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0.1 Introductory remarks

Quantum field theory (QFT) is the quantum mechanics of *extensive degrees of freedom*. What I mean by this is that at each point of space, there’s some stuff that can wiggle.

‘Extensive degrees of freedom’ are those which, if we like, we can sprinkle over vast tracts of land, like sod (depicted in the figure at right). And also like sod, each little patch of degrees of freedom only interacts with its neighboring patches: this property of sod and of QFT is called *locality*.

More precisely, in a quantum mechanical system, we specify the degrees of freedom by their Hilbert space; by an extensive system, I’ll mean one in which the Hilbert space is of the form \( \mathcal{H} = \bigotimes \text{patches of space} \mathcal{H}_{\text{patch}} \) and the interactions are local \( \mathcal{H} = \sum_{\text{patches}} \mathcal{H}(\text{nearby patches}) \).\(^1\)

It’s not surprising that QFT is so useful, since this situation happens all over the place. Some examples of ‘stuff’ are: the atoms in a solid, or the electrons in those atoms, or the spins of those electrons. A less obvious, but more visible, example is the electromagnetic field, even in vacuum. More examples are provided by other excitations of the vacuum, and it will be our job here to understand those very electrons and atoms that make up a solid in these terms. The vacuum has other less-long-lasting excitations which are described by the Standard Model of particle physics.

Some examples of QFT are Lorentz invariant (‘relativistic’). That’s a nice simplification when it happens. Indeed this seems to happen in particle physics. We’re going to focus on this case for much of this quarter. Still I would like to emphasize: though some of the most successful applications of QFT are in the domain of high energy particle physics, this is not a class on that subject, and I will look for opportunities to emphasize the universality of QFT.

Last quarter you saw that the low-energy excitations of weakly-coupled fields are *particles*. A consequence of relativity is that the number of particles isn’t fixed. That is: there are processes where the number of particles changes in time. Sometimes this is used to motivate the study of QFT. It’s a necessary consequence of Lorentz symmetry, but the converse is false: particle production and destruction can happen without relativity.

\(^1\)Actually, the Hilbert space of a gauge theory is *not* of this form; rather, it is a subspace of such a space which satisfies the Gauss law. This is a source of a lot of confusion, which I hope to dispel.
‘Divergences’. Another intrinsic and famous feature of QFT discernible from the definition I gave above is its flirtation with infinity. I said that there is ‘stuff at each point of space’; how much stuff is that? Well, there are two senses in which ‘the number of points of space’ is infinite: (1) space can go on forever (the infrared (IR)), and (2) in the continuum, in between any two points of space are more points (the ultraviolet (UV)). The former may be familiar from statistical mechanics, where it is associated with the thermodynamic limit, which is where interesting things happen. For our own safety, our discussion will take place in a padded room, protected on both sides from the terrors of the infinite.

Last quarter 215A ended right when you learned to compute amplitudes for simple processes in QED. There are many measurable quantities that can be computed using the formalism you developed, and the success of leading-order QED is a real high point of physics. I’ll have to say a few words about that success.

Lurking behind that success, however, is a dark cloud. The leading order of perturbation theory is given by tree diagrams; more complicated diagrams should be suppressed by more powers of $\frac{e^2}{4\pi} \equiv \alpha$. You might think that if the leading calculation worked so well, we should do even better by looking at the next term. But there is a surprise: naively calculating the next term gives an infinite correction.

So an important job will be to explain the non-naive point of view on this calculation which allows us to extract finite, meaningful answers from perturbation theory.

Even more important will be to give a better point of view, from which we never would have encountered divergences in the first place. The (silly) name for this point of view is the renormalization group.

So here are some goals for the quarter, both practical and philosophical:

- There is more to QFT than the S-matrix. In a particle-physics QFT course (like 215 so far) you learn that the purpose in life of correlation functions or green’s functions or off-shell amplitudes is that they have poles (at $p^\mu p_\mu - m^2 = 0$) whose residues are the S-matrix elements, which are what you measure (or better, are the distribution you sample) when you scatter the particles which are the quanta of the fields of the QFT. I want to make two extended points about this:

  1. In many physical contexts where QFT is relevant, you can actually measure the off-shell stuff. This is yet another reason why including condensed matter in our field of view will deepen our understanding of QFT.

  2. This is good, because the Green’s functions don’t always have simple poles! There are lots of interesting field theories where the Green’s functions instead have power-law singularities, like $G(p) \sim \frac{1}{|p|^2}$. If you Fourier trans-
form this, you don’t get an exponentially-localized packet. The elementary excitations created by a field whose two point function does this are not particles. (Any conformal field theory (CFT) is an example of this.) The theory of particles (and their dance of creation and annihilation and so on) is an important but proper subset of QFT.

- In addition to its importance in high energy physics, I want to emphasize that QFT is also quite central in many aspects of condensed matter physics. From the point of view of someone interested in QFT, high energy particle physics has the severe drawback that it offers only one example! (OK, for some purposes we can think about QCD and the electroweak theory separately...)

From the high-energy physics point of view, we could call this the study of regulated QFT, with a particular kind of lattice regulator. Why make a big deal about ‘regulated’? Besides the fact that this is how QFT comes to us (when it does) in condensed matter physics, such a description is required if we want to know what we’re talking about. For example, we need it if we want to know what we’re talking about well enough to explain it to a computer. Many QFT problems are too hard for our brains. A related but less precise point is that I would like to do what I can to erase the problematic, theorist-centered perspective on QFT which ‘begins from a classical lagrangian and quantizes it’.

- A central theme this quarter will be coarse-graining in quantum systems with extensive degrees of freedom, aka the renormalization group (RG) in QFT.

By ‘coarse-graining’ I mean ignoring things we don’t care about, or rather only paying attention to them to the extent that they affect the things we do care about. And the things we should care about the most are the biggest ones – the modes with the longest wavelength. So the ‘better perspective’ alluded to above is: we should try to understand QFT scale by scale.

To continue the sod example in 2+1 dimensions, a person laying the sod in the picture above cares that the sod doesn’t fall apart, and rolls nicely onto the ground (as long as we don’t do high-energy probes like bending it violently or trying to lay it down too quickly). These long-wavelength properties of rigidity and elasticity are collective, emergent properties of the microscopic constituents (sod molecules) – we can describe the dynamics involved in covering the Earth with sod (never mind whether this is a good idea in a desert climate) without knowing the microscopic theory of the sod molecules (‘grass’). Our job is to think about the relationship between the microscopic model (grassodynamics) and its macroscopic counterpart (in this case, suburban landscaping). In my experience, learning to do this is approximately synonymous with understanding.
• I would like to convince you that “non-renormalizable” does not mean “not worth your attention,” and explain the incredibly useful notion of an Effective Field Theory.

• There is more to QFT than perturbation theory about free fields in a Fock vacuum. In particular, it is worthwhile to spend some some time thinking about non-perturbative physics, effects of topology, solitons. Topology is one tool for making precise statements without perturbation theory (the basic idea: if we know something is an integer, it is easy to get many digits of precision!). Maybe this will wait until 215C.

• Given time, I would like to show that many fancy phenomena precious to particle physicists can emerge from humble origins in the kinds of (completely well-defined) local quantum lattice models we will study. Here I have in mind: fermions, gauge theory, photons, anyons, strings, topological solitons, CFT, and many other sources of wonder I’m forgetting right now.

0.2 Sources and acknowledgement

The material in these notes is collected from many places, among which I should mention in particular the following:

   - Peskin and Schroeder, *An introduction to quantum field theory* (Wiley)
   - Banks, *Modern Quantum Field Theory: A Concise Introduction* (Cambridge)
   - Schwartz, *Quantum field theory and the standard model* (Cambridge)
   - David Tong’s lecture notes

Many other bits of wisdom come from the Berkeley QFT courses of Prof. L. Hall and Prof. M. Halpern.

   - Xiao-Gang Wen, *Quantum Field Theory of Many-Body Systems*
   - Sidney Coleman, *Aspects of Symmetry*
   - Alexander Polyakov, *Gauge Fields and Strings*
   - Eduardo Fradkin, *Field Theories of Condensed Matter Systems*
0.3 Conventions

Following most QFT books, I am going to use the \(+\,−−\) signature convention for the Minkowski metric. I am used to the other convention, where time is the weird one, so I’ll need your help checking my signs. More explicitly, denoting a small spacetime displacement as \(dx^\mu \equiv (dt, d\vec{x})^\mu\), the Lorentz-invariant distance is:

\[
ds^2 = +dt^2 - d\vec{x} \cdot d\vec{x} = \eta_{\mu\nu} dx^\mu dx^\nu \quad \text{with} \quad \eta^{\mu\nu} = \eta_{\mu\nu} = \begin{pmatrix} +1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}.
\]

(spacelike is negative). We will also write \(\partial_\mu \equiv \frac{\partial}{\partial x^\mu} = \left(\partial_t, \vec{\nabla}_x\right)\), and \(\partial^\mu \equiv \eta^{\mu\nu} \partial_\nu\). I’ll use \(\mu, \nu, \ldots\) for Lorentz indices, and \(i, j, k, \ldots\) for spatial indices.

The convention that repeated indices are summed is always in effect unless otherwise indicated.

