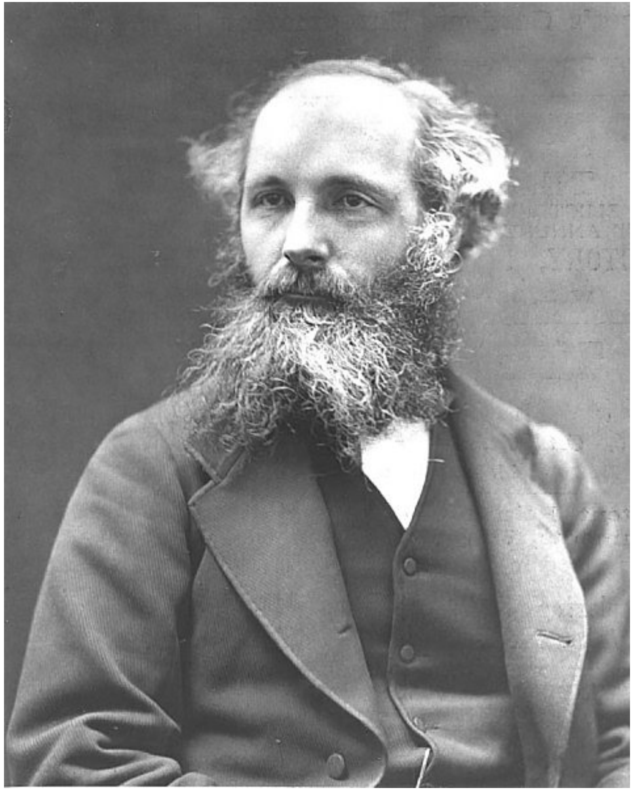
Feynmanova–Wheelerova symetrická elektrodynamika

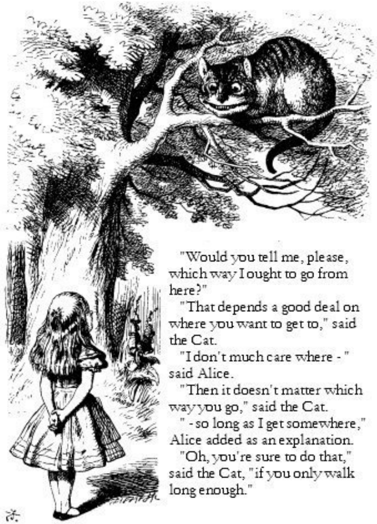
John A. Wheeler (1911-2008)

Richard P. Feynman (1918-1988)

James Clerk Maxwell
(1831-1879)



Albert Einstein
(1879-1955)



"Would you tell me, please, which way I ought to go from here?"

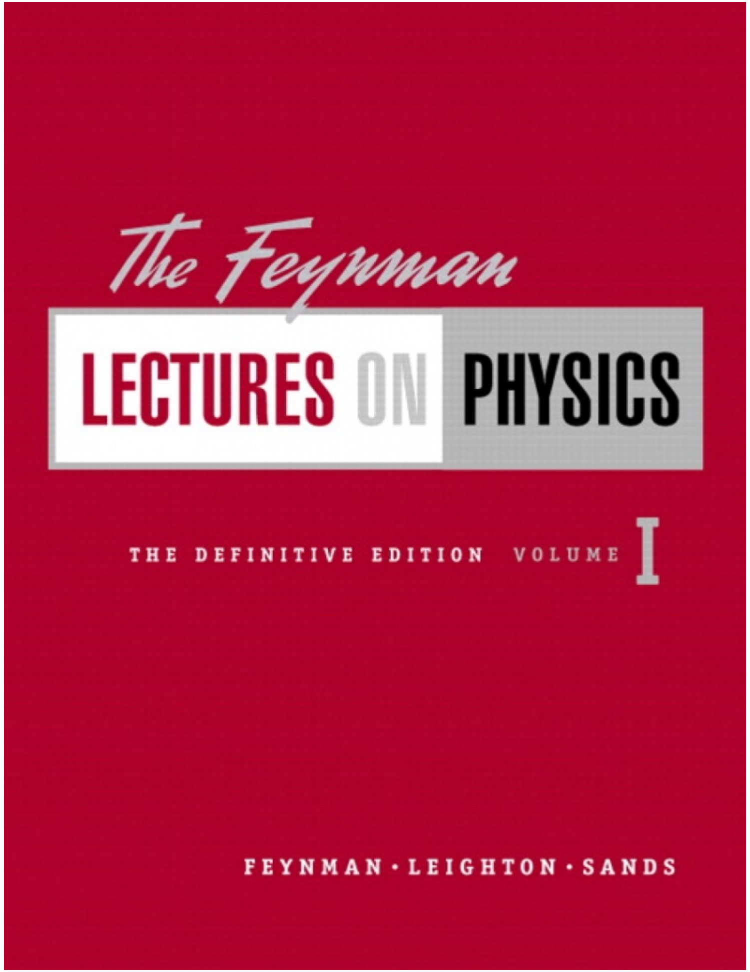
"That depends a good deal on where you want to get to," said the Cat.

"I don't much care where - " said Alice.

"Then it doesn't matter which way you go," said the Cat.

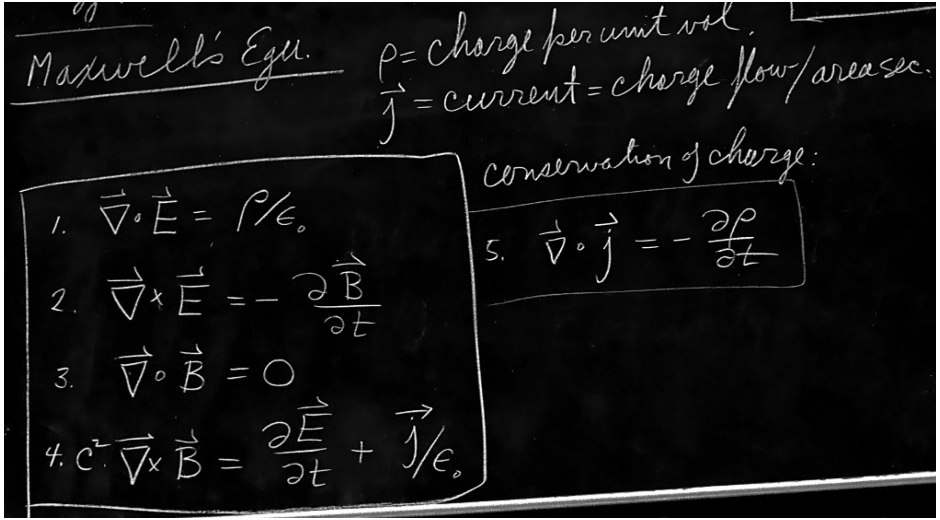
" - so long as I get somewhere," Alice added as an explanation.

"Oh, you're sure to do that," said the Cat, "if you only walk long enough."



www.feynmanlectures.caltech.edu

Maxwellovy rovnice


Maxwell's Equ.

ρ = charge per unit vol.

$\vec{j}$ = current = charge flow/area sec.

1. $\vec{\nabla}\cdot\vec{E} = \rho/\epsilon_0$
2. $\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$
3. $\vec{\nabla}\cdot\vec{B} = 0$
4. $c^2\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + \vec{j}/\epsilon_0$

conservation of charge:

5. $\vec{\nabla}\cdot\vec{j} = -\frac{\partial\rho}{\partial t}$

Maxwell's Equations

$$
\begin{aligned}
&(1) & \nabla\cdot\boldsymbol{E} &= \frac{\rho}{\epsilon_0}\\
&(2) & \nabla\times\boldsymbol{E} &= -\frac{\partial\boldsymbol{B}}{\partial t}\\
&(3) & \nabla\cdot\boldsymbol{B} &= 0\\
&(4) & c^2\,\nabla\times\boldsymbol{B} &= \frac{\partial\boldsymbol{E}}{\partial t} + \frac{\boldsymbol{j}}{\epsilon_0}
\end{aligned}
\tag{2.41}
$$

Feynman, Leighton, Sands: *The Feynman Lectures on Physics*

28 Electromagnetic Radiation

The electric field, $\boldsymbol{E}$, is given by

$$\boldsymbol{E} = \frac{-q}{4\pi\epsilon_0}\left[\frac{\boldsymbol{e}_{r'}}{r'^2} + \frac{r'}{c}\frac{d}{dt}\left(\frac{\boldsymbol{e}_{r'}}{r'^2}\right) + \frac{1}{c^2}\frac{d^2}{dt^2}\boldsymbol{e}_{r'}\right]. \tag{28.3}$$

What do the various terms tell us? Take the first term, $\boldsymbol{E} = -q\boldsymbol{e}_{r'}/4\pi\epsilon_0 r'^2$. That, of course, is Coulomb's law, which we already know: q is the charge that is producing the field; $\boldsymbol{e}_{r'}$ is the unit vector in the direction from the point P where $\boldsymbol{E}$ is measured, r is the distance from P to q. But, Coulomb's law is wrong. The discoveries of the 19th century showed that influences cannot travel faster than a certain fundamental speed c, which we now call the speed of light. It is not correct that the first term is Coulomb's law, not only because it is not possible to know where the charge is *now* and at what distance it is *now*, but also because the only thing that can affect the field at a given place and time is the behavior of the charges in the *past*. How *far* in the past? The time delay, or *retarded time*, so-called, is the time it takes, at speed c, to get from the charge to the field point P. The delay is r'/c.

