

the handy booklet of

# **Constantly Asked Physics Questions**

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## Kinematics/General Physics

### KGP1 - Why is $c/\hbar/k_B$ (other fundamental constant) the value it is? What would happen if it was different?

Why is  $c$  (the speed of light in a vacuum) exactly 299 792 458 m/s?

The metre and the second are arbitrary units that originally referred in their definition to natural phenomena that were relevant to the daily life of humans. A second would be 1/86400 of a day, the period of rotation of the Earth. The metre is one ten-millionth of the distance between the equator and the North Pole.

As soon as the necessary physics was consolidated, these definitions were replaced with the modern ones:

- 1) The second is 9 192 631 770 times the period of the radiation emitted in a specific atomic transition of  $^{133}\text{Cs}$ .
- 2) The metre is the length travelled by light in vacuum in 1/299 792 458 of a second.

The first definition is still referring to a natural process, albeit much more exact than the rotation of the Earth. The bizarre number involved is to make sure the new definition makes a modern second as similar as possible to the older second. Basically, the period of the transition radiation had been previously *measured* as being 1/9192631770 s (in older seconds).

The second one rests on the first and simultaneously fixes the value of  $c$ . The units are explicitly *designed* so that the value of  $c$  is 299 792 458. This value is similar to the previous, measured value of  $c$  in the older units.

Instead, the value of  $c$  in the new system is defined, not measured.

This means we can actually make  $c$  have any value we want by redefining the units. If we use lightyears and years for measuring lengths and times, we get

$$c = 1 \text{ ly/y}$$

But here it seems like we're just playing around with units. We aren't apparently actually *changing the speed of light*. Here's a little gedankenexperiment about that.

Assume there was a Universe where the speed of light was twice ours:

$$c' = 2c$$

Since the speed of light enters basically every relativistic phenomenon and many things about light and electromagnetism, you can bet the dynamics in this primed Universe will be very different from those in our unprimed one. For example, it's very likely it won't develop human life, at least in the same way as it happened for us.

However.

Consider the following change of variables in the primed Universe:

$$x' \rightarrow \tilde{x}' = x'/2, \quad t' \rightarrow \tilde{t}' = x'$$

The tilded coordinates are just the normal coordinates, but with space stretched by a factor of 2. In these coordinates, the value of the speed of light is:

$$\tilde{c} = \left( \frac{\tilde{x}'}{\tilde{t}'} \right)_{\text{computed for a light ray}} = \frac{1}{2} \frac{x'}{t'} = \frac{1}{2} c' = c$$

So we have to admit that, in the tilded coordinates, the speed of light is back to its original value in our Universe. In those coordinates, the primed Universe satisfies the same equations of motion as our own, and evolves identically. It has the same Big Bang, the same primordial nucleosynthesis, the same star formation, a Sun identical to ours, and an Earth and humans.

The humans are twice as tall as us, yes. But they don't know that. Since their Earth is twice as big, their metre (the tilded metre) is twice ours, and they measure their height to be normal in their tilded metres.

They finally measure the speed of light to be 299 792 458 metres per second.

So, nothing would happen. This is the manifestation of how fundamentally meaningless the value of the speed of light is. Mainly because there is no independent other speed with which to compare it, as all speeds in physics ultimately depend on it.

All of the above applies to the following set of independent fundamental physical constants:

$$c, \hbar, k_B, \epsilon_0, G$$

and all those auxiliary constants formed by products of powers of those above. The above set is a maximal set of independent constants and is the largest set of constant for which you can simultaneously impose a fixed value by redefining the units. If you fix less than all of these, you get freedom in your system of units. For example, setting

$$c = \hbar = k_B = \epsilon_0 = 1$$

gives natural units (Lorentz-Heaviside variant), useful in high-energy physics. Since you omitted  $G$ , you still have a single arbitrary unit to fix. You can use

the metre, for example, and the rest of the units follow. The time unit is  $cm$ , the energy unit is  $\frac{c\hbar}{m}$  and so on.

Adding  $G = 1$  instead gives Planck units.