\(d\) is the number of space dimensions, \(D\) is the number of spacetime dimensions (it’s bigger!).

A consequence of the fact that english and math are written from left to right is that time goes to the left.

A useful generalization of the shorthand \(\hbar \equiv \frac{\hbar}{2\pi}\) is \(dk \equiv \frac{dk}{2\pi}\). I will also write \(\delta^d(q) \equiv (2\pi)^d \delta^{(d)}(q)\). I will try to be consistent about writing Fourier transforms as

\[
\int \frac{d^d k}{(2\pi)^d} e^{ikx} \tilde{f}(k) \equiv \int d^d k \ e^{ikx} \tilde{f}(k) \equiv f(x).
\]

IFF \(\equiv\) if and only if.

RHS \(\equiv\) right-hand side. LHS \(\equiv\) left-hand side. BHS \(\equiv\) both-hand side.

IBP \(\equiv\) integration by parts. WLOG \(\equiv\) without loss of generality.

\(+\mathcal{O}(x^n)\) \(\equiv\) plus terms which go like \(x^n\) (and higher powers) when \(x\) is small.

\(+h.c.\) \(\equiv\) plus hermitian conjugate.

\(\mathcal{L} \ni \mathcal{O}\) means the object \(\mathcal{L}\) contains the term \(\mathcal{O}\).

We work in units where \(\hbar\) and the speed of light, \(c\), are equal to one unless otherwise noted. When I say ‘Peskin’ I usually mean ‘Peskin & Schroeder’.

Please tell me if you find typos or errors or violations of the rules above.
1 To infinity and beyond

At this point I believe you are able to use QED to compute the amplitudes and cross-sections for many physical processes involving electrons, photons and positrons. More precisely, you know how to compute the leading-order-in-$\alpha$ amplitudes, using Feynman diagrams which are trees – diagrams without loops. The natural next step is to look at the next terms in the perturbation expansion in $\alpha$, which come from diagrams with one loop. This innocent-seeming step opens a big can of worms. The reason this is a big step is that tree-level processes are actually classical.

In a tree-level diagram, the quantum numbers (and in particular the momenta) of the intermediate states are fixed by the external states. In contrast, once there is a loop, there are undetermined momenta which must be summed, and this sum includes, it seems, arbitrarily high momentum modes. Surely we have no information yet about these modes from our piddling low-energy experiments. (Perhaps this is an opportunity to learn about them?) What do we do?

In order to put ourselves in the right frame of mind to think about this stuff, we'll make a brief retreat to a parable about a system with finitely many degrees of freedom in §1.1. A second useful parable in §1.2 will come from the Casimir effect – the additive constant in the energy of free fields raises the same issues. Then we'll apply these lessons to a simple field theory example, namely scalar field theory. Then we'll come back to perturbation theory in QED. Reading assignment for this chapter: Zee §III.

1.1 A parable from quantum mechanics on the breaking of scale invariance

Recall that the coupling constant in $\phi^4$ theory in $D = 3 + 1$ spacetime dimensions is dimensionless, and the same is true of the electromagnetic coupling $e$ in QED in $D = 3+1$ spacetime dimensions. In fact, the mass parameters are the only dimensionful quantities in those theories, at least in their classical avatars. This means that if we ignore the masses, for example because we are interested in physics at much higher energies, then these models seem to possess scale invariance: the physics is unchanged under zooming in.

Here we will study a simple quantum mechanical example (that is: an example with a finite number of degrees of freedom)\textsuperscript{2} with such (classical) scale invariance. It exhibits many interesting features that can happen in strongly interacting quantum

\textsuperscript{2}I learned this example from Marty Halpern.
field theory – asymptotic freedom, dimensional transmutation. Because the model is simple, we can understand these phenomena without resort to perturbation theory. They will nevertheless illuminate some ways of thinking which we’ll need in examples where perturbating is our only option.

Consider the following (‘bare’) action:

\[ S[q] = \int dt \left( \frac{1}{2} \dot{\vec{q}}^2 + g_0 \delta^{(2)}(\vec{q}) \right) \equiv \int dt \left( \frac{1}{2} \dot{\vec{q}}^2 - V(\vec{q}) \right) \]

where \( \vec{q} = (x, y) \) are two coordinates of a quantum particle, and the potential involves \( \delta^{(2)}(\vec{q}) \equiv \delta(x)\delta(y) \), a Dirac delta function. I chose the sign so that \( g_0 > 0 \) is attractive. (Notice that I have absorbed the inertial mass \( m \) in \( \frac{1}{2}mv^2 \) into a redefinition of the variable \( q \), \( q \to \sqrt{m}q \).)

First, let’s do dimensional analysis (always a good idea). Since \( \hbar = c = 1 \), all dimensionful quantities are some power of a length. Let \(-[X]\) denote the number of powers of length in the units of the quantity \( X \); that is, if \( X \sim (\text{length})^\nu \) then we have \([X] = -\nu(X)\), a number. We have:

\[ [t] = [\text{length}/c] = -1 \implies [dt] = -1. \]

The action appears in the exponent in the path integrand, and is therefore dimensionless (it has units of \( \hbar \)), so we had better have:

\[ 0 = [S] = [\hbar] \]

and this applies to each term in the action. We begin with the kinetic term:

\[ 0 = \left[ \int dt \dot{\vec{q}}^2 \right] \implies [\dot{\vec{q}}^2] = +1 \implies [\dot{\vec{q}}] = +\frac{1}{2} \implies [\vec{q}] = -\frac{1}{2}. \]

Since \( 1 = \int dq \delta(q) \), we have \( 0 = [dq] + [\delta(q)] \) and

\[ [\delta^d(\vec{q})] = -[q]d = \frac{d}{2}, \quad \text{and in particular} \quad [\delta^2(\vec{q})] = 1. \]

This implies that when \( d = 2 \) the naive (“engineering”) dimensions of the coupling constant \( g_0 \) are \([g_0] = 0\) – it is dimensionless. Classically, the theory does not have a special length scale; it is scale invariant.
The Hamiltonian associated with the Lagrangian above is

$$H = \frac{1}{2} (p_x^2 + p_y^2) + V(\vec{q}).$$

Now we treat this as a quantum system. Acting in the position basis, the quantum Hamiltonian operator is

$$H = -\frac{\hbar^2}{2} \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) - g_0 \delta^{(2)}(\vec{q}).$$

So in the Schrödinger equation $H\psi = \left( -\frac{\hbar^2}{2} \nabla^2 + V(\vec{q}) \right) \psi = E\psi$, the second term on the LHS is

$$V(\vec{q})\psi(\vec{q}) = -g_0 \delta^{(2)}(\vec{q})\psi(0).$$

To make it look more like we are doing QFT, let’s solve it in momentum space:

$$\psi(\vec{q}) \equiv \int \frac{d^2p}{(2\pi\hbar)^2} e^{i\vec{p} \cdot \vec{q}/\hbar} \varphi(\vec{p}) \equiv \int d^2p \ e^{i\vec{p} \cdot \vec{q}} \varphi(\vec{p}) \quad (1.1)$$

where I used some notation from §0.3 and set $\hbar = 1$. The delta function is

$$\delta^{(2)}(\vec{q}) = \int \frac{d^2p}{(2\pi\hbar)^2} e^{i\vec{p} \cdot \vec{q}/\hbar}. \quad (1.2)$$

So the Schrödinger equation says

$$\left( -\frac{1}{2} \nabla^2 - E \right) \psi(q) = -V(q)\psi(q)$$

$$\int d^2p e^{i\vec{p} \cdot \vec{q}} \left( \frac{p^2}{2} - E \right) \varphi(p) = +g_0 \delta^{(2)}(q)\psi(0)$$

$$(1.2) \quad \Rightarrow \quad +g_0 \left( \int d^2p e^{i\vec{p} \cdot \vec{q}} \right) \psi(0) \quad (1.3)$$

where to get to the second line, we just plugged in (1.1). Integrating the both-hand side of (1.3) over $q$: $(\int d^2q e^{-i\vec{p} \cdot \vec{q}} ((1.3)) )$ says

$$\left( \frac{p^2}{2} - E \right) \varphi(\vec{p}) = +g_0 \int \frac{d^2p'}{(2\pi\hbar)^2} \varphi(\vec{p}')$$

$$= \psi(0)$$

There are two cases to consider:

- $\psi(\vec{q} = 0) = \int d^2p \varphi(\vec{p}) = 0$. Then this case is the same as a free theory, with the constraint that $\psi(0) = 0$,

$$\left( \frac{p^2}{2} - E \right) \varphi(\vec{p}) = 0$$

i.e. plane waves which vanish at the origin, e.g. $\psi \propto \sin \frac{p_x}{\hbar} e^{\pm ip_y y/\hbar}$. These scattering solutions don’t see the delta-function potential at all.
• $\psi(0) \equiv \alpha \neq 0$, some constant to be determined. This means $\vec{p}^2/2 - E \neq 0$, so we can divide by it:

$$\varphi(\vec{p}) = \frac{g_0}{E^2/2 - E} \left( \int d^2p' \varphi(\vec{p}') \right) = \frac{g_0}{E^2/2 - E} \alpha.$$ 

The integral of the RHS (for $\psi(0) = \alpha$) is a little problematic if $E > 0$, since then there is some value of $p$ where $p^2 = 2E$. Avoid this singularity by going to the boundstate region: consider $E = -\epsilon_B < 0$. So:

$$\varphi(\vec{p}) = \frac{g_0}{E^2/2 + \epsilon_B} \alpha.$$ 

What happens if we integrate this $\int d^2p$ to check self-consistency – the LHS should give $\alpha$ again:

$$0 \overset{!}{=} \int d^2p \varphi(\vec{p}) \left( 1 - \int d^2p \frac{g_0}{E^2/2 + \epsilon_B} \right)$$

$$\Rightarrow \quad \int d^2p \frac{g_0}{E^2/2 + \epsilon_B} = 1$$

is a condition on the energy $\epsilon_B$ of possible boundstates.