So to allow for this time delay, we put a little prime on r, meaning how far away it *was* when the information now arriving at P left q. Just for a moment suppose that the charge carried a light, and that the light could only come to P at the speed c. Then when we look at q, we would not see where it is now, of course, but where it *was* at some earlier time. What appears in our formula is the *apparent* direction $\boldsymbol{e}_{r'}$ the direction it used to be the so-called *retarded* direction and at the *retarded* distance r'. That would be easy enough to understand, too, but it is also wrong. The whole thing is much more complicated.

There are several more terms. The next term is as though nature were trying to allow for the fact that the effect is retarded, if we might put it very crudely. It suggests that we should calculate the delayed Coulomb field and add a correction to it, which is its rate of change times the time delay that we use. Nature seems to be attempting to guess what the field at the present time is going to be, by taking the rate of change and multiplying by the time that is delayed. But we are not yet through. There is a third term—the second derivative, with respect to t, of the unit vector in the direction of the charge. Now the formula *is* finished, and that is all there is to the electric field from an arbitrarily moving charge.

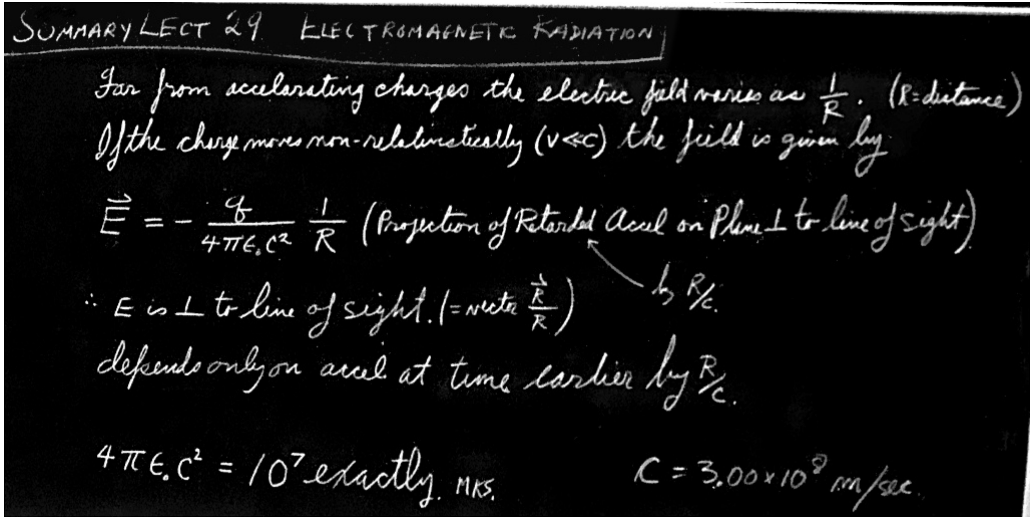
The magnetic field is given by

$$\boldsymbol{B} = -\boldsymbol{e}_{r'} \times \boldsymbol{E}/c. \tag{28.4}$$

Next, the laws of electricity and magnetism, as known at the end of the 19th century, are these: the electrical forces acting on a charge q can be described by two fields, called $\boldsymbol{E}$ and $\boldsymbol{B}$, and the velocity $\boldsymbol{v}$ of the charge q, by the equation

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}). \tag{28.2}$$

Feynman, Leighton, Sands: *The Feynman Lectures on Physics*



SUMMARY LECT 29 ELECTROMAGNETIC RADIATION

Far from accelarating charges the electric field varies as $\frac{1}{R}$. (R=distance)
If the charge moves non-relativistically ($v \ll c$) the field is given by

$$\vec{E} = -\frac{q}{4\pi\epsilon_0 c^2}\frac{1}{R}\left(\text{Projection of Retarded Accel on Plane} \perp \text{to line of sight}\right)$$

by R/c.

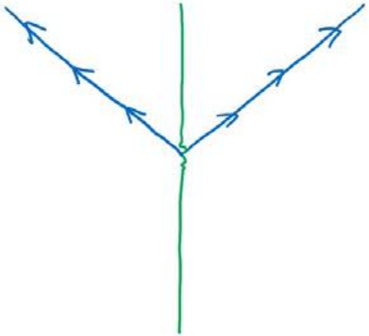
∴ E is ⊥ to line of sight. (= vector $\frac{\vec{R}}{R}$)
depends only on accel at time earlier by R/c.

$4\pi\epsilon_0 c^2 = 10^7$ exactly. MKS. $c = 3.00\times10^8$ m/sec.

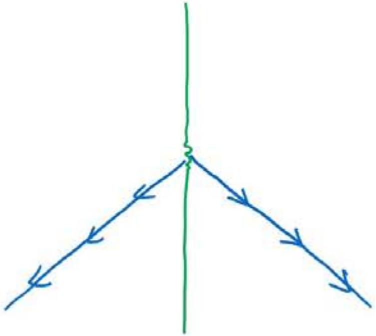
$$\boldsymbol{E} = \frac{-q}{4\pi\epsilon_0}\left[\frac{\boldsymbol{e}_{r'}}{r'^2} + \frac{r'}{c}\,\frac{d}{dt}\left(\frac{\boldsymbol{e}_{r'}}{r'^2}\right) + \frac{1}{c^2}\,\frac{d^2}{dt^2}\,\boldsymbol{e}_{r'}\right]$$

