MARKUS KLUTE: Welcome back to 8.701. So we continue our discussion, our development of QED as a discussion of the photon. We have already seen how we can describe electrons and positrons, anti-electrons. And now it's time to actually look at the quantum of electromagnetic fields.

A few general remarks first, quantum electrodynamic is a quantum field theory-- the quantum field theory of electrodynamic processes describing how light interacts with matter. Specifically, all processes where a photon is used as an exchange particle involving electrically-charged particles can be described by QED.

The photon is in the limit theory particle. And it's a quantum of the electromagnetic field. But the real power in QED lies in the fact that we can describe it as a perturbation theory. We'll see that we can write down Feynman diagrams, calculate them, and use those calculations to describe processes we can observe in experiment.

And since we can do this with a very high precision, we can use QED in order to make forecasts, in order to understand, in order to understand inner dynamics of processes we can measure. Feynman called QED our pride and joy. And it's in the really unmatched precision of this theory where the pride and joy lies.

But stepping back one step. Let's start with just local election dynamics. And let's start from Maxwell's equations. And I'm going to use this just to make a few points and remarks. This is really not in the direct path of our development, but it connects the dots to something you have already started, meaning classical electrodynamics.

So you all have seen Maxwell equations. They can be expressed in integral or differential form. And you can write this even more compact than it's given here.

So you see Gauss's law. And you see that electric charge generate electric fields you can see that you can produce currents by time changing electric fields or by spatially changing magnetic fields. Gauss's law for magnetic fields saying that there is no magnetic charge, no magnetic monopole, at least as far as we know. We have not observed those. And then there's Faraday's law as well.

You can express the magnetic field and the electric field through vector potentials. And if you go one step further, you see this very nice form using four vectors for the potential and the vector potential and the charge and the current.

So what we're really doing here right now is we're just rewriting the very same equations. And so when we use this [INAUDIBLE] operator, the form of this equation looks like this. You can already see this form is very similar to the Klein-Gordon equation we just looked at.

So let's go down this path a little bit more. So this here is yet another form to write the Maxwell equations, where f is our field strength tensor. And the field strength tenor has all the physics involved. You see that you're describing the electromagnetic field and its components. And then the simplification of the Maxwell equations are sitting here. So we have the Maxwell equation in this form. We have the Maxwell equation in this form here.

So there's one interesting thing when we use potential in order to describe electromagnetic processes or properties, is that we can actually choose the specifics of the gauge. There's a degree of freedom which we can choose, which doesn't have any impact on the physics, on the reality of the physics.

And you can see this here. If you do the choice that this component is 0, this is called the Coulomb gauge. We basically simplify again our Maxwell equations to this point here.

Great. So there's a number of things to be said. So what we are basically doing here, if we fix a gauge, so if you fix our potential, we tie the choice of the potential to the inertial frame we're using here.

And you could say that's not nice. That doesn't seem [INAUDIBLE] invariant. It is actually OK to do this. The issue with that is that you tie-- if you go from one frame in the other, you have to actually change the gauge as you go along with changing the reference frame.

But there's nothing bad, it's just a little bit awkward. All right, then moving back so we have this equation now. And this equation, obviously simplifies. If there's no current or no charge around for free photons.

So this one, and for this you can find the solution is again the free rates. This was the goal of this lecture, finding this free weight. So you could have probably written this down before any of the discussion, but I just want to makes some connection.

So now this in the QED, this a mu, becomes our big function for the photon. Again, we have to this is as a result of the we gauge made. So we made specific choice in our reference frame. And then we can describe the photon with our wave function.

That is epsilon here, epsilon is our polarization vector. And is a normalization factor. We always have to normalize our wave function to a specific set of unit.

All right, that's good. We can now analyze this. We find that those conditions are fulfilled here, basically saying that photon decays like a photon. The energy of the photon is equal to the momentum times C.

That's great. But it's also not a surprise because the form of this equation here is exactly that of the Klein-Gordon equation not for massless particles. In the Klein-Gordon equation we got from this very same relationship, so I was not surprised that this works out.

All right, one more word on the polarization vector. So the choice you just made-- I'm resulting the choice here. This is our Coulomb requires that the zeros component of our polarization vector is a0. And that the polarization vector is orthogonal to the momentum vector.

So in principle, you have the three vector. The three vector is perpendicular to the direction of motion. And that allows us to find two polarization states which are independent of each other.

So different to our electrons before. Now we don't have four states. You only have two states with independent solutions for a given momentum.

All right, so with this now, we have elections. We can describe those. We can describe photons. The next step now is to look at the Feynman rules which allows us to describe the interaction between those two.