But there’s a problem: the integral on the LHS behaves at large $p$ like

$$\int \frac{d^2p}{p^2} = \infty.$$ 

At this point in an undergrad QM class, you would give up on this model. In QFT we don’t have that luxury, because this kind of thing happens all over the place. Here’s what we do instead.

We cut off the integral at some large $p = \Lambda$:

$$\int^\Lambda \frac{d^2p}{p^2} \sim \log \Lambda.$$ 

This our first example of the general principle that a classically scale invariant system will exhibit logarithmic divergences (rather: logarithmic dependence on the cutoff). It’s the only kind allowed by dimensional analysis.

The introduction of the cutoff can be thought of in many ways: we could say there are no momentum states with $|p| > \Lambda$, or maybe we could say that the potential is not really a delta function if we look more closely. The choice of narrative here shouldn’t affect our answers to physics questions at energies far below the cutoff.
More precisely:
\[ \int_{\frac{\Lambda}{2}}^{\Lambda} \frac{d^2p}{\sqrt{p^2 + \epsilon_B}} = 2\pi \int_{0}^{\Lambda} \frac{pdp}{\sqrt{p^2 + \epsilon_B}} = 2\pi \log \left( 1 + \frac{\Lambda^2}{2\epsilon_B} \right). \]

So in our cutoff theory, the boundstate condition is:
\[ 1 = g_0 \int_{\frac{\Lambda}{2}}^{\Lambda} \frac{d^2p}{\sqrt{p^2 + \epsilon_B}} = \frac{g_0}{2\pi \hbar^2} \log \left( 1 + \frac{\Lambda^2}{2\epsilon_B} \right). \]

A solution only exists for \( g_0 > 0 \). This makes sense since only then is the potential attractive (recall that \( V = -g_0 \delta \)).

Now here’s a trivial-seeming step that offers a dramatic new vista: solve for \( \epsilon_B \).

\[ \epsilon_B = \frac{\Lambda^2}{2} \frac{1}{e^{\frac{2\pi \hbar^2}{g_0}} - 1}. \]  

(1.4)

As we remove the cutoff (\( \Lambda \to \infty \)), we see that \( E = -\epsilon_B \to -\infty \), the boundstate becomes more and more bound – the potential is too attractive.

Suppose we insist that the boundstate energy \( \epsilon_B \) is a fixed thing – imagine we’ve measured it to be 200 MeV\(^3\). We should express everything in terms of the measured quantity. Then, given some cutoff \( \Lambda \), we should solve for \( g_0(\Lambda) \) to get the boundstate energy we have measured:

\[ g_0(\Lambda) = \frac{2\pi \hbar^2}{\log \left( 1 + \frac{\Lambda^2}{2\epsilon_B} \right)}. \]

This is the crucial step: this silly symbol \( g_0 \) which appeared in our action doesn’t mean anything to anyone (see Zee’s dialogue with the S.E. in section III). We are allowing \( g_0 \equiv \) the bare coupling to be cutoff-dependent.

Instead of a dimensionless coupling \( g_0 \), the useful theory contains an arbitrary dimensionful coupling constant (here \( \epsilon_B \)). This phenomenon is called dimensional transmutation (d.t.). The cutoff is supposed to go away in observables, which depend on \( \epsilon_B \) instead.

In QCD we expect that in an identical way, an arbitrary scale \( \Lambda_{QCD} \) will enter into physical quantities. (If QCD were the theory of the whole world, we would work in units where it was one.) This can be taken to be the rest mass of some mesons – boundstates of quarks. Unlike this example, in QCD there are many boundstates, but their energies are dimensionless multiplies of the one dimensionful scale, \( \Lambda_{QCD} \). Nature chooses \( \Lambda_{QCD} \simeq 200 \text{ MeV}. \)

\(^3\)Spoiler alert: I picked this value of energy to stress the analogy with QCD.
[This d.t. phenomenon was maybe first seen in a perturbative field theory in S. Coleman, E. Weinberg, *Phys Rev* D7 (1973) 1898. Maybe we’ll come back to their example.]

There are more lessons in this example. Go back to (1.4):

\[ \epsilon_B = \frac{\Lambda^2}{2} \frac{1}{e^{2\pi h^2/\epsilon_B} - 1} \approx e^{-2\pi h^2/\epsilon_B} \neq \sum_{n=0}^{\infty} g_0^n f_n(\Lambda) \]

it is *not* analytic (i.e. a power series) in \( g_0(\Lambda) \) near small \( g_0 \); rather, there is an essential singularity in \( g_0 \). (All derivatives of \( \epsilon_B \) with respect to \( g_0 \) vanish at \( g_0 = 0 \).) You can’t expand the dimensionful parameter in powers of the coupling. This means that you’ll never see it in perturbation theory in \( g_0 \). Dimensional transmutation is an inherently non-perturbative phenomenon.

Notice furthermore that even for moderately weak coupling, \( \epsilon_B \ll \Lambda^2 \). For example, when \( g_0 = .1, \epsilon_B/\Lambda^2 = 10^{-28}! \) Dimensional transmutation generates a hierarchy of scales. This phenomenon explains why the critical temperature below which metals go superconducting is much less than their intrinsic energy scale (the Fermi energy).

Look at how the bare coupling depends on the cutoff in this example:

\[ g_0(\Lambda) = \frac{2\pi h^2}{\log \left( 1 + \frac{\Lambda^2}{2\epsilon_B} \right)} \xrightarrow{\Lambda^2 \gg \epsilon_B} \frac{2\pi h^2}{\log \left( \frac{\Lambda^2}{2\epsilon_B} \right)} \xrightarrow{\epsilon_B \gg \Lambda^2} 0 \]

– the bare coupling vanishes in this limit, since we are insisting that the parameter \( \epsilon_B \) is fixed. This is called *asymptotic freedom* (AF): the bare coupling goes to zero (i.e. the theory becomes free) as the cutoff is removed. This also happens in QCD.

[End of Lecture 1]

**RG flow equations.** Define the *beta-function* as the logarithmic derivative of the bare coupling with respect to the cutoff:

\[ \text{Def:} \quad \beta(g_0) \equiv \frac{\Lambda}{\partial \Lambda} g_0(\Lambda) . \]

For this theory

\[ \beta(g_0) = \Lambda \frac{\partial}{\partial \Lambda} \left( \frac{2\pi h^2}{\log \left( 1 + \frac{\Lambda^2}{2\epsilon_B} \right)} \right) = \frac{g_0^2}{\pi h^2} \left( \frac{1}{\text{perturbative}} - \frac{e^{-2\pi h^2/g_0}}{\text{not perturbative}} \right) . \]

Notice that it’s a function only of \( g_0 \), and not explicitly of \( \Lambda \). Also, in this simple toy theory, the perturbation series for the beta function happens to stop at order \( g_0^2 \).
\( \beta \) measures the failure of the cutoff to disappear from our discussion – it signals a quantum mechanical violation of scale invariance. What’s \( \beta \) for? Flow equations:

\[
\dot{g}_0 = \beta(g_0).
\]

4 This is a tautology. The dot is

\[
\dot{A} = \partial_s A, \quad s \equiv \log \Lambda / \Lambda_0 \implies \partial_s = \Lambda \partial_\Lambda.
\]

(\( \Lambda_0 \) is some reference scale.) But forget for the moment that this is just a definition:

\[
\dot{g}_0 = -\frac{g_0^2}{\pi \hbar^2} \left(1 - e^{-2\pi \hbar^2/g_0}\right).
\]

This equation tells you how \( g_0 \) changes as you change the cutoff. Think of it as a nonlinear dynamical system (fixed points, limit cycles...)

**Def:** A fixed point \( g_0^* \) of a flow is a value of the coupling \( g_0 \) where the flow stops:

\[
0 = \dot{g}_0|_{g_0^*} = \beta(g_0^*)
\]

a zero of the beta function. (Note: if we have many couplings \( g_i \), then we have such an equation for each \( g_i \): \( \dot{g}_i = \beta_i(g) \). So \( \beta_i \) is (locally) a vector field on the space of couplings.)

Where are the fixed points in our example?

\[
\beta(g_0) = -\frac{g_0^2}{\pi \hbar^2} \left(1 - e^{-2\pi \hbar^2/g_0}\right).
\]

There’s only one: \( g_0^* = 0 \), near which \( \beta(g_0) \sim -\frac{g_0^2}{\pi \hbar^2} \), the non-perturbative terms are small. What does the flow look like near this point? For \( g_0 > 0, \dot{g}_0 = \beta(g_0) < 0 \). With this (high-energy) definition of the direction of flow, \( g_0 = 0 \) is an attractive fixed point:

*<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<-<
we can get good results near the fixed point from the perturbative part of $\beta$. That is: we can reliably compute the behavior of the flow of couplings near an AF fixed point perturbatively, and be sure that it is an AF fixed point. This is the situation in QCD.