$$\boldsymbol{B} = -\boldsymbol{e}_{r'} \times \boldsymbol{E}/c$$

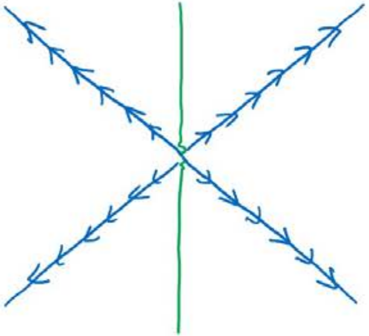
$\nabla \cdot F_{ret} = J$



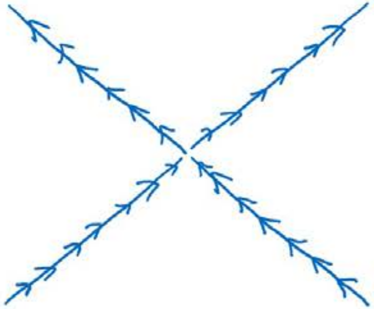
$\nabla \cdot F_{adv} = J$



$\nabla \cdot \frac{1}{2}(F_{ret} + F_{adv}) = J$

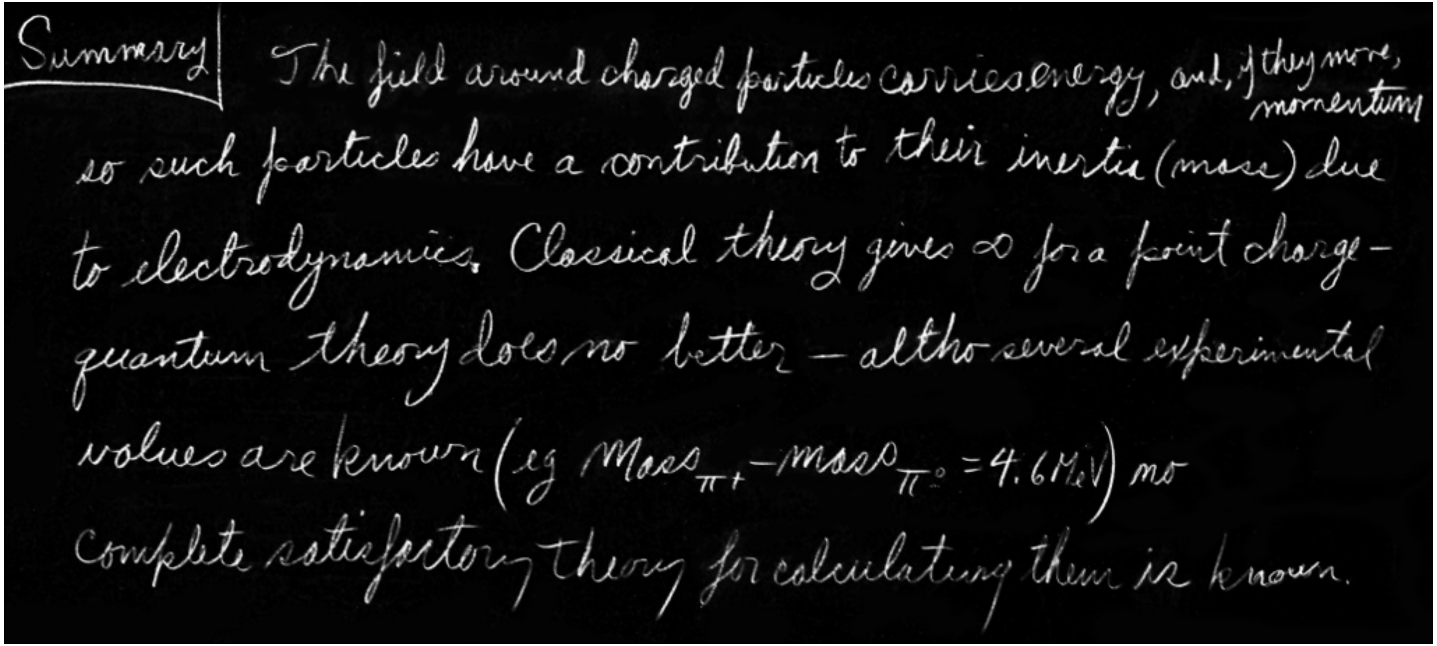


$\nabla \cdot \frac{1}{2}(F_{ret} - F_{adv}) = 0$



volné pole!

Problémy s nekonečny



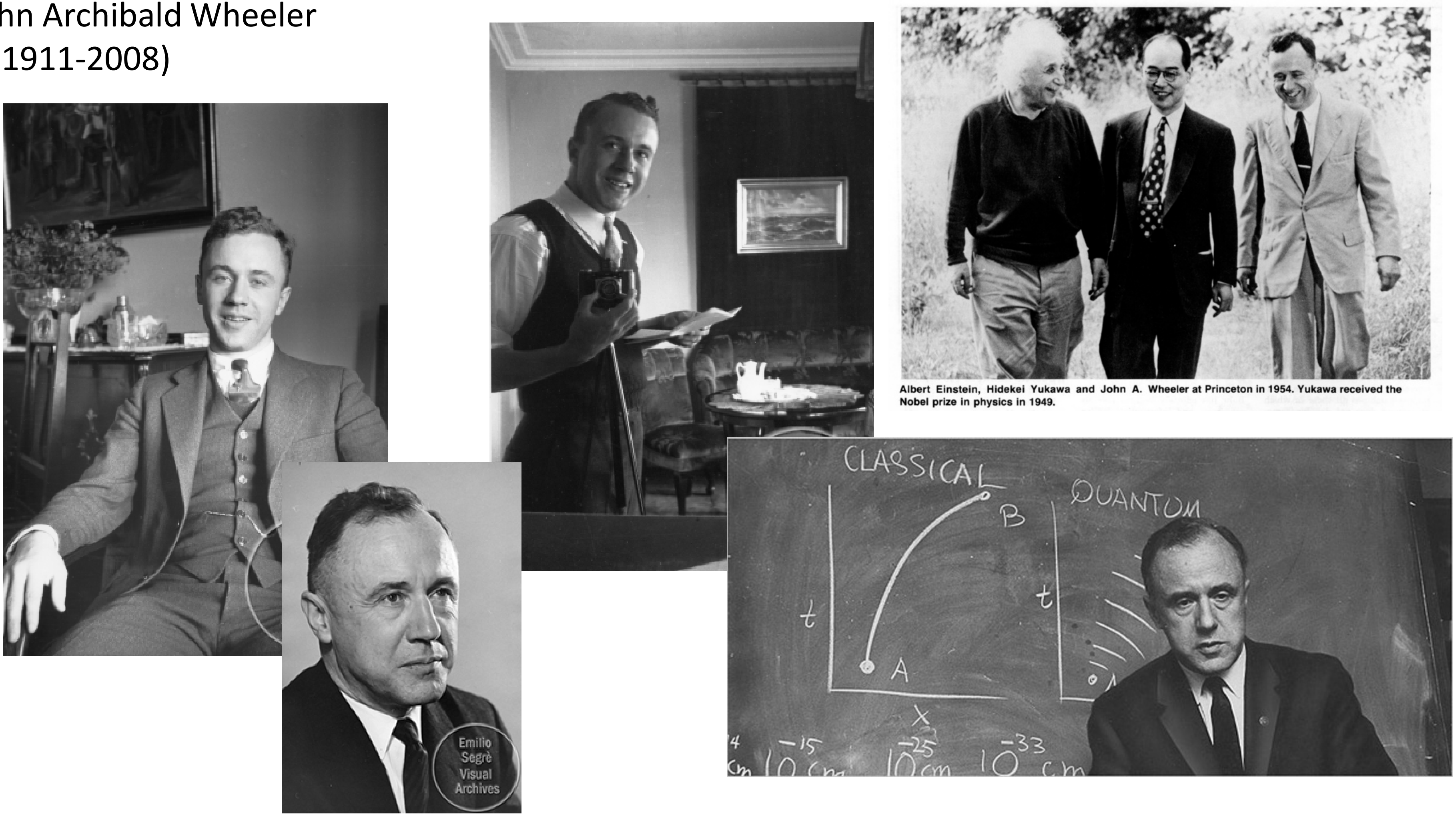
Summary

The field around charged particles carries energy, and, if they move, momentum so such particles have a contribution to their inertia (mass) due to electrodynamics. Classical theory gives ∞ for a point charge – quantum theory does no better – altho several experimental values are known (eg $\text{Mass}_{\pi^+} - \text{mass}_{\pi^\circ} = 4.6\,\text{MeV}$) no complete satisfactory theory for calculating them is known.

$$F = \alpha \frac{e^2}{ac^2}\,\ddot{x} - \frac{2}{3}\,\frac{e^2}{c^3}\,\dddot{x} + \gamma \frac{e^2 a}{c^4}\,\ddddot{x} + \cdots, \qquad (28.9)$$

Feynman, Leighton, Sands: *The Feynman Lectures on Physics*

John Archibald Wheeler
(1911-2008)