## Classical Mechanics

## Thermodynamics

## Celestial/Orbital Mechanics

## Fluid Mechanics

## Classical Electrodynamics

### CED1 - What is the Maxwell/Stress tensor and how does it work?

Consider linear momentum:

$$P^i$$

it's the  $i$  component of the total linear momentum in the system. It will be an integral over space of some linear momentum density I'll call  $p^i$ :

$$P^i = \int d^3x p^i(x)$$

This quantity is conserved. It's also pretty reasonable that it's somewhat conserved *locally*, meaning that it doesn't just disappear somewhere and reappear magically somewhere else, it has to *flow*.

What I mean is that if the amount of linear momentum in a certain region of space changes, it must be because of some flux in/out the surface of that region:

$$\frac{d}{dt}P_V^i = \int_V d^3x \frac{d}{dt}p^i(x) = - \oint_{\partial V} d^2\vec{\Sigma} \cdot \vec{\Phi}^i$$

I just wrote that the variation of  $P_V^i$  ( $P^i$  restricted to the volume  $V$ ), which is equal to the integral of the variation of the density, must be counterbalanced by some flux  $\vec{\Phi}$  that crosses the boundary  $\partial V$ . If it's decreasing, then it must be leaking.

Now here's the thing: the stress tensor element  $\sigma_{ij}$  is precisely the *flux of  $P^i$  in the  $j$  direction*. It's how much  $P^i$  is flowing through a unit surface orthogonal to

the  $j$ -direction. It is also symmetric (nontrivial, and in fact dependent on some choices) and it does transform like a 2-tensor, a matrix, which justifies the name.

So let's rewrite what we had:

$$\int_V d^3x \frac{d}{dt} p^i = - \oint_{\partial V} d^2\Sigma^j \sigma^{ij}$$

What I've done is:

- Rewritten the scalar product  $\vec{\Sigma} \cdot \vec{\Phi}^i$  using indices as  $\Sigma^j \Phi^{ij}$ . Be careful about these indices:  $i$  means which component of the momentum we're talking about,  $j$  is the vector index of the flux itself (which is a vector).
- Recognized that  $\Phi^{ij} = \sigma^{ij}$  from what we said earlier.

Now what you would like to do is to deduce a differential, infinitesimal form of the equation above (which is known as the integral continuity equation). You do this by integrating over a very small cube; I'll spare you the details, but it's an easy computation, and you end up with:

$$\frac{\partial p^i}{\partial t} + \partial_j \sigma^{ij} = 0$$

or, in vector form:

$$\frac{\partial \vec{p}}{\partial t} + \vec{\nabla} \cdot \sigma = 0$$

this is the continuity equation or local conservation (in differential form). (note that the density  $\vec{p}$  is a vector, because it's the density of the vector  $\vec{P}$ .)

In an interacting theory of electromagnetic fields and matter, both contribute to total linear momentum. So, reasonably, both will have a stress tensor:

$$\sigma^{ij} = \sigma_f^{ij} + \sigma_m^{ij}$$

and they will **not** be separately conserved. Only their sum, total stress, obeys the continuity equation we just found. The physical interpretation is that momentum can be exchanged between fields and matter. When an electron produces radiation, for example, that radiation carries away momentum from the electron. We can substitute the decomposition in the continuity equation to obtain:

$$\frac{\partial \vec{p}_f}{\partial t} + \vec{\nabla} \cdot \sigma_f = - \frac{\partial \vec{p}_m}{\partial t} + \vec{\nabla} \cdot \sigma_m =: \vec{s}$$

Where I have defined the source term  $s$ .

This source term encapsulate the passage of momentum from charged matter to fields. So field momentum is not conserved separately, and  $s$  represents “generation” of momentum from charges. Fittingly, the equation is now called a continuity equation with sources.

So the Maxwell stress tensor is just  $\sigma_f$ , the stress tensor for only the electromagnetic field.

What I’ve detailed up to now is the physical interpretation in general of the stress tensor in any local theory, which is what you asked about. The actual form of the tensor for electromagnetism in terms of  $E$  &  $B$  is computed from the Poynting vector in a way that Griffiths can explain much better than me.

## Analytical Mechanics

### Special Relativity

#### SR1 - In what sense does $E = mc^2$ , and what does it mean?

Ok, ok, ok. Let’s take a deep breath.

When switching from Newtonian to relativistic physics, a couple of formulas have to be explicitly replaced. In particular, we can summarize this shift in the following substitutions for the mechanical energy and linear momentum of a body:

$$E_N = \frac{1}{2}mv^2 \longrightarrow E = \frac{1}{\sqrt{1 - (v/c)^2}}mc^2$$

$$p_N = mv \longrightarrow p = \frac{v/c}{\sqrt{1 - (v/c)^2}}mc$$

These might look a bit daunting, and additionally I just pulled them out of my ass. Just trust me that they can be derived rigorously. Let us concentrate on interpreting them and their consequences.