On the other hand, the d.t. phenomenon that we’ve shown here is something that we can’t prove in QCD. However, the circumstantial evidence is very strong!

Another example where this happens is quantum mechanics in any number of variables with a central potential $V = -\frac{g^2}{r^2}$. It is also classically scale invariant:

$$[r] = -\frac{1}{2}, \quad \left[\frac{1}{r^2}\right] = +1 \quad \Rightarrow \quad [g_0] = 0.$$ 

This model was studied in K.M. Case, Phys Rev 80 (1950) 797 and you will study it on the first homework. The resulting boundstates and d.t. phenomenon are called Efimov states; this model preserves a discrete scale invariance.

Here’s a quote from Marty Halpern from his lecture on this subject:

*I want you to study this set of examples very carefully, because it’s the only time in your career when you will understand what is going on.*

In my experience it’s been basically true. For real QFTs, you get distracted by Feynman diagrams, gauge invariance, regularization and renormalization schemes, and the fact that you can only do perturbation theory.
1.2 Casimir effect: vacuum energy is real

[A. Zee, Quantum Field Theory in a Nutshell, §I.9]

Our success in the last subsection relied on our ability to completely solve the
theory, which we could do because there was just a single degree of freedom. Now we
will be brave and think about a system with extensive degrees of freedom.

This subsection has two purposes. The main purpose is to give an object lesson in
asking the right questions. In physics, the right question is often a question which can
be answered by an experiment, at least in principle. The answers to such questions are
less sensitive to our silly theoretical prejudices, e.g. about what happens to physics at
very short distances.

A second purpose is to show that the $\frac{1}{2}\hbar\omega$ energy of the vacuum of the quantum
harmonic oscillator is real. Sometimes we can get rid of it by choosing the zero of
energy (which doesn’t matter unless we are studying dynamical gravity). But it is
meaningful if we can vary $\omega$ (or the collection of $\omega$s if we have many oscillators as for
the radiation field) and compare the difference.

In the context of the bunch of oscillators making up the radiation field, we can
change the spectrum of frequencies of these oscillators $\{\omega_k\}$ by putting it in a box and
varying the size of the box. In particular, two parallel conducting plates separated by
some distance $d$ experience an attractive force from the change in the vacuum energy
of the EM field resulting from their presence. The plates put boundary conditions on
the field, and therefore on which normal modes are present.

To avoid some complications of E&M which are not essential for our point here,
we’re going to make two simplifications:

- we’re going to solve the problem in 1+1 dimensions
- and we’re going to solve it for a scalar field.

To avoid the problem of changing the boundary conditions outside the plates we
use the following device with three plates:

$$
| \leftarrow d \rightarrow | \leftarrow \quad L-d \quad \rightarrow |
$$

(We will consider $L \gg d$, so we don’t really care about the far right plate.) The
‘perfectly conducting’ plates impose the boundary condition that our scalar field $q(x)$
vanishes there. The normal modes of the scalar field $q(x)$ in the left cavity are then

$$
q_j = \sin \left( j\pi x / d \right), \quad j = 1, 2, \ldots
$$
with frequencies $\omega_j = \frac{\pi |j|}{d} c$. There is a similar expression for the modes in the right cavity which we won’t need. We’re going to add up all the $\frac{1}{2} \hbar \omega$s for all the modes in both cavities to get the vacuum energy $E_0(d)$; the force on the middle plate is then $-\partial_d E_0$.

The vacuum energy in the whole region of interest between the outer plates is the sum of the vacuum energies of the two cavities

$$E_0(d) = f(d) + f(L - d)$$

where

$$f(d) = \frac{1}{2} \hbar \sum_{j=1}^{\infty} \omega_j = \hbar c \frac{\pi}{2d} \sum_{j=1}^{\infty} j \equiv \infty.$$  

We have done something wrong. What?

Our crime is hubris: we assumed that we knew what the modes of arbitrarily large mode number $k$ (arbitrarily short wavelength, arbitrarily high frequency) are doing, and in particular we assumed that they cared about our silly plates. In fact, no metal in existence can put boundary conditions on the modes of large enough frequency – those modes don’t care about $d$. The reason a conductor puts boundary conditions on the EM field is that the electrons move around to compensate for an applied field, but there is a limit on how fast the electrons can move (e.g. the speed of light). The resulting cutoff frequency is called the plasma frequency but we don’t actually need to know about all these details. To parametrize our ignorance of what the high-frequency modes do, we must cut off (or regularize) the contribution of the high-frequency modes. Let’s call modes with $\omega_j \gg \pi / a$ high frequency, where $a$ is some short time\(^5\), $a \ll d$. Replace

$$f(d) \rightarrow f(a, d) = \hbar \frac{\pi}{2d} \sum_{j=1}^{\infty} e^{-\omega_j / \pi j}$$

$$= -\frac{\pi \hbar}{2} \partial_a \left( \sum_{j=1}^{\infty} e^{-aj/d} \right)_{1-e^{-a/d}}^{-1}$$

$$= +\frac{\pi \hbar}{2d} \frac{e^{a/d}}{(e^{a/d} - 1)^2}$$

$$= h \left( \frac{\pi d}{2a^2} - \frac{\pi}{24d} + \frac{\pi a^2}{480d^3} + \ldots \right) \quad (1.5)$$

\(^5\)You can think of $a$ as the time it takes the waves to move by one lattice spacing. If we work in units where the velocity is $c = 1$, this is just the lattice spacing. I will do so for the rest of this discussion.
Answers which don’t depend on $a$ have a chance of being meaningful. The thing we can measure is the force:

$$F = -\partial_d E_0 = -(f'(d) - f'(L - d))$$

$$= -\hbar \left( \left( \frac{\pi}{2a^2} + \frac{\pi}{24d^2} + O(a^2) \right) - \left( \frac{\pi}{2a^2} + \frac{\pi}{24(L - d)^2} + O(a^2) \right) \right)$$

$$\xrightarrow{a \to 0} -\frac{\hbar}{24} \left( \frac{1}{d^2} - \frac{1}{(L - d)^2} \right)$$

$$L \gg d = -\frac{\pi \hbar c}{24d^2} \left( 1 + O(d/L) \right). \quad (1.6)$$

This is an attractive force between the plates. (I put the $c$ back in the last line by dimensional analysis.)

The analogous force between real conducting plates, caused by the change of boundary conditions on the electromagnetic field, has been measured.

The string theorists will tell you that $\sum_{j=1}^{\infty} j = -\frac{1}{12}$, and our calculation above agrees with them in some sense. But what this foolishness means is that if we compute something which is not dependent on the cutoff we have to get the same answer no matter what cutoff we use. Notice that it is crucial to ask the right questions.

An important question is to what extent could we have picked a different cutoff function (instead of $e^{-\pi\omega/a}$) and gotten the same answer for the physics. This interesting question is answered affirmatively in Zee’s wonderful book, 2d edition, section I.9 Appendix (available electronically [here](#)). Go study this appendix now.

A comment about possible physical applications of the calculation we actually did: you could ask me whether there is such a thing as a Casimir force due to the vacuum fluctuations of phonons. Certainly it’s true that the boundary of a chunk of solid puts boundary conditions on the phonon modes, which change when we change the size of the solid. The problem with the idea that this might produce a measurable force (which would lead the solid to want to shrink) is that it is hard to distinguish the ‘phonon vacuum energy’ from the rest of the energy of formation of the solid, that is, the energy difference between the crystalline configuration of the atoms and the configuration when they are all infinitely separated. Certainly the latter is not well-described in the harmonic approximation.

Lest this seem too disconnected from the other ‘divergences’ we will encounter in QFT associated with loop amplitude, let me emphasize that the vacuum energy is a loop amplitude in this free field theory (the only one). Specifically

$$E_0 = \langle 0 | H_0 | 0 \rangle = \langle 0 | \int d^4x \, \phi(x) \left( -\partial_t^2 + \nabla^2 + m^2 \right) \phi(x) | 0 \rangle = \text{(graph)}.$$
A few comments about the 3+1 dimensional case of E&M. Assume the size of the plates is much larger than their separation $L$. Dimensional analysis shows that the force per unit area from vacuum fluctuations must be of the form

$$P = A \frac{\hbar c}{L^4}$$

where $A$ is a numerical number. $A$ is not zero!

Use periodic boundary conditions in the xy planes (along the plates). The allowed wave vectors are then

$$\vec{k} = \left( \frac{2\pi n_x}{L_x}, \frac{2\pi n_y}{L_y} \right)$$

with $n_x, n_y$ integers.

We have to do a bit of E&M here. Assume the plates are perfect conductors (this where the hubris about the high-frequency modes enters). This means that the transverse component of the electric field must vanish at the surface. Instead of plane waves in $z$, we get standing waves: $\phi(z) \propto \sin \left( \frac{n\pi z}{L} \right)$.