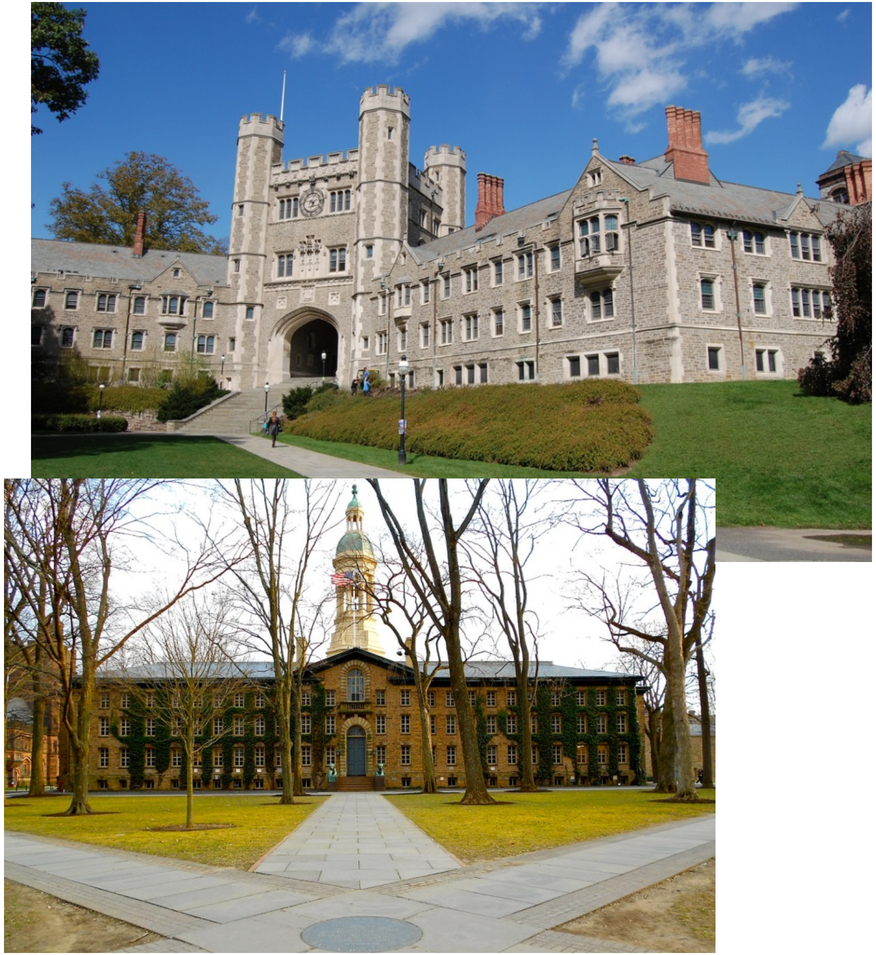


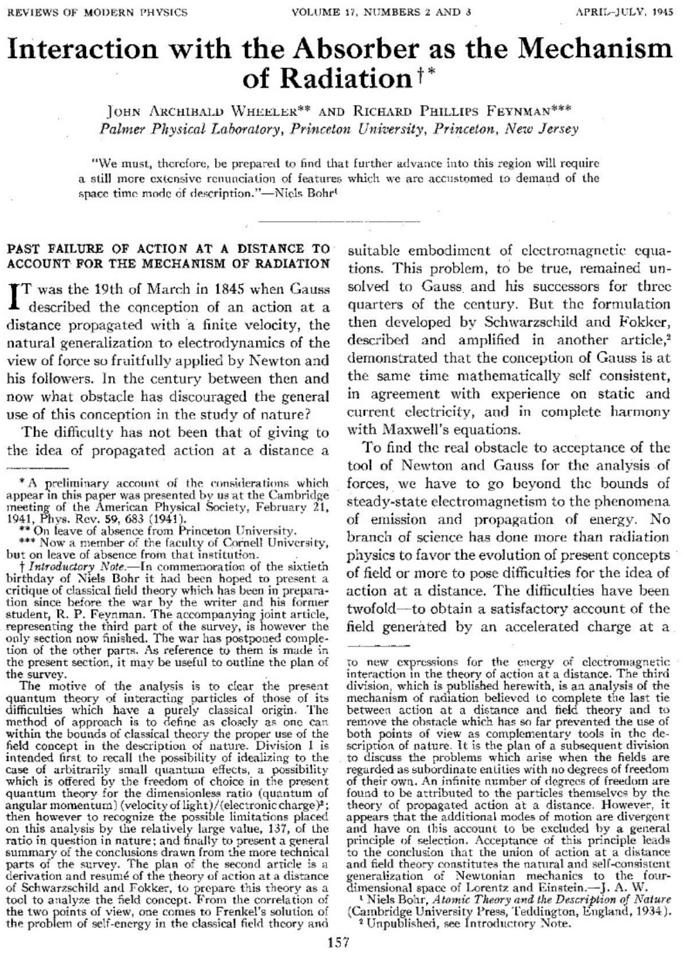
Albert Einstein, Hidekei Yukawa and John A. Wheeler at Princeton in 1954. Yukawa received the Nobel prize in physics in 1949.

Richard P. Feynman (1918-1988)

Institute for Advanced Study, Princeton

Princeton University





REVIEWS OF MODERN PHYSICS VOLUME 17, NUMBERS 2 AND 3 APRIL-JULY, 1945

Interaction with the Absorber as the Mechanism of Radiation†*

JOHN ARCHIBALD WHEELER** AND RICHARD PHILLIPS FEYNMAN***
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

> "We must, therefore, be prepared to find that further advance into this region will require a still more extensive renunciation of features which we are accustomed to demand of the space time mode of description."—Niels Bohr[1]

PAST FAILURE OF ACTION AT A DISTANCE TO ACCOUNT FOR THE MECHANISM OF RADIATION

IT was the 19th of March in 1845 when Gauss described the conception of an action at a distance propagated with a finite velocity, the natural generalization to electrodynamics of the view of force so fruitfully applied by Newton and his followers. In the century between then and now what obstacle has discouraged the general use of this conception in the study of nature?

The difficulty has not been that of giving to the idea of propagated action at a distance a suitable embodiment of electromagnetic equations. This problem, to be true, remained unsolved to Gauss and his successors for three quarters of the century. But the formulation then developed by Schwarzschild and Fokker, described and amplified in another article,[2] demonstrated that the conception of Gauss is at the same time mathematically self consistent, in agreement with experience on static and current electricity, and in complete harmony with Maxwell's equations.

To find the real obstacle to acceptance of the tool of Newton and Gauss for the analysis of forces, we have to go beyond the bounds of steady-state electromagnetism to the phenomena of emission and propagation of energy. No branch of science has done more than radiation physics to favor the evolution of present concepts of field or more to pose difficulties for the idea of action at a distance. The difficulties have been twofold—to obtain a satisfactory account of the field generated by an accelerated charge at a

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* A preliminary account of the considerations which appear in this paper was presented by us at the Cambridge meeting of the American Physical Society, February 21, 1941, Phys. Rev. 59, 683 (1941).

** On leave of absence from Princeton University.

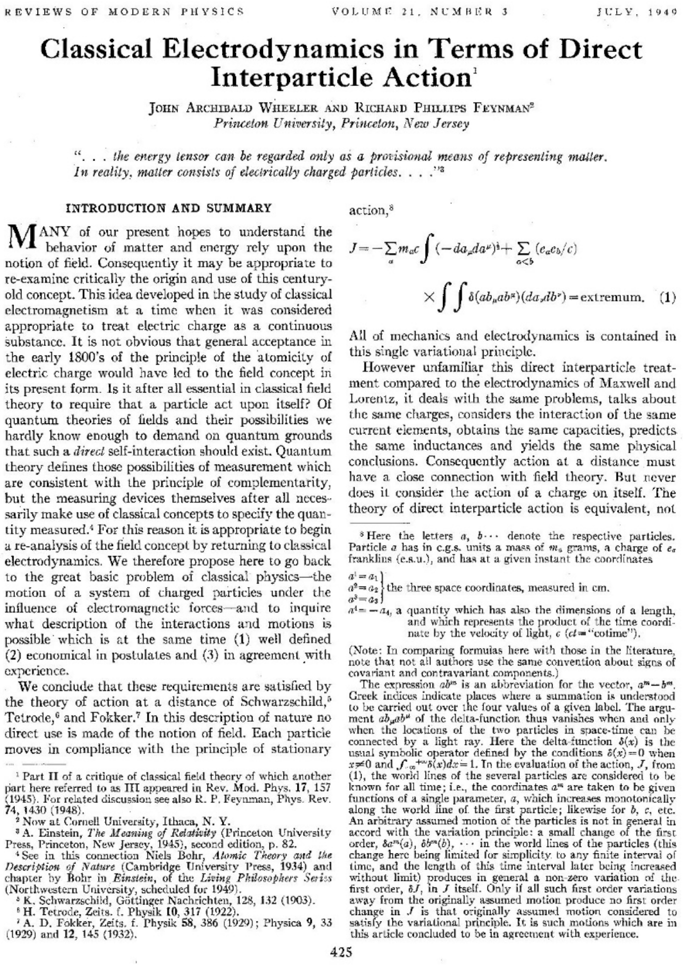
*** Now a member of the faculty of Cornell University, but on leave of absence from that institution.