The Newtonian expressions should be well-known; they are however incorrect when speed becomes relativistic ( $(v/c) > 0.1$  is a good rule-of-thumb) and must be replaced by the formulas on the right.

$m$  is the mass. Just mass. It’s a constant *and* an invariant for the object. It does not depend on the frame of reference nor the *global* state of motion of the body (I’ll clarify this adjective in a minute). Do not trust anyone talking about “relativistic mass”, it’s an old concept from when people were still trying to figure out this stuff and it makes everything *immensely* more complex (just a taste:

there is a transverse and a longitudinal relativistic mass). Only ever discuss invariant mass, or just mass.

$v$  is simply how much space the body travels over how much time, with space and time measured in a certain inertial frame. I really want to stress the simplicity of this definition, because people often get confused with time dilation and length contraction and other complications, while this definition is absolutely crystal clear:

$$v = \frac{dx}{dt}$$

where  $x$  and  $t$  are the space and time coordinates of the body in some coordinate system (reference frame), nothing to do with proper time or anything of that sort. No magic here.

And  $c$ , of course, is the speed of light in vacuum.

The  $v/c$  ratio and the  $(1 - (v/c)^2)^{-1/2}$  thing are so ubiquitous in SR that we give them the following names:

$$\beta := v/c \qquad \gamma := \frac{1}{\sqrt{1 - \beta^2}}$$

So the formulas simplify to  $E = \gamma mc^2$  and  $p = \beta \gamma mc$ .

Now, the burden of proving that the relativistic expressions do actually reduce to the Newtonian expressions in the nonrelativistic limit is on us. The nonrelativistic limit is when  $v \ll c$ , or equivalently  $\beta \ll 1$ . To do so, let us recall the following Taylor expansion from calculus:

$$(1 + \epsilon)^\alpha = 1 + \alpha\epsilon + \frac{\alpha(\alpha - 1)}{2!}\epsilon^2 + \dots$$

this is simply the Binomial expansion and it's a really useful one to keep in mind (at least the first order term). We expand the  $\gamma$  factor using  $\epsilon = -\beta^2$  as such:

$$\gamma = (1 - \beta^2)^{-1/2} = 1 + \frac{1}{2}\beta^2 + \dots$$

Second-order in  $\beta$  is all we really need. So, finally, for the mechanical energy and momentum in the nonrelativistic limit we get:

$$E = mc^2 + \frac{1}{2}mv^2 + \dots$$

$$p = mv + \dots$$



In the expression for  $p$  I've stopped at the first term because the next is order  $\beta^3$ .

There's something seriously wrong.  $p$  looks like its Newtonian counterpart  $p_N$ , while  $E$  has an additional spurious term,  $mc^2$ . This is not a small term. In fact it's huge.

$E_0 := mc^2$  is the energy the body has when  $v = 0$ , so it's called the rest energy. Why does it not completely invalidate Newtonian mechanics?

Mostly, it's because it's impossible to tap into this energy. In nonrelativistic mechanics, mass is conserved (it is **not** conserved in special relativity). This means that in any physical process,  $E_0$  is untouched. It decouples completely from the physics, and thus it's just an invisible energy shift.

Mechanics (and Physics in general) is insensible to global energy shifts. For example, if your mechanical energy is

$$E = \frac{1}{2}mv^2 + 49 \text{ J}$$

nothing changes in your dynamics. You just added a constant, so what. Since  $mc^2$  is effectively a constant in nonrelativistic physics, it does not affect dynamics and could not be derived even in principle by a nonrelativist not aware of special relativity. In fact, Newton just set that constant to zero for simplicity.

Now, we said that  $E_0$  is the energy the body has when it's at rest. So we can conveniently divide our total energy in  $E_0$  and a term we rightfully call kinetic energy:

$$E = \gamma mc^2 = mc^2 + (\gamma - 1)mc^2 =: E_0 + E_K$$

Since  $\gamma - 1 \sim \frac{1}{2}\beta^2$  it's clear that the nonrelativistic limit is just  $E_K \ll E_0$ .