The frequencies of the associated standing waves are then

$$\omega_n(\vec{k}) = c \sqrt{\frac{\pi^2 n^2}{L^2} + \vec{k}^2}, n = 0, 1, 2$$

Also, there is only one polarization state for $n = 0$.

So the zero-point energy is

$$E_0(L) = \frac{\hbar}{2} \left( 2 \sum_{n, \vec{k}} \omega_n(\vec{k}) \right)$$

where it’s useful to define

$$\sum_{n, \vec{k}}' \equiv \frac{1}{2} \sum_{n=0, \vec{k}} + \sum_{n \geq 1, \vec{k}}$$

Now you can imagine introducing a regulator like the one we used above, and replacing

$$\sum_{n, \vec{k}}' \simto \sum_{n, \vec{k}} e^{-a\omega_n(\vec{k})/\pi},$$

and doing the sums and integrals and extracting the small-$a$ behavior.
1.3 A simple example of perturbative renormalization in QFT

[Zee §III.1, Schwartz §15.4] Now let’s consider an actual, interacting field theory but a simple one, namely the theory of a real scalar field in four dimensions, with

\[ \mathcal{L} = -\frac{1}{2} \phi \Box \phi - \frac{1}{2} m^2 \phi^2 - \frac{g}{4!} \phi^4. \]  

Demanding that the action is dimensionless means that \([\phi] = D - 2 \) so \([m] = 1\) and \([g] = \frac{4-D}{2}\), so \(g\) is dimensionless in \(D = 4\). As above, this will mean logarithms!

Let’s do \(2 \leftarrow 2\) scattering of \(\phi\) particles.

\[
i M_{2 \leftarrow 2} = \begin{pmatrix} \square \end{pmatrix} + \begin{pmatrix} \square \end{pmatrix} + \begin{pmatrix} \square \end{pmatrix} + \begin{pmatrix} \square \end{pmatrix} + \mathcal{O}(g^3)
= -ig + iM_s + iM_t + iM_u + \mathcal{O}(g^3)
\]

where, in terms of \(q_s \equiv k_1 + k_2\), the \(s\)-channel 1-loop amplitude is

\[
i M_s = \frac{1}{2}(-ig)^2 \int d^4k \frac{i}{k^2 - m^2 + i\epsilon} (q_s - k)^2 - m^2 + i\epsilon \sim \int \Lambda d^4k \frac{k^4}{k^4}.
\]

**Parametrizing ignorance.** What is a scalar field? One way to discover scalar field theory is to start with a chain of masses connected by springs, like a mattress, and look at the long-wavelength (small-wavenumber) modes. So the coherent excitations of such a field are sound waves and the quanta of the field are called phonons. In the sum, \(\int d^4k\), the region of integration that’s causing the trouble is not the part where the system looks most like a field theory. That is: if we look closely enough (small enough \(1/k\)), we will see that the mattress is made of springs. In terms of the microscopic description with springs, there is a smallest wavelength, of order the inverse lattice spacing: the sum over \(k\) stops.

Field theories arise from many such models, which may differ dramatically in their short-distance physics. We’d like to not worry too much about which one, but rather say things which do not depend on this choice. Recall the discussion of the Casimir force from §1.2: in that calculation, different choices of regulators for the mode sum corresponded (for example) to different material properties of the conducting plates. The Casimir force was independent of this choice; more generally, it is an important part of the physics problem to identify which quantities are UV sensitive and which are not.

If we had an actual lattice (like the chain of springs), we would replace the inverse propagator \(p^2 - m^2 = \omega^2 - k^2 - m^2\) with \(\omega^2 - \omega_p^2 - m^2\), where \(\omega_p\) is the dispersion...
relation \( e.g. \omega_p = 2t \sum_{i=1}^d (1 - \cos p_i a) \) for nearest-neighbor hopping on the cubic lattice, and \( p \) is restricted to the Brillouin zone \((-\pi/a \leq p_i < \pi/a \) for the cubic lattice). Instead, for simplicity, let’s keep just impose a hard cutoff on the euclidean momentum \( \sum_{i=0}^d p_i^2 \leq \Lambda^2 \).

Parametrizing ignorance is another way to say ‘doing science’. In the context of field theory, at least in the high-energy community, it is called ‘regularization’.

Now we need to talk about the integral a little more. The part which is causing the trouble is the bit with large \( k \), which might as well be \(|k| \approx \Lambda \gg m \), so let’s set \( m = 0 \) for simplicity.

We’ll spend lots of time learning to do integrals below. Here’s the answer:

\[
iM = -ig + iCg^2 \left( \log \frac{\Lambda^2}{s} + \log \frac{\Lambda^2}{t} + \log \frac{\Lambda^2}{u} \right) + \mathcal{O}(g^3)
\]

If you must know, \( C = \frac{1}{16\pi^2} \).

Observables can be predicted from other observables. Again, the boldface statement might sound like some content-free tweet from a boring philosophy-of-science twitter feed, but actually it’s a very important thing to remember here.

What is \( g \)? As Zee’s Smart Experimentalist says, it is just a letter in some theorist’s lagrangian, and it doesn’t help anyone to write physical quantities in terms of it. Much more useful would be to say what is the scattering amplitude in terms of things that can be measured. So, suppose someone scatters \( \phi \) particles at some given \((s, t, u) = (s_0, t_0, u_0)\), and finds for the amplitude \( iM(s_0, t_0, u_0) = -ig_P \) where \( P \) is for ‘physical’.

This we can relate to our theory letters:

\[
-i g_P = iM(s_0, t_0, u_0) = -ig + iCg^2L_0 + \mathcal{O}(g^3)
\] (1.8)

where \( L_0 \equiv \log \frac{\Lambda^2}{s_0} + \log \frac{\Lambda^2}{t_0} + \log \frac{\Lambda^2}{u_0} \). (Note that quantities like \( g_P \) are often called \( g_R \) where ‘R’ is for ‘renormalized,’ whatever that is.) I emphasize that this much we would have to do to make useful predictions, even if there were no specter of infinity or dependence on a fictitious cutoff.

---

\( ^6 \)You might hesitate here about my referring to the amplitude \( M \) as an ‘observable’. The difficult and interesting question of what can actually be measured in experiments can be decoupled a bit from this discussion. If you want to worry about this, see the beginning of Schwartz, chapter 18.
Renormalization. Now here comes the big gestalt shift: Solve this equation (1.8) for the stupid letter $g$

\[-ig = -ig_P - ig^2{L_0} + O(g^3)\]
\[= -ig_P - ig^2{L_0} + O(g^3).\]  

and eliminate $g$ from the discussion:

\[i{\mathcal{M}}(s, t, u) = -ig + ig^2{L} + O(g^3)\]
\[= -ig_P - ig^2{L_0} + ig^2{L} + O(g^3)\]
\[= -ig_P + ig^2{P} \left( \log \frac{s_0}{s} + \log \frac{t_0}{t} + \log \frac{u_0}{u} \right) + O(g^3).\]  

This expresses the amplitude at any momenta (within the range of validity of the theory!) in terms of measured quantities, $g_P, s_0, t_0, u_0$. The cutoff $\Lambda$ is gone! Just like in our parable in §1.1, it was eliminated by letting the coupling vary with it, $g = g(\Lambda)$, according to (1.9). We’ll say a lot more about how to think about that dependence.

Renormalized perturbation theory. To slick up this machinery, consider the following Lagrangian density (in fact the same as (1.7), with $m = 0$ for simplicity):

\[\mathcal{L} = -\frac{1}{2} \phi \Box \phi - \frac{g_P}{4!} \phi^4 - \frac{\delta g}{4!} \phi^4\]  

but written in terms of the measured coupling $g_P$, and some as-yet-undefined ‘counterterm’ $\delta g$. Then (with some foresight, we treat $\delta g \sim g_P^2$, since its job is to cancel a term of this order)

\[\mathcal{M}(s, t, u) = -g_P - \delta g - CG^2_P \left( \log \frac{s_0}{s} + \log \frac{t_0}{t} + \log \frac{u_0}{u} \right) + O(g^3_P).\]

If, in order to enforce the renormalization condition $\mathcal{M}(s_0, t_0, u_0) = -g_P$, we choose

\[\delta g = -g_P^2 C \left( \log \frac{s_0}{s} + \log \frac{t_0}{t} + \log \frac{u_0}{u} \right),\]

then we find

\[\mathcal{M}(s, t, u) = -g_P - CG^2_P \left( \log \frac{s_0}{s} + \log \frac{t_0}{t} + \log \frac{u_0}{u} \right) + O(g^3_P)\]

– all the dependence on the unknown cutoff is gone, we satisfy the observational demand $\mathcal{M}(s_0, t_0, u_0) = -g_P$, and we can predict the scattering amplitude (and others!) at any momenta.

The only price is that the ‘bare coupling’ $g$ depends on the cutoff, and becomes infinite if we pretend that there is no cutoff. Happily, we didn’t care about $g$ anyway. We can just let it go.
The step whereby we were able to absorb all the dependence on the cutoff into the bare coupling constant involved some apparent magic. It is not so clear that the same magic will happen if we study the next order $O(g^3)$ terms, or if we study other amplitudes. A QFT where all the cutoff dependence to all orders can be removed with a finite number of counterterms is called ‘renormalizable’. As we will see, such a field theory is less useful because it allows us to pretend that it is valid up to arbitrarily high energies. The alternative, where we must add more counterterms (such as something like $\frac{\Lambda^6}{g^6}$) at each order in perturbation theory, is called an effective field theory, which is a field theory that has the decency to predict its regime of validity.