† *Introductory Note.*—In commemoration of the sixtieth birthday of Niels Bohr it had been hoped to present a critique of classical field theory which has been in preparation since before the war by the writer and his former student, R. P. Feynman. The accompanying joint article, representing the third part of the survey, is however the only section now finished. The war has postponed completion of the other parts. As reference to them is made in the present section, it may be useful to outline the plan of the survey.

The motive of the analysis is to clear the present quantum theory of interacting particles of those of its difficulties which have a purely classical origin. The method of approach is to define as closely as one can within the bounds of classical theory the proper use of the field concept in the description of nature. Division I is intended first to recall the possibility of idealizing to the case of arbitrarily small quantum effects, a possibility which is offered by the freedom of choice in the present quantum theory for the dimensionless ratio (quantum of angular momentum) (velocity of light)/(electronic charge)^2; then however to recognize the possible limitations placed on this analysis by the relatively large value, 137, of the ratio in question in nature; and finally to present a general summary of the conclusions drawn from the more technical parts of the survey. The plan of the second article is a derivation and resumé of the theory of action at a distance of Schwarzschild and Fokker, to prepare this theory as a tool to analyze the field concept. From the correlation of the two points of view, one comes to Frenkel's solution of the problem of self-energy in the classical field theory and to new expressions for the energy of electromagnetic interaction in the theory of action at a distance. The third division, which is published herewith, is an analysis of the mechanism of radiation believed to complete the last tie between action at a distance and field theory and to remove the obstacle which has so far prevented the use of both points of view as complementary tools in the description of nature. It is the plan of a subsequent division to discuss the problems which arise when the fields are regarded as subordinate entities with no degrees of freedom of their own. An infinite number of degrees of freedom are found to be attributed to the particles themselves by the theory of propagated action at a distance. However, it appears that the additional modes of motion are divergent and have on this account to be excluded by a general principle of selection. Acceptance of this principle leads to the conclusion that the union of action at a distance and field theory constitutes the natural and self-consistent generalization of Newtonian mechanics to the four-dimensional space of Lorentz and Einstein.—J. A. W.

[1] Niels Bohr, *Atomic Theory and the Description of Nature* (Cambridge University Press, Teddington, England, 1934).

[2] Unpublished, see Introductory Note.



REVIEWS OF MODERN PHYSICS VOLUME 21, NUMBER 3 JULY, 1949

Classical Electrodynamics in Terms of Direct Interparticle Action[1]

JOHN ARCHIBALD WHEELER AND RICHARD PHILLIPS FEYNMAN[2]
Princeton University, Princeton, New Jersey

> *". . . the energy tensor can be regarded only as a provisional means of representing matter. In reality, matter consists of electrically charged particles. . . ."*[3]

INTRODUCTION AND SUMMARY

MANY of our present hopes to understand the behavior of matter and energy rely upon the notion of field. Consequently it may be appropriate to re-examine critically the origin and use of this century-old concept. This idea developed in the study of classical electromagnetism at a time when it was considered appropriate to treat electric charge as a continuous substance. It is not obvious that general acceptance in the early 1800's of the principle of the atomicity of electric charge would have led to the field concept in its present form. Is it after all essential in classical field theory to require that a particle act upon itself? Of quantum theories of fields and their possibilities we hardly know enough to demand on quantum grounds that such a *direct* self-interaction should exist. Quantum theory defines those possibilities of measurement which are consistent with the principle of complementarity, but the measuring devices themselves after all necessarily make use of classical concepts to specify the quantity measured.[4] For this reason it is appropriate to begin a re-analysis of the field concept by returning to classical electrodynamics. We therefore propose here to go back to the great basic problem of classical physics—the motion of a system of charged particles under the influence of electromagnetic forces—and to inquire what description of the interactions and motions is possible which is at the same time (1) well defined (2) economical in postulates and (3) in agreement with experience.

We conclude that these requirements are satisfied by the theory of action at a distance of Schwarzschild,[5] Tetrode,[6] and Fokker.[7] In this description of nature no direct use is made of the notion of field. Each particle moves in compliance with the principle of stationary action,[8]

$$J=-\sum_a m_a c\int(-da_\mu da^\mu)^{\frac{1}{2}}+\sum_{a<b}(e_ae_b/c)$$

$$\times\int\int\delta(ab_\mu ab^\mu)(da_\nu db^\nu)=\text{extremum.} \quad (1)$$

All of mechanics and electrodynamics is contained in this single variational principle.

However unfamiliar this direct interparticle treatment compared to the electrodynamics of Maxwell and Lorentz, it deals with the same problems, talks about the same charges, considers the interaction of the same current elements, obtains the same capacities, predicts the same inductances and yields the same physical conclusions. Consequently action at a distance must have a close connection with field theory. But never does it consider the action of a charge on itself. The theory of direct interparticle action is equivalent, not

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[1] Part II of a critique of classical field theory of which another part here referred to as III appeared in Rev. Mod. Phys. **17**, 157 (1945). For related discussion see also R. P. Feynman, Phys. Rev. **74**, 1430 (1948).

[2] Now at Cornell University, Ithaca, N. Y.

[3] A. Einstein, *The Meaning of Relativity* (Princeton University Press, Princeton, New Jersey, 1945), second edition, p. 82.

[4] See in this connection Niels Bohr, *Atomic Theory and the Description of Nature* (Cambridge University Press, 1934) and chapter by Bohr in *Einstein*, of the *Living Philosophers Series* (Northwestern University, scheduled for 1949).

[5] K. Schwarzschild, Göttinger Nachrichten, 128, 132 (1903).

[6] H. Tetrode, Zeits. f. Physik **10**, 317 (1922).

[7] A. D. Fokker, Zeits. f. Physik **58**, 386 (1929); Physica **9**, 33 (1929) and **12**, 145 (1932).

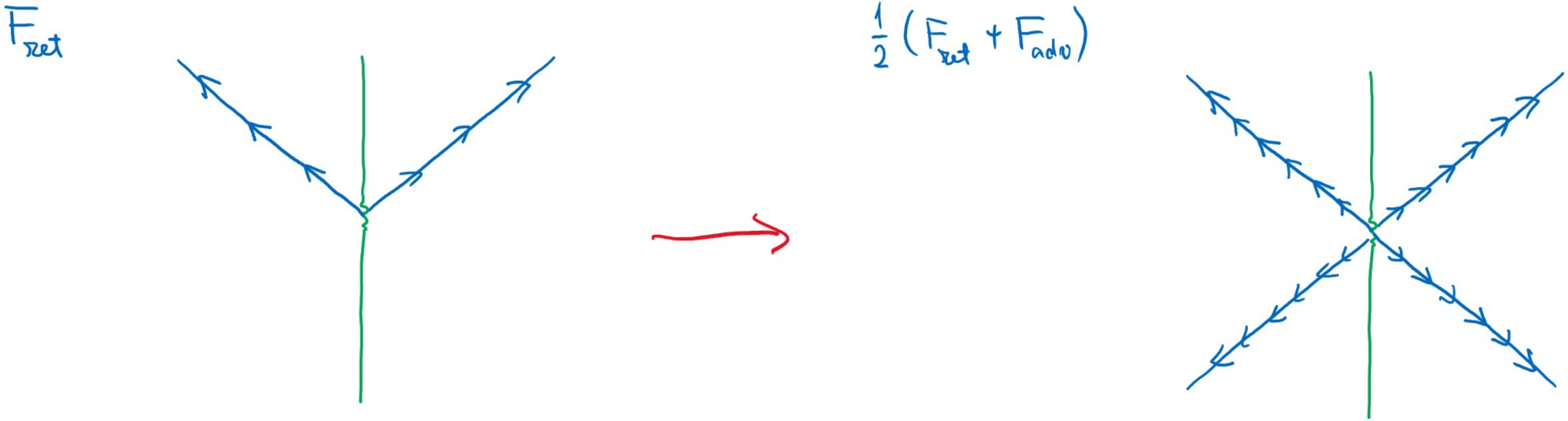
[8] Here the letters a, $b\cdots$ denote the respective particles. Particle a has in c.g.s. units a mass of m_a grams, a charge of e_a franklins (e.s.u.), and has at a given instant the coordinates

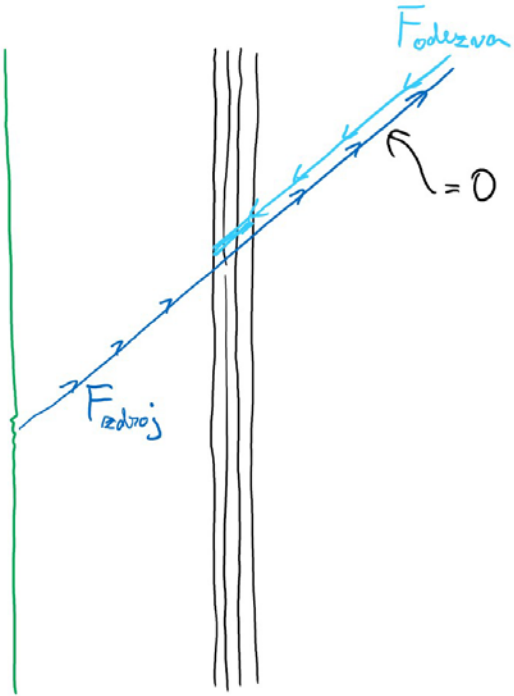
$$\left.\begin{array}{l} a^1=a_1 \\ a^2=a_2 \\ a^3=a_3 \end{array}\right\}\text{the three space coordinates, measured in cm.}$$

$a^4=-a_4$, a quantity which has also the dimensions of a length, and which represents the product of the time coordinate by the velocity of light, c (ct = "cotime").