This is starting to make sense:  $E_0$  is the energy the object has simply for existing, there is an energy cost associated with just having a mass. It is the difference between the energy of a state where the object exists (and is still) and one where it doesn't. It's the required energy to create it, or the yield if it's destroyed. Of course, this does not prove that it's possible to create or destroy mass, just that *if* there is a channel for that creation or destruction, that is the energy requirement.

Since in nonrelativistic mechanics the energies involved in processes ( $E_K$ ) are much smaller than the  $E_0$  for an object, creation and destruction of mass most certainly do not happen in nonrelativistic physics.

Since  $E_0$  is the total energy of the object when it's still, it's reasonable that if the object was a composite system made of smaller units, it also includes the internal energy, not just the sum of the rest energies of the components.

Take for example a stationary box filled with a gas at temperature  $T$ . The overall, or average velocity of the gas is zero, but the single particle of the gas will have a nonzero velocity and consequently a kinetic energy  $E_K^i$ . The total energy is

$$\sum_i E^i = \sum_i mc^2 + \sum_i E_K^i$$

but we have said that this must be  $E_0 = Mc^2$ , with  $M$  the mass of the box, so

$$M = \sum_i m + \frac{1}{c^2} (\sum_i E_K^i)$$

So, the mass of the box is actually greater than the sum of the masses of the particles! Albeit, by a very, very small amount, that only gets relevant if  $E_K^i$  is at least of order  $mc^2$ . This shows that mass is not additive, and displays the so called “mass-energy equivalence” which is more correctly expressed as:

$$U = mc^2$$

that is, mass (as in, the inertia measured in Newtonian mechanics) is equivalent to the *total internal* energy, also including the energy to create the constituents.

This is why people will shout at you that  $E = mc^2$  is not the full formula/is wrong. They’re right. That  $E$  is supposed to be  $E_0$ .

## SR2 - if photons are massless, how can $E = mc^2$ ?

Read [SR1](#).

The formulas in SR1 are singular if  $v = c$ , which is certainly the case for a photon, a quantum of light. We need to rewrite them by getting rid of the velocity. (Or take a careful limit. That’s a nice alternative. But we won’t do that).

In classical mechanics, this is already done when switching from the Lagrangian to the Hamiltonian. You want to write  $E(v)$  in function of  $p(v)$ . So you invert  $p(v)$  as  $v(p)$  and then substitute  $E(v(p))$ . Easier done than said:

$$\begin{aligned} p_N &= mv \Rightarrow \\ v &= \frac{p_N}{m} \\ E_N(v) &= \frac{1}{2}mv^2 \Rightarrow E_N(p) = \frac{p_N^2}{2m} \end{aligned}$$

Which you’ll recognize as a standard kinetic Hamiltonian if you’re into Hamiltonian mechanics and you’ll ignore this sentence if you don’t.

We can do the same with the relativistic case. But first, a neat fact about  $\beta$  and  $\gamma$ :

$$\gamma^2 - (\beta\gamma)^2 = 1$$

try it. It's very boring, but it's true. (It's cool because it implies that if  $\gamma = \cosh(\eta)$ , then  $\sinh(\eta) = \beta\gamma$  and  $\tanh(\eta) = \beta$  and if you don't think hyperbolic functions are the shit then I don't know what to tell you).

So, we write

$$\begin{aligned}\gamma &= \sqrt{1 + (\beta\gamma)^2} \\ E &= \gamma mc^2 = \sqrt{1 + (\beta\gamma)^2} mc^2 \\ &= \sqrt{(mc^2)^2 + (\beta\gamma mc^2)^2} \\ &= \sqrt{(mc^2)^2 + (pc)^2}\end{aligned}$$

So this is our  $E(p)$ , the so-called “full expression” for the mechanical energy of a relativistic body.

(If you Taylor-expand  $E(p)$  around  $p = 0$ , you get  $E = mc^2 + \frac{p^2}{2m} + \dots$ . Go figure.)

