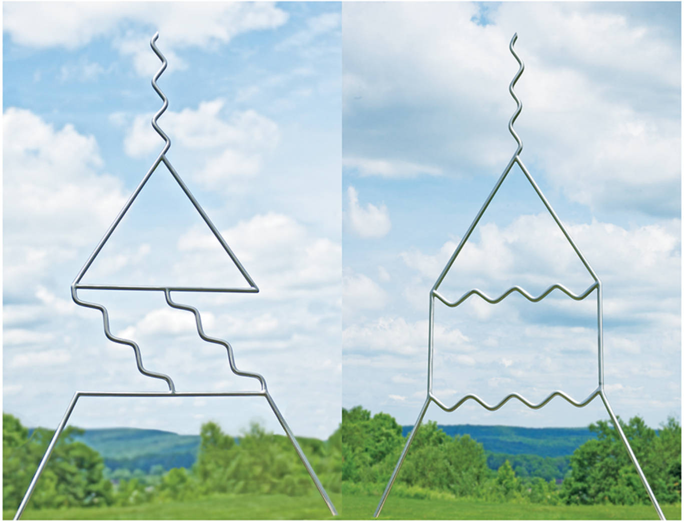
"Poets say science takes away from the beauty of the stars - mere globs of gas atoms. I too can see the stars on a desert night, and feel them. But do I see less or more? The vastness of the heavens stretches my imagination - stuck on this carousel my little eye can catch one-million-year-old light. A vast pattern - of which I am a part. What is the pattern, or the meaning, or the why? **It does not do harm to the mystery to know a little about it.** For far more marvelous is the truth than any artists of the past imagined it. Why do the poets of the present not speak of it?
What men are poets who can speak of Jupiter if he were a man, but if he is an immense spinning sphere of methane and ammonia must be silent?"

Poetry science

I have a friend who's an artist and has sometimes taken a view which I don't agree with very well. He'll hold up a flower and say "look how beautiful it is," and I'll agree. Then **he says "I as an artist can see how beautiful this is but you as a scientist take this all apart and it becomes a dull thing," and I think that he's kind of nutty.** First of all, the beauty that he sees is available to other people and to me too, I believe?

I can appreciate the beauty of a flower. At the same time, I see much more about the flower than he sees. I could imagine the cells in there, the complicated actions inside, which also have a beauty. I mean it's not just beauty at this dimension, at one centimeter; there's also beauty at smaller dimensions, the inner structure, also the processes. The fact that the colors in the flower evolved in order to attract insects to pollinate it is interesting; it means that insects can see the color. It adds a question: does this aesthetic sense also exist in the lower forms? Why is it aesthetic? **All kinds of interesting questions which the science knowledge only adds to the excitement, the mystery and the awe of a flower. It only adds. I don't understand how it subtracts.**

Sculpters inspired by Feynman



2 Space-Time Feynman Diagrams (Aztec) 2012 stainless steel 30.5 x 49 x 3.5 in or .8 x 1.2 x .1 m