1.4 Classical interlude: Mott formula

As a prelude to studying loops in QED, and to make clear what is at stake, let me fill in some of the details of the leading-order calculation. By studying scattering of an electron from a heavy charged fermion (a muon is convenient) we will reconstruct the cross section for scattering off a Coulomb potential (named after Mott). This will emphasize the fact that the tree-level process is classical. Then we’ll figure out how it is corrected by other QED processes.

**Crossing symmetry.** If you look at a Feynman diagram on its side (for example because someone else fails to use the convention that time goes to the left) it is still a valid amplitude for some process. Similarly, dragging particles between the initial and final state also produces a valid amplitude. Making this relation precise can save us some work. The precise relation for dragging an incoming particle into the final state, so that it is an outgoing antiparticle, is:

\[
iM_{f\leftarrow iA}(pf;pi,pA) = \sum_{r} \bar{u}^{\sigma}(p)\bar{v}^{\sigma}(p) = iM_{Af\leftarrow i}(pf,k = -pA;pi) = \sum_{r} \bar{u}^{\sigma}(k)\bar{v}^{\sigma}(k) = \bar{k} - m = -(\bar{p} + m).
\]

(If you must, note that this is another sense in which an antiparticle is a particle going backwards in time.) If $A$ is a spinor particle, the sum relations for particles and antiparticles are different:

\[
\sum_{r} u^{\sigma}(p)\bar{u}^{\sigma}(p) = \not{p} + m, \quad \sum_{r} v^{\sigma}(k)\bar{v}^{\sigma}(k) = \not{k} - m = -(\not{p} + m)
\]

— after accounting for $k = -pA$, they differ by an overall sign. Hence we must also append a fermion sign factor $(-1)^{\text{number of fermions shuffled between in and out}}$ in the unpolarized scattering probability. Here is an example.
For example, consider the process $\mu^+\mu^- \leftrightarrow e^+e^-$. To try to keep things straight, I’ll call the electron momenta $p, p'$ and the muon momenta $k, k'$, since that won’t change under crossing. The amplitude is

$$iM_{\mu^+\mu^- \leftrightarrow e^+e^-} = \left(-ie\bar{u}^s(k)\gamma^\mu v^s(p')\right)_{\text{muons}} \frac{-i(\eta_{\mu\nu} - \frac{(1-\xi)q_\mu q_\nu}{q^2})}{q^2} \left(-ie\bar{v}^{s'}(p')\gamma^\nu u^{s'}(p)\right)_{\text{electrons}}$$

(1.12)

(with $q \equiv p + p' = k + k'$). If we don’t keep track of the spins, then we must average over initial states and sum over final states, so the unpolarized scattering probability density is

$$\frac{1}{4} \sum_{\text{spins}} |M|^2 \text{spinor traces} = \frac{1}{4} \frac{e^4}{s^2} E^{\mu\nu} M_{\mu\nu},$$

where the tensor objects $E^{\mu\nu}, M^{\mu\nu}$ come respectively from the electron and muon lines,

$$\frac{1}{4} E^{\mu\nu} = p_\mu p_\nu + p'_\mu p'_\nu - \eta_{\mu\nu}(p \cdot p' + m_e^2)$$

$$\frac{1}{4} M_{\mu\nu} = k_\mu k_\nu + k'_\mu k'_\nu - \eta_{\mu\nu}(k \cdot k' + m_\mu^2),$$

and they are contracted by the photon line, with $s = q^2 = (p + p')^2$.

**Spinor trace ninjutsu.** In case you missed it, here is how to evaluate the spinor traces:

The trace is cyclic: $\text{tr} (AB \cdots C) = \text{tr} (CAB \cdots)$.  

$$\text{Our gamma matrices are } 4 \times 4, \text{ so } \text{tr} \mathbb{I} = 4.$$ 

$$\text{tr} \gamma^\mu = \text{tr} (\gamma^5)^2 \gamma^\mu \overset{(1.13)}{=} \text{tr} \gamma^5 \gamma^\mu \gamma^5 \overset{(\gamma^5 \gamma^\mu = 0)}{=} -\text{tr} \gamma^\mu = 0.$$  

(1.14)

The same trick shows that the trace of any odd number of gammas vanishes. The idea is that an odd number of gammas is a map between the $L$ and $R$ subspaces, so it has only off-diagonal terms in the Weyl basis.

$$\text{tr} \gamma^\mu \gamma^\nu \text{\textnormal{clifford}} = -\text{tr} \gamma^\nu \gamma^\mu + 2 \eta^{\mu\nu} \text{tr} \mathbb{I} \overset{(1.13)}{=} -\text{tr} \gamma^\mu \gamma^\nu + 8 \eta^{\mu\nu} \implies \text{tr} \gamma^\mu \gamma^\nu = 4 \eta^{\mu\nu}.$$  

(1.15)

$$\text{tr} \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma = 4 (\eta^{\mu\nu} \eta^{\rho\sigma} + \eta^{\sigma\mu} \eta^{\nu\rho} - \eta^{\mu\rho} \eta^{\nu\sigma}).$$  

(1.16)
Why is this? The completely antisymmetric bit vanishes because it is proportional to $\gamma^5$ which is traceless (by the same argument as (1.14)). If any pair of indices is the same then the other two must be too by (1.15). If adjacent pairs are the same they can just square to one and we get +1; if alternating pairs are the same (and different from each other) then we must move them through each other with the anticommutator. If they are all the same we get 4.

$$\text{tr} \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma^5 = -4i \epsilon^{\mu\nu\rho\sigma}.$$ 

To get from our previous work the amplitude (tree level, so far) for the process $e^-\mu^- \leftarrow e^-\mu^-$, we must move the incoming positron line to an outgoing electron line, and move the outgoing antimuon line to an incoming muon line (hence the sign in $\sigma$ will be $(-1)^{\text{number of fermions shuffled between in and out}} = (-1)^2 = 1$). Relative to the amplitude for $\mu^+\mu^- \leftarrow e^+e^-$ (1.12), we must replace the relevant $v$s with $u$s for the initial/final antiparticles that were moved into final/initial particles, and we must replace $p' \rightarrow -p', k' \rightarrow -k'$:

$$iM = (-ie\bar{u}(p')\gamma^\mu u(p))_{\text{electrons}} \frac{-i}{q_t^2} \frac{(1-\xi)q'_i q'_j}{q_t^2} (-ie\bar{u}(k)\gamma^\nu u(k'))_{\text{muons}} (1.17)$$

with $q_t \equiv p - p' = k - k'$. After the spin sum,

$$\frac{1}{4} \sum_{s,s',r,r'} |M|^2 = 4 \frac{e^4}{t^2} \left( -p^\mu p'^\nu - p'^\mu p^\nu - \eta^{\mu\nu}(-p \cdot p' + m_e^2) \right) \cdot \left( -k^\mu k'_\nu - k'_\mu k^\nu - \eta_{\mu\nu}(-k \cdot k' + m_\mu^2) \right) (1.18)$$

On the Mandelstam variables, this is just the permutation $(s, t, u) \rightarrow (t, u, s)$.

**Payoff: the Mott formula.** Recall other ways of figuring out the scattering cross section from a Coulomb potential from a point charge of charge $ze$.

We think about scattering from a fixed electrostatic potential $A_0 = \frac{ze}{r}$ and do classical mechanics. I can never remember how this goes. Instead, let’s just scatter an electron off a heavy charge, such as a muon. If the charge of the heavy object were $z$ times that of the electron, we would multiply the amplitude by $z$ and the cross section by $z^2$. 

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'Heavy' here means that we can approximate the CoM frame by its rest frame, and its initial and final energy as $k'_0 = m_\mu, k_0 = \sqrt{m_\mu^2 + \vec{k}'^2} = m_\mu + \frac{1}{2} \vec{k}'^2 / m_\mu + \cdots \simeq m_\mu$. Also, this means the collision is approximately elastic. In the diagram of the kinematics at right, $c \equiv \cos \theta, s \equiv \sin \theta$.

This means that the muon-line tensor factor $M_{\mu\nu}$ in (1.18) simplifies dramatically:

$$\frac{1}{4} M_{\mu\nu} \simeq k_\mu k'_\nu + k'_\mu k_\nu - \eta_{\mu\nu} \left( \frac{k \cdot k' - m_\mu^2}{m_\mu^2 - m_\mu^2 = 0} \right) \simeq \delta_{\mu0}\delta_{\nu0}2m_\mu^2.$$  

In the electron line, we get

$$-p \cdot p' + m_e^2 = -E^2 + \vec{p}^2 \cos \theta + m_e^2 = -\vec{p}^2(1 - \cos \theta). \quad (1.19)$$

So

$$E^{\mu\nu}M_{\mu\nu} = 32m_\mu^2 E^{00} = 32m_\mu^2(2E^2 + \eta^{00}(p \cdot p' - m_e^2)) \quad (1.19)$$

$$= 32m_\mu^2(2E^2 - \vec{p}^2(1 - \cos \theta)) \quad \text{trig} = 32m_\mu^2 2(E^2 - \vec{p}^2 \sin^2 \theta/2) \equiv \vec{p}^2/E^2 64m_\mu^2 E^2(1 - \beta^2 \sin^2 \theta/2).$$

Note that $t = (p - p')^2 = -2\vec{p}^2(1 - \cos \theta)$.