Ok, so we've gotten rid of the gammas and betas. Just a last thing about them! The speed of an object is always recoverable from the energy and momentum:

$$\frac{p}{E}c^2 = \frac{\beta\gamma mc}{\gamma mc^2}c^2 = \beta c = v$$

And only now that we have built this architecture we plug in  $m = 0$  to find about massless particles. We get

$$E = pc$$

and

$$v = c, \quad \gamma = \infty$$

So massless particles move always at the speed of light and have energy proportional to their momentum. In the limit where the momentum goes to zero,  $p \rightarrow 0$ , the energy also goes to zero. Instead, for massive objects the energy tends to the rest energy  $mc^2$ . Therefore it makes sense to extend the definition of the rest energy  $E_0 = mc^2$  to photons, with  $m = 0$ , even if they cannot ever be brought to rest.

The energy of a photon is entirely kinetical.

Note that the previous expressions  $E = \gamma(v)mc^2$  and  $p = \beta(v)\gamma(v)mc$  when  $m = 0$  are both indeterminate forms  $(0 \cdot \infty)$ . This makes sense: we have many photons, all with  $v = c$ , with different momentum and energy. We shouldn't be able therefore to determine the energy/momentum exactly just from the speed, so the math honourably breaks down.

## General Relativity

## Quantum Mechanics

## General Quantum Field Theory/Many Body/Relativistic QM

## Nuclear Physics

## Quantum Electrodynamics

## Particle Physics/High Energy Physics

### HEP1 - Why are photons massless?

Photons, being gauge bosons of a gauge theory, are a priori massless. However, they could in principle acquire a mass through at least a couple of mechanisms. The first is also present at the classical level and is the Higgs mechanism and variants. Why the photon is not affected by the Higgs mechanism is treated in [HEP2](#). The second happens upon quantization and is the quantum correction to the mass. Particles in general acquire quantum corrections to their physical parameters that can be investigated as being due with interaction with virtual particles as the original particle travels from point A to point B. The photon is again protected from this phenomenon and this is explained in [HEP3](#).

### HEP2 - Why do photons not acquire a mass through the Higgs mechanism?

By definition!

Photons are by definition the single component of the original  $SU(2) \times U(1)$  electroweak gauge field that leaves the Higgs vacuum expectation value invariant. This means that the VEV is uncharged for the photon, and the photon acquires no mass.

A little simpler: basically,  $SU(2) \times U(1)$  is a four dimensional group of transformation. The Higgs is a field which takes value in a four-dimensional (two-complex

dimensional) vector space and which is transformed (“rotated”) by these transformations. Now after electroweak symmetry breaking the Higgs acquires a VEV, which just mean that in all of space it assumes the value of a specific vector in that 4-dimensional space. This vector is not invariant under the original gauge group, this means that it breaks the symmetry. There is however a 1-dimensional subgroup of the gauge group that still leaves the VEV invariant and thus that symmetry remains unbroken. That group’s generator is defined to be the photon and the preserved gauge symmetry assures the photon has no mass. The other three generators instead do interact with the VEV and acquire mass. They are decomposed in three orthogonal generators by electric charge:  $W^+$ ,  $W^-$ ,  $Z^0$ .

And now, more detailed: assume WLOG that the Higgs has VEV as such:

$$\phi = \begin{pmatrix} 0 \\ \phi_0 \end{pmatrix}$$

with  $\phi_0$  real, and the generic gauge group element acts on  $\phi$  as

$$\phi \rightarrow \exp \left( i \left( \frac{g'}{2} B \cdot \mathbb{K} + gW_1 T^1 + gW_2 T^2 + gW_3 T^3 \right) \right) \phi$$

Where  $B$  and  $W_i$  are respectively the gauge field for weak hypercharge ( $U(1)$ ) and weak isospin ( $SU(2)$ ),  $T^i = \frac{\sigma^i}{2}$  are generators for  $SU(2)$ , and  $g, g'$  are the corresponding coupling constants.

We impose  $\phi' = \phi$  to find the little group of the VEV (the isotropy group). For infinitesimal generators, the above reduces to:

$$\begin{pmatrix} g'B + gW_3 & g(W_1 + iW_2) \\ g(W_1 - iW_2) & g'B - gW_3 \end{pmatrix} \begin{pmatrix} 0 \\ \phi_0 \end{pmatrix} = 0$$

This gives immediately  $W_1 = W_2 = 0$  (as they are real generators) and  $g'B - gW_3 = 0$ ; this means that the generator  $A = \frac{1}{\sqrt{g'^2 + g^2}}(g'W_3 + gB)$  solution to the latter two equations generates the one-dimensional isotropy group. This generator is the photon.