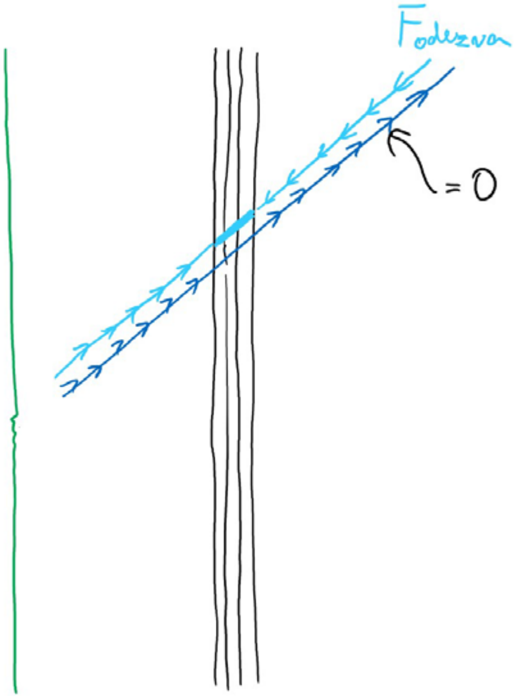
(Note: In comparing formulas here with those in the literature, note that not all authors use the same convention about signs of covariant and contravariant components.)

The expression ab^m is an abbreviation for the vector, a^m-b^m. Greek indices indicate places where a summation is understood to be carried out over the four values of a given label. The argument $ab_\mu ab^\mu$ of the delta-function thus vanishes when and only when the locations of the two particles in space-time can be connected by a light ray. Here the delta-function $\delta(x)$ is the usual symbolic operator defined by the conditions $\delta(x)=0$ when $x\neq0$ and $\int_{-\infty}^{+\infty}\delta(x)dx=1$. In the evaluation of the action, J, from (1), the world lines of the several particles are considered to be known for all time; i.e., the coordinates a^m are taken to be given functions of a single parameter, a, which increases monotonically along the world line of the first particle; likewise for b, c, etc. An arbitrary assumed motion of the particles is not in general in accord with the variation principle: a small change of the first order, $\delta a^m(a)$, $\delta b^m(b)$, $\cdots$ in the world lines of the particles (this change here being limited for simplicity to any finite interval of time, and the length of this time interval later being increased without limit) produces in general a non-zero variation of the first order, δJ, in J itself. Only if all such first order variations away from the originally assumed motion produce no first order change in J is that originally assumed motion considered to satisfy the variational principle. It is such motions which are in this article concluded to be in agreement with experience.

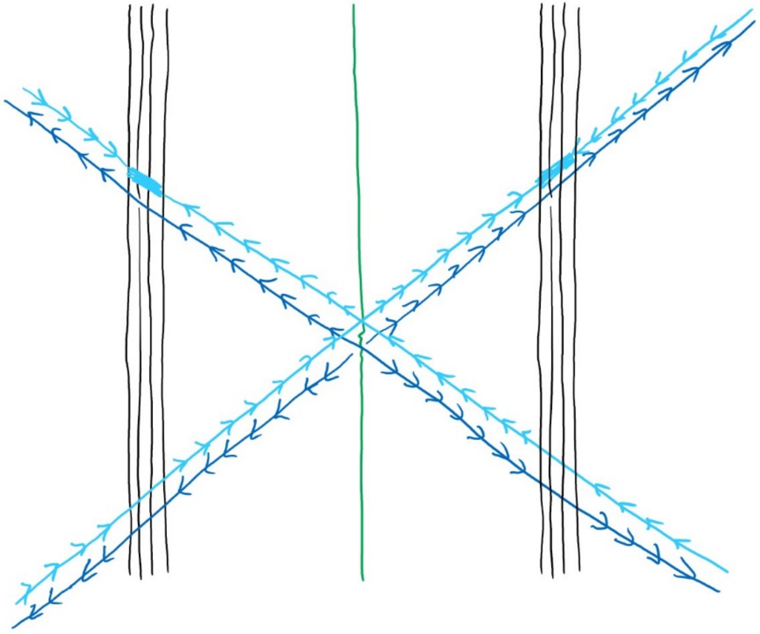

F_{ret}
$\frac{1}{2}\left(F_{ret} + F_{adv}\right)$



pro retardované působení



pro symetrické působení



F_{syn} + F_{adv} odezwa na ret

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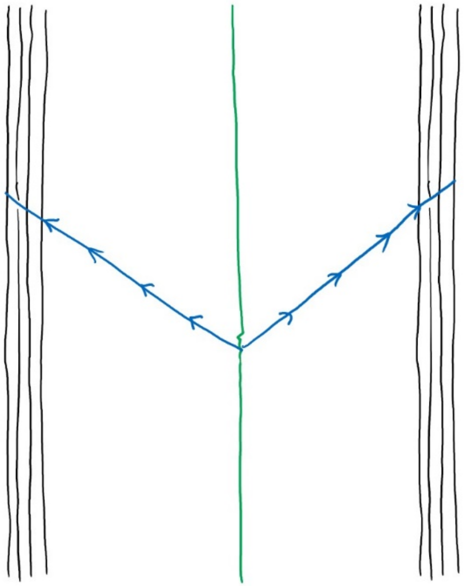
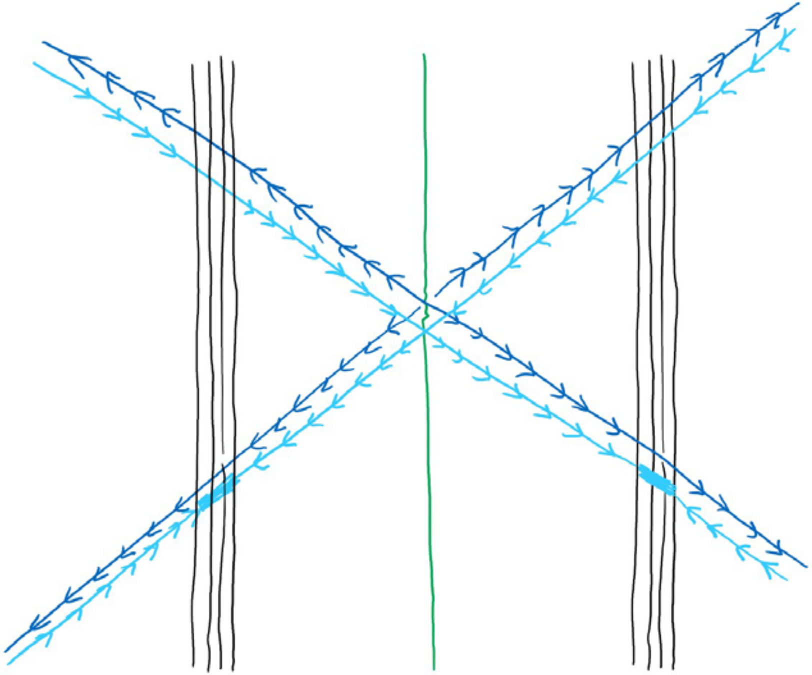
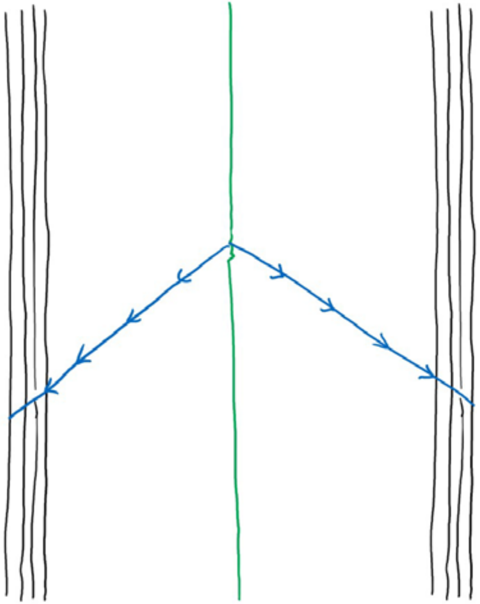