Now we can use the formula for the cross section (for the derivation, see these notes, §4.7):

$$d\sigma = \frac{1}{v_{\text{rel}}} \frac{1}{2E_A2E_B} \left( \frac{1}{4} \sum_{\text{spins}} |M|^2 \right) d\Pi_{LI}. \quad (1.21)$$

So the differential cross section is

$$d\sigma = \frac{1}{v_{\text{rel}}} \frac{1}{2E_A2m_\mu} \frac{1}{t^2} \frac{\alpha^2 e^4}{16\pi^2 E_{\text{total}}} \frac{\beta E^2(1 - \beta^2 \sin^2 \theta/2)}{16\pi^2 E_{\text{total}}} \frac{d\Omega}{E_{\text{total}}} \frac{p}{4\beta^2 \vec{p}^2 \sin^4 \theta/2}$$

from which we get

$$\frac{d\sigma}{d\Omega}_{\text{Mott}} = \frac{\alpha^2(1 - \beta^2 \sin^2 \theta/2)}{4\beta^2 \vec{p}^2 \sin^4 \theta/2}.$$
If we take $\beta \ll 1$ in this formula we get the Rutherford formula. Notice that it blows up at $\theta \to 0$. This is a symptom of the long-range nature of the Coulomb potential, i.e. the masslessness of the photon.

**Radiative corrections.** Now it’s time to think about perturbative corrections to this cross section. Given that the leading-order calculation reproduced the classical physics of the Coulomb potential, you can think of what we are doing as effectively discovering (high-energy or short-distance) quantum corrections to the Coulomb law. The diagrams we must include are these (I made the muon lines thicker and also red):

\[
iM_{e\mu-e\mu} = \begin{pmatrix}
\begin{pmatrix}
+ \end{pmatrix} + \begin{pmatrix}
+ \end{pmatrix} + O(e^6)
\end{pmatrix}
\end{pmatrix}
\]

- What do the one-loop diagrams in the second line have in common? They have an internal muon line. Why does this matter? When the energy going through the line is much smaller than the muon mass, then the propagator is $i \frac{k^2 - m_{\mu}^2}{k^2 + m_{\mu}^2} \sim \frac{1}{m_{\mu}}$ and its relative contribution is down by $k/m_{\mu} \ll 1$. So let’s neglect these for now.

- Why don’t we include diagrams like ? The LSZ formula tells us that their effects on the $S$-matrix are accounted for by the wavefunction renormalization factors $Z$

\[
S_{e\mu-e\mu} = \sqrt{Z_e} \sqrt{Z_{\mu}} \left( \begin{pmatrix}
\begin{pmatrix}
+ \end{pmatrix} + \begin{pmatrix}
+ \end{pmatrix} + \cdots
\end{pmatrix}
\end{pmatrix}
\]

and in determining the locations of the poles whose residues are the $S$-matrix elements. We’ll take care of these when we talk about the electron self-energy.

- Notice that the one-loop *amplitudes* are suppressed relative to the tree level amplitude by two factors of $e$, hence one factor of the fine structure constant $\alpha = \frac{e^2}{4\pi}$. Their leading effects on the cross section come from

\[
\sigma \sim \left| \begin{pmatrix}
\begin{pmatrix}
+ \end{pmatrix} + \begin{pmatrix}
+ \end{pmatrix} + \cdots
\end{pmatrix}
\end{pmatrix}^2 \sim \sigma_{\text{tree}} + O(\alpha^3)
\]
from the cross term between the tree and one-loop amplitudes.

In the above discussion, we encounter all three ‘primitive’ one-loop divergent amplitudes of QED, which we’ll study in turn:

- electron self-energy:

- vertex correction:

- vacuum polarization (photon self-energy):

1.5 Electron self-energy in QED

Let’s think about the electron two-point function in momentum space:

\[ \tilde{G}^{(2)}(p) = + + + + \ldots \]

We’ve grouped the diagrams according to their behavior when we divide input and output by cutting a single line. A diagram which cannot be divided by cutting a single line is called one-particle irreducible (1PI). The blue blob is defined to be the sum of all 1PI diagrams. We will denote the 1PI two-point function by

\[ -i\Sigma(p) \equiv 1PI \]
a blob with nubbins; for fermions with conserved particle number, the nubbins carry arrows indicating the particle number flow. Let me call the tree level propagator

\[ iS(p) \equiv \frac{i(p + m_0)}{p^2 - m_0^2 + i\epsilon} = \frac{i}{p - m_0} \]

– notice that I added a demeaning subscript to the notation for the mass appearing in the Lagrangian. Foreshadowing.

The full two point function is then:

\[ \tilde{G}^{(2)}(p) = iS + iS(-i\Sigma(p))iS + iS(-i\Sigma(p))iS(-i\Sigma(p))iS + \cdots \]
\[ = iS\left(1 + \Sigma S + \Sigma S\Sigma S + \cdots\right) = iS\frac{1}{1 - \Sigma S} \]
\[ = \frac{i}{p - m_0} \frac{1}{1 - \frac{1}{p - m_0}} = \frac{i}{p - m_0 - \Sigma(p)} \quad (1.23) \]

A comment about summing this infinite series:

\[ 1 + x + x^2 + \cdots = \frac{1}{1 - x} \quad (1.24) \]

You probably know that a geometric series has a radius of convergence of 1. This is because the function to which it sums has a pole at \( x = 1 \), and the radius of convergence is at most the distance to the nearest singularity.

On the other hand, there is a theorem of complex analysis that if two functions analytic in an open set \( D \) agree in \( D \) then they are the same. This is the basis for analytic continuation.

The LHS of (1.24) is not a priori defined when \( |x| > 1 \). The relation (1.24) therefore gives a useful meaning to it in this regime.

[End of Lecture 3]

Are you worried about these manipulations because \( \Sigma \) and \( S \) are matrices in the spinor indices? Don’t be: they are both made entirely from the matrix \( p \), and therefore they commute; we could do these manipulations in the eigenbasis of \( p \). This fully corrected propagator has a pole at

\[ p = m \equiv m_0 + \Sigma(m) \quad (1.25) \]

This means that the actual mass of the particle is this new quantity \( m \). But what is \( m \) (it is called the ‘renormalized mass’)? To figure it out, we need to know about \( \Sigma \).
In QED we must study $\Sigma$ in perturbation theory. As you can see from (1.22), the leading (one-loop) contribution is

$$-i\Sigma_2(p) = \frac{-i\epsilon}{k^2 - m_0^2 + i\epsilon} \int d^4k \gamma^\mu \frac{i(k + m_0)}{k^2 - m_0^2 + i\epsilon} \gamma^\nu \gamma^{\nu}(p - k)^2 - \mu^2 + i\epsilon .$$

Notice that I am relying on the Ward identity to enforce the fact that only the transverse bit of the photon propagator matters. Also, I added a mass $\mu$ for the photon as an IR regulator. We must keep the external momentum $p$ arbitrary, since we don’t even know where the mass-shell is!

Finally, I can’t put it off any longer: how are we going to do this loop-momentum integral?

Step 1: Feynman parameter trick. It is a good idea to consider the integral

$$\int_0^1 dx \frac{1}{(xA + (1-x)B)^2} = \int_0^1 dx \frac{1}{x(A - B) + B} = \frac{1}{A - B} \frac{1}{x(A - B) + B} \bigg|_{x=0}^{x=1}$$

This allows us to combine the denominators into one:

$$I = \frac{1}{k^2 - m_0^2 + i\epsilon} \left( (p - k)^2 - \mu^2 + i\epsilon \right) = \int_0^1 dx \frac{1}{x((p^2 - 2pk + k^2) - \mu^2 + i\epsilon) + (1-x)(k^2 - m_0^2 + i\epsilon))^2}$$

Step 2: Now we can complete the square

$$I = \int_0^1 dx \frac{1}{\left( (k - px)^2 - \Delta + i\epsilon \right)^2}$$

with

$$\ell^\mu \equiv k^\mu - p^\mu x, \quad \Delta \equiv +p^2 x^2 + x\mu^2 - xp^2 + (1-x)m_0^2 = x\mu^2 + (1-x)m_0^2 - x(1-x)p^2 .$$

Step 3: Wick rotate. Because of the $i\epsilon$ we’ve been dutifully carrying around, the poles of the $p^0$ integral don’t occur in the first and third octants of the complex $p^0$ plane. (And the integrand decays at large $|p^0|$. ) This means that we can rotate the contour to euclidean time for free: $\ell^0 \equiv i\ell^4$. Equivalently: the integral over the contour at right vanishes, so the real time contour gives the same answer as the (upward-directed) Euclidean contour. Notice that $\ell^2 = -\ell^2_E$. Altogether

$$-i\Sigma_2(p) = -e^2 \int d^4\ell \int_0^1 dx \frac{N}{(\ell^2 - \Delta + i\epsilon)^2} = -e^2 \int_0^1 dx i \int d^4\ell_E \frac{N}{(\ell^2_E + \Delta)^2}$$
where the numerator is

\[ N = \gamma^\mu \left( \ell + x\phi + m_0 \right) \gamma_\mu = -2 \left( \ell + x\phi \right) + 4m_0. \]