The other three generators do modify the value of the Higgs and are orthogonalized into the  $W^\pm = \frac{1}{\sqrt{2}}(W_1 \pm iW_2)$  and  $Z^0 = \frac{1}{g^2 + g'^2}(gW_3 - g'B)$ .

The mass generation is evidenced by expanding the kinetic term of the Higgs Lagrangian around the VEV. This gives a mass term for the gauge boson which is precisely the norm squared of  $\left( \frac{g'}{2} B \cdot \mathbb{K} + gW_i T^i \right) \begin{pmatrix} 0 \\ \phi_0 \end{pmatrix}$ . Therefore the orthonormal states  $A, W^\pm, Z^0$  above diagonalize the mass matrix, and  $A$  is the single one with eigenvalue 0, as was shown before.

### HEP3 - Why do photons not acquire a mass through quantum corrections/interaction with virtual particles? What is charge renormalization?

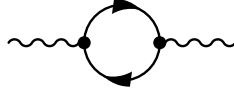
The short answer is that quantum corrections to the photon propagator do not give it a mass because of the Ward identity, which is a consequence of gauge invariance.

The probability amplitude for a photon to go from point A to point B is given by what is called the propagator. The “bare” propagator is given by the following expression:

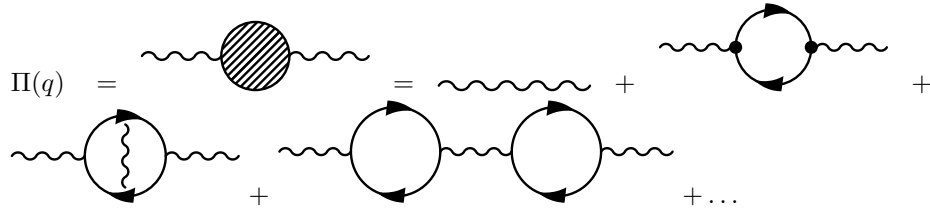
$$\text{~~~~~} = \pi^{\mu\nu}(q) = \frac{-iq^{\mu\nu}}{q^2 + i\epsilon}$$

where  $q$  is the four-momentum of the photon and  $\epsilon$  is a funny thing you shouldn't worry about. In fact, put it to 0. This is how a massless propagator should look. The mass of the particle is given by where the propagator is singular (has a pole), so in this case  $q^2 = m^2 = 0$ . (If the photon was massive, in the denominator we would have  $q^2 - m_\gamma^2 + i\epsilon$ ). The propagator has two Lorentz indices  $\mu$  and  $\nu$  because the photon has a polarization. To get the probability amplitude, you actually have to contract the indices of the propagator with your desired polarization  $\varepsilon_\mu$

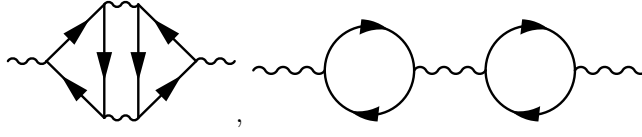
But this is just the bare propagator, this is all tree-level. We want to compute what happens to the propagator when we include higher-order corrections. More practically: the fact that a photon can produce a virtual electron-positron pair, which then reannihilate into a photon, as such:



*should* affect the probability of the photon going from point A to point B. In fact, when summing over all possible diagrams for the  $\gamma \rightarrow \gamma$  process:



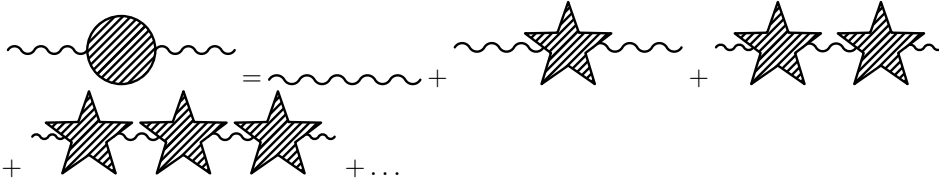
we should get the “dressed”, or physical propagator  $\Pi^{\mu\nu}$ . (A quick review of Feynman diagrams: time goes from left to right, wavy lines are photons, solid lines going right are electrons, left are positrons). Now we want to rearrange the terms of the previous series. Call a diagram one-particle-irreducible (1PI) if you cannot split it in two by cutting one of the internal lines (the two wavy lines at the beginning and end don't count). For example, the following diagrams are respectively 1PI and not 1PI.