F_{ret} wnitrz



F_{sym} + F_{ret} odezva na adv



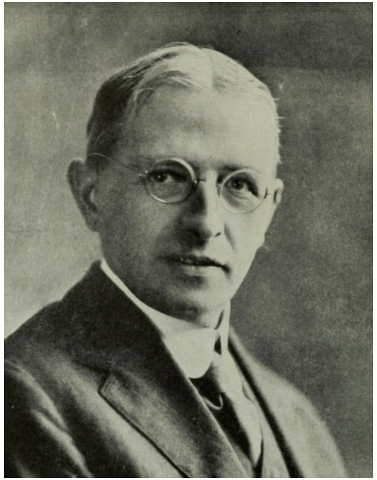
F_{adv} uvnitř

Richard P Feynman

Eugen Wigner

Richard P Feynman

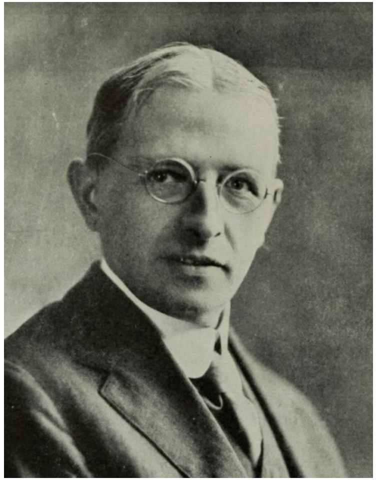
Eugen Wigner



Henry N. Russell

Richard P Feynman

Eugen Wigner



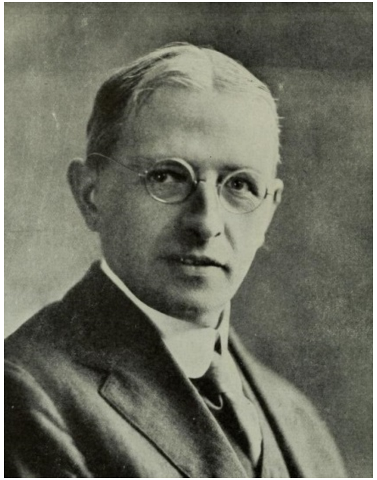
Henry N. Russell

John von Neumann

Richard P Feynman

Eugen Wigner

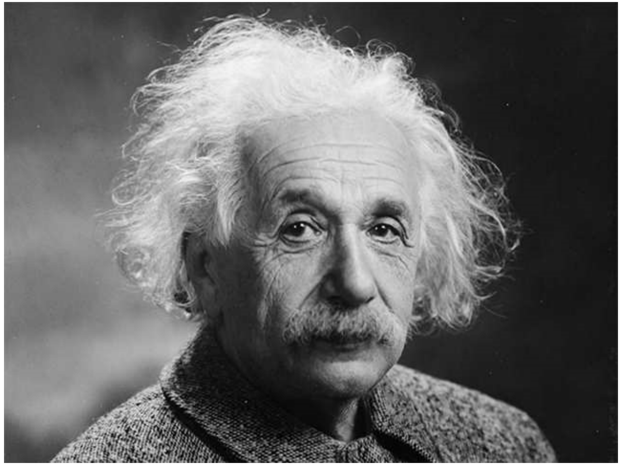
Wolfgang Pauli



Henry N. Russell

John von Neumann

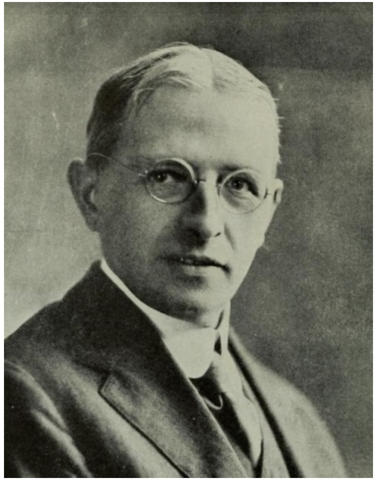
Richard P Feynman



Albert Einstein

Wolfgang Pauli

Eugen Wigner



Henry N. Russell

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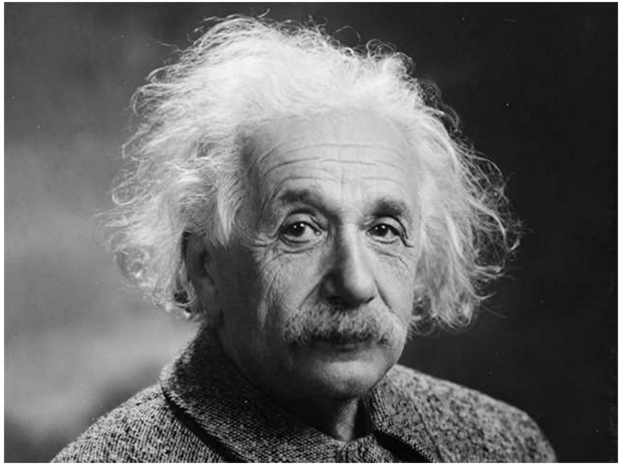

Albert Einstein

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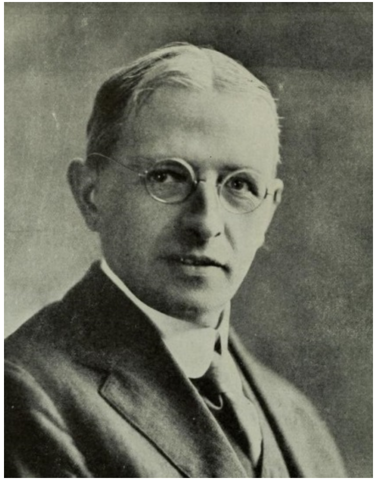

Henry N. Russell

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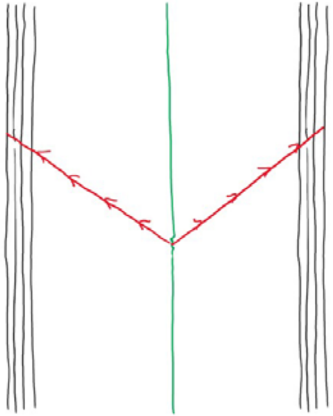
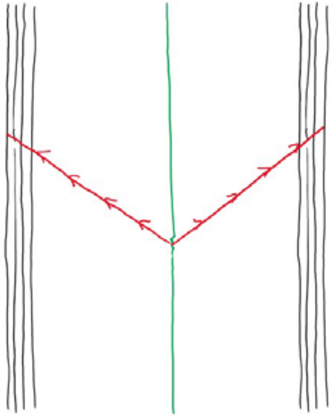
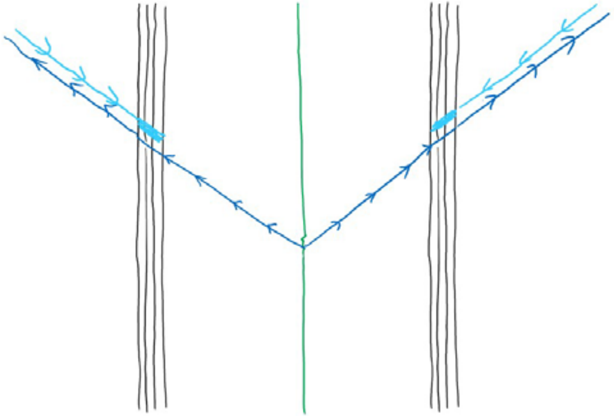