Now consider the sum of all 1PI diagrams in the original series, and denote it as:



My claim is that the full series of all diagrams for the photon propagator is equal to:



This is actually really simple. Think about it.

So, remembering that concatenating Feynman diagrams means we have to multiply them, we get the geometric series:

$$\Pi = \pi + \pi S \pi + \pi S \pi S \pi + \pi S \pi S \pi S \pi + \dots = \pi (1 + S \pi + (S \pi)^2 + (S \pi)^3 + \dots)$$

except these are matrices (with  $\mu$  and  $\nu$  indices), so we have to fix that before summing the geometric series. Here we introduce the fundamental Ward identity. If you have any process in which a photon is one of the external lines (incoming or outgoing particles), then the probability amplitude  $\mathcal{M}$  satisfies

$$\mathcal{M}^\mu q_\mu = 0$$

where  $q_\mu$  is the momentum of the photon.

Our 1PI propagator  $S^{\mu\nu}(q)$  should satisfy the Ward identity. It must therefore be proportional to the projector on the subspace orthogonal to  $q_\mu$ . It's not hard to convince oneself that this is given by

$$S^{\mu\nu}(q) = (q^2 g^{\mu\nu} - q^\mu q^\nu) \Phi(q^2) = \Delta^{\mu\nu}(q) \Phi(q^2)$$

Where  $\Phi(q^2)$  is some scalar function (we also have used that the propagator must be Lorentz-invariant). Since  $\Delta$  is a projector,  $\Delta^2 = \Delta$  (in the sense of matrices). Moreover, also the product  $\Delta' = \Delta \pi$  is a projector, as you can readily compute. We return to our series:

$$\Pi(q) = \pi \left( 1 + \Delta' \Phi + \Delta' \Phi^2 + \Delta' \Phi^3 + \dots \right) = \pi + \pi \left( \Delta' \left( \frac{1}{1 - \Phi(q)} - 1 \right) \right) \pi$$

So, finally

$$\Pi^{\mu\nu}(q) = \frac{-i}{q^2(1 - \Phi(q^2))} \left( g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) + \frac{-i}{q^2} \left( \frac{q^\mu q^\nu}{q^2} \right)$$

Now, we can just drop all terms with  $q_\mu q_\nu$ , because the Ward identity tells us they will not contribute to the scattering amplitude (the Ward identity is just telling us that the longitudinal polarization of the photon is unphysical). Our final expression for the dressed propagator is

$$\Pi^{\mu\nu} = \frac{-i g^{\mu\nu}}{q^2(1 - \Phi(q^2))}$$

which is identical to our original bare propagator  $\pi$ , just multiplied by the function  $(1 - \Phi(q^2))^{-1}$ . Remembering what we said about poles and masses, for the photon mass to be preserved we would need that this function does not cancel the pole at  $q^2 = 0$  of  $\pi$ . The cancellation would need  $\Phi(q^2)$  to have itself a second-order pole at  $q^2 = 0$ , but this would seem impossible. However, it is absolutely not obvious, and in fact it is false in 2 spacetime dimensions. In the Schwinger model, in 2D,  $\Phi(0)$  has a pole canceling  $q^2$  and the photon mass is shifted to a finite value.

But our world is luckily higher-dimensional and the photon is safe from mass renormalization.

However, the propagator still acquires a global multiplicative factor

$$Z_3 := \frac{1}{1 - \Pi(q^2)}$$

Since the photon propagator connects two interaction vertices, and these bring each a power of the fundamental charge  $e$ , the quantum correction to the photon propagators is making the electromagnetic interaction stronger. In particular, for each photon line there are two vertices and one factor of  $Z_3$ , so

$$e^2 \rightarrow Z_3 e^2$$

which basically mean we could understand this shift as  $e \rightarrow \sqrt{Z_3} e$ . This is why the procedure we performed above is called charge renormalization. We just derived the well-known fact that the strength of the EM interaction depends on the four-momenta involved.



To derive exactly that  $\Phi$  has no unwanted pole and how exactly  $e(q^2)$  runs with energy we would need to compute  $\Phi$  explicitly (with some clever regularization, since it's divergent) and I don't want to do that. For that, refer to any good QFT/QED textbook.

## Quantum Gravity/String Theory

**QG1 - If the Planck length/Planck time is the smallest measurable/possible length/time, then...?**