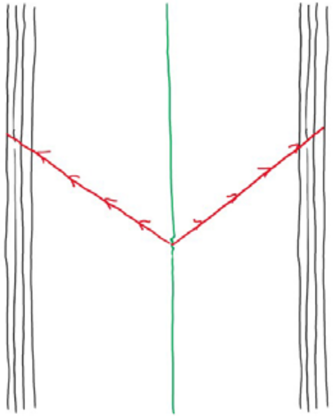
pozorování



pozorování



F_{ret} vysvětlení



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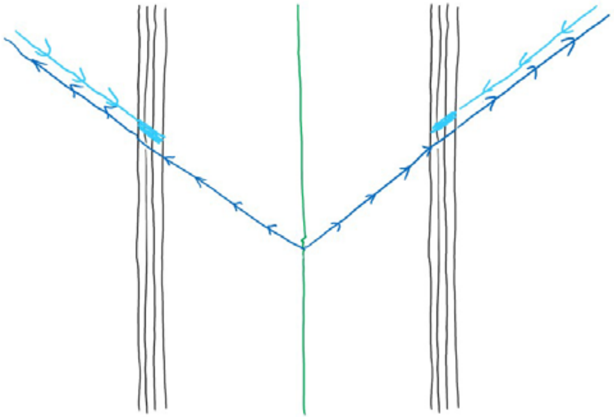

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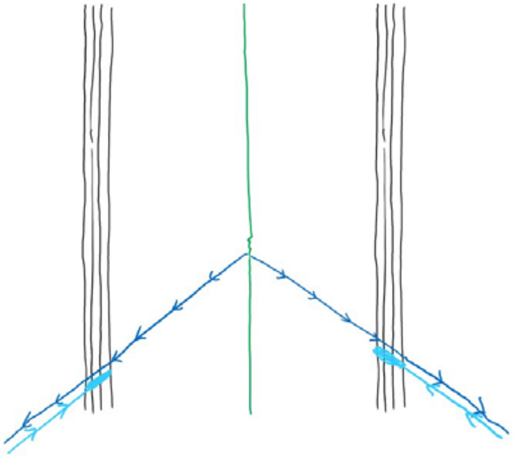

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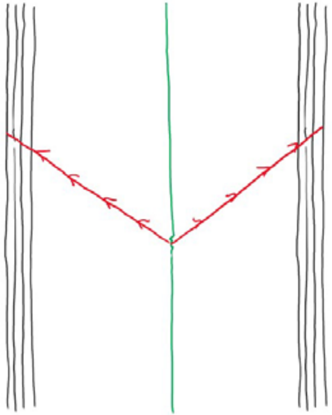

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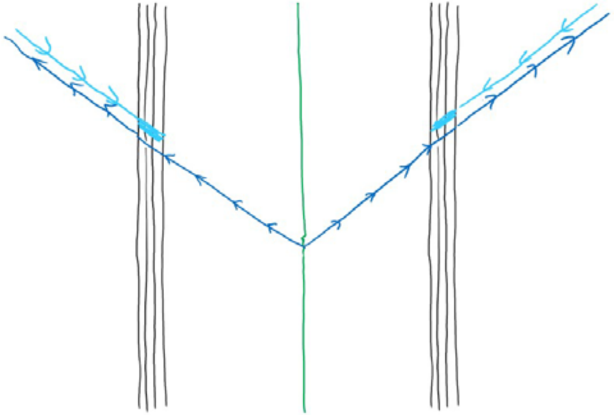
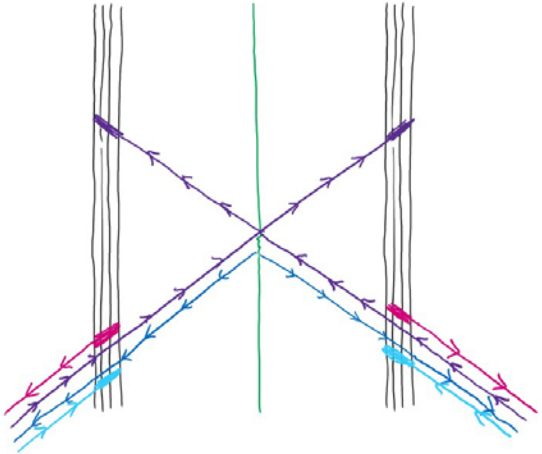
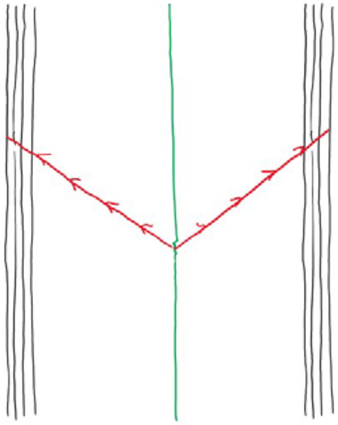


F_{zet} vysvětlení



F_{ado} vysvětlení



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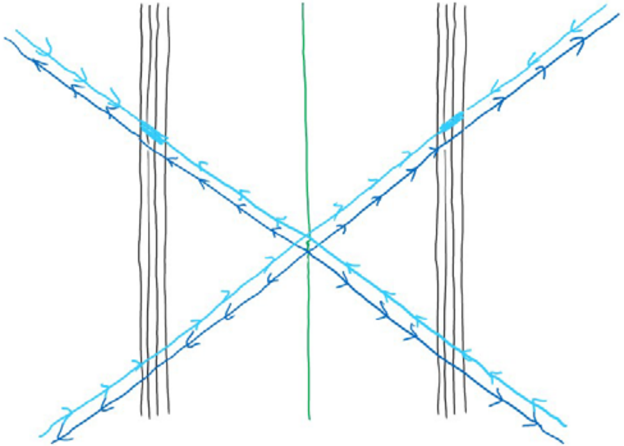
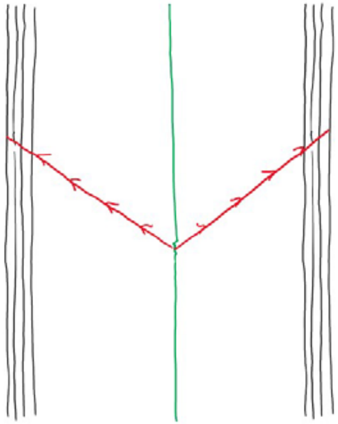


F_{sym} vysvětlení



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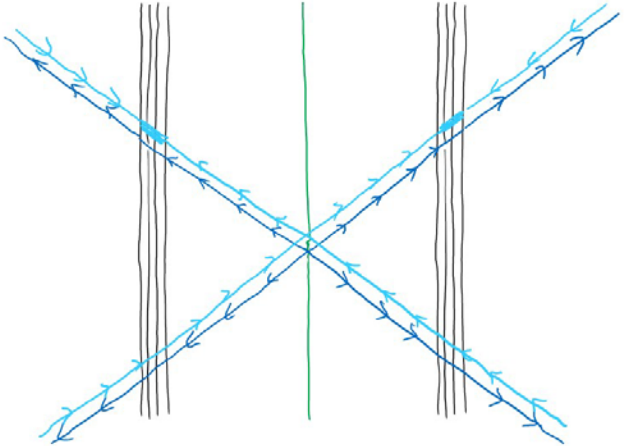
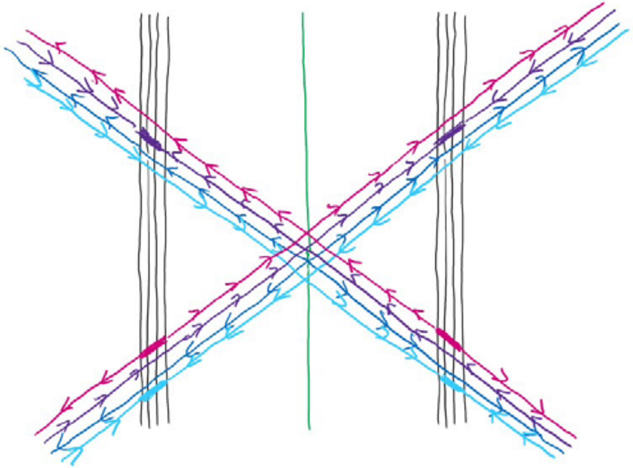


F_{sym} vysvětlení



F_{sym} vysvětlení