Here I used two Clifford algebra facts: \( \gamma^\mu \gamma_\mu = 4 \) and \( \gamma^\mu \phi \gamma_\mu = -2\phi \). Think about the contribution from the term with \( \ell \) in the numerator: everything else is invariant under rotations of \( \ell \)

\[ d^4\ell_E = \frac{1}{(2\pi)^4} d\Omega_3 \ell^3 d\ell = \frac{d\Omega_3}{(2\pi)^4} \ell^2 \frac{d\ell^2}{2}, \]

so this averages to zero. The rest is of the form (using \( \int_{S^3} d\Omega_3 = 2\pi^2 \))

\[ \Sigma_2(p) = e^2 \int_0^1 dx \int \frac{\ell^2 d\ell^2 (2\pi^2)}{2} \frac{2(2m_0 - x\phi)}{(\ell^2 + \Delta)^2} = \frac{e^2}{8\pi^2} \int_0^1 dx (2m_0 - x\phi) J \]

with

\[ J = \int_0^\infty d\ell^2 \frac{\ell^2}{(\ell^2 + \Delta)^2}. \]

In the large \( \ell \) part of the integrand this is

\[ \int_0^\Lambda \frac{d\ell^2}{\ell^2} \sim \log \Lambda. \]

You knew this UV divergence was coming. To be more precise, let’s add zero:

\[ J = \int d\ell^2 \left( \frac{\ell^2 + \Delta}{(\ell^2 + \Delta)^2} - \frac{\Delta}{(\ell^2 + \Delta)^2} \right) = \int_0^\infty d\ell^2 \left( \frac{1}{\ell^2 + \Delta} - \frac{\Delta}{(\ell^2 + \Delta)^2} \right) = \ln(\ell^2 + \Delta)\bigg|_{\ell^2=0}^\infty + \frac{\Delta}{\ell^2 + \Delta}\bigg|_{\ell^2=0}^\infty = \ln(\ell^2 + \Delta)\bigg|_{\ell^2=0}^\infty - 1. \]

Recall that

\[ \Delta = x\mu^2 + (1 - x)m_0^2 - x(1 - x)p^2 \equiv \Delta(\mu^2). \]

**Pauli-Villars regularization.** Here is a convenient fiction: when you exchange a photon, you also exchange a very heavy particle, with mass \( m^2 = \Lambda^2 \), with an extra \((-1)\) in its propagator. This means that (in this Pauli-Villars regulation scheme) the Feynman rule for the wiggly line is instead

\[
\begin{align*}
\begin{picture}(20,20)
\put(0,0){\line(1,0){20}}
\put(0,10){\line(1,0){20}}
\put(0,10){\line(0,-1){20}}
\end{picture}
\end{align*}
\sim -\eta_{\mu\nu} \left( \frac{1}{k^2 - 2\mu^2 + i\epsilon} - \frac{1}{k^2 - \Lambda^2 + i\epsilon} \right)
\end{align*}
\]

\[
= -\eta_{\mu\nu} \left( \frac{\mu^2 - \Lambda^2}{(k^2 - \mu^2 + i\epsilon)(k^2 - \Lambda^2 + i\epsilon)} \right)
\]

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This goes like $\frac{1}{k^4}$ at large $k$, so the integrals are more convergent. Yay.

Notice that the contribution from the Pauli-Villars photon to tree-level amplitudes goes like $|\frac{1}{k^2 - \Lambda^2}|^{\Lambda \gg k} \frac{1}{\Lambda^4}$ (where $k$ is the momentum going through the photon line, determined by the external momenta), which innocuously vanishes as $\Lambda \to \infty$.

Remembering that the residue of the pole in the propagator is the probability for the field operator to create a particle from the vacuum, you might worry that this is a negative probability, and unitarity isn’t manifest. This particle is a ghost. However, we will choose $\Lambda$ so large that the pole in the propagator at $k^2 = \Lambda^2$ will never be accessed and we’ll never have external Pauli-Villars particles. We are using this as a device to define the theory in a regime of energies much less than $\Lambda$. You shouldn’t take the regulated theory too seriously: for example, the wrong-sign propagator means wrong-sign kinetic terms for the PV fields. This means that very wiggly configurations will be energetically favored rather than suppressed by the Hamiltonian. It will not make much sense non-perturbatively.

I emphasize that this regulator is one possibility of many. They each have their drawbacks. They all break scale invariance. Nice things about PV are that it is Lorentz invariant and gauge invariant; the bad thing is it’s not unitary. A class of regulators which make perfect sense non-perturbatively is the lattice (as in the model with masses on springs). The price is that it really messes up the spacetime symmetries.

Applying this to the self-energy integral amounts to the replacement

$$J \sim J_{\Delta(\mu^2)} - J_{\Delta(\Lambda^2)} = \left[ (\ln (\ell^2 + \Delta(\mu^2)) - 1) - (\ln (\ell^2 + \Delta(\Lambda^2)) - 1) \right]_0^\infty$$

$$= \ln \left( \frac{\ell^2 + \Delta(\mu^2)}{\ell^2 + \Delta(\Lambda^2)} \right)_0^\infty$$

$$= \ln 1/1 - \ln \frac{\Delta(\mu^2)}{\Delta(\Lambda^2)} = \ln \frac{\Delta(\Lambda^2)}{\Delta(\mu^2)}.$$

Notice that we can take advantage of our ignorance of the microphysics to make the cutoff (the PV scale $\Lambda$) as big as we like and thereby simplify our lives:

$$\Delta(\Lambda^2) = x\Lambda^2 + (1 - x)m_0^2 - x(1 - x)p^2 \gg everyone \approx x\Lambda^2.$$  

Finally then

$$\Sigma_2(p)_{PV} = \frac{\alpha}{2\pi} \int_0^1 dx (2m_0 - xp) \ln \frac{x\Lambda^2}{x\mu^2 + (1 - x)m_0^2 - x(1 - x)p^2}.$$  

Having arrived at this regulated expression for the self-energy we need to “impose a renormalization condition,” i.e. introduce some observable physics in terms of which
to parametrize our answers. We return to (1.25): the shift in the mass as a result of
this one-loop self-energy is

$$\delta m \equiv m - m_0 = \Sigma_2(\phi = m) + O(e^4) = \Sigma_2(\phi = m_0) + O(e^4)$$

$$= \frac{\alpha}{2\pi} \int_0^1 dx (2-x)m_0 \ln \frac{x\Lambda^2}{x\mu^2 + (1-x)m_0^2 + x(1-x)m_0^2}$$

$$= \frac{\alpha}{2\pi} \int_0^1 dx (2-x)m_0 \left( \ln \frac{\Lambda^2}{m_0^2} + \ln \frac{xm_0^2}{f(x, m_0, \mu)} \right)$$

$$\approx \frac{\alpha}{2\pi} \left( 2 - \frac{1}{2} \right) m_0 \ln \frac{\Lambda^2}{m_0^2} = \frac{3\alpha}{4\pi} m_0 \ln \frac{\Lambda^2}{m_0^2}. \quad (1.28)$$

In the penultimate step (with the $\approx$), we’ve neglected the finite bit (labelled ‘relatively
small’) compared to the logarithmically divergent bit: we’ve already assumed $\Lambda \gg$ all
other scales in the problem.

**Mass renormalization.** Now the physics input: The mass of the electron is 511
keV (you can ask how we measure it and whether the answer we get depends on the
resolution of the measurement, and indeed there is more to this story; this is a low-
energy answer, for example we could make the electron go in a magnetic field and
measure the radius of curvature of its orbit and set $m_e v^2/r = eBv/c$), so

$$511 \text{ keV} \approx m_e = m_0 \left( 1 + \frac{3\alpha}{4\pi} m_0 \ln \frac{\Lambda^2}{m_0^2} \right) + O(\alpha^2).$$

In this equation, the LHS is a measured quantity. In the correction on the RHS
$\alpha \approx \frac{1}{137}$ is small, but it is multiplied by $\ln \frac{\Lambda^2}{m_0^2}$ which is arbitrarily large. This means that the
bare mass $m_0$, which is going to absorb the cutoff dependence here, must actually be
really small. (Notice that actually I’ve lied a little here: the $\alpha$ we’ve been using is
still the bare charge; we will need to renormalize that one, too, before we are done.) I
emphasize: $m_0$ and the other fake, bare parameters in $\mathcal{L}$ depend on $\Lambda$ and the order of
perturbation theory to which we are working and other theorist bookkeeping garbage;
$m_e$ does not. At each order in perturbation theory, we eliminate $m_0$ and write our
predictions in terms of $m_e$. It is not too surprising that the mass of the electron
includes such contributions: it must be difficult to travel through space if you are
constantly emitting and re-absorbing photons.

**Wavefunction renormalization.** The actual propagator for the electron, near
the electron pole is

$$\tilde{G}^{(2)}(p) = \frac{i}{\not{p} - m_0 - \Sigma(p)} \stackrel{p \to m}{\approx} \frac{iZ}{\not{p} - m} + \text{regular terms}. \quad (1.29)$$
The residue of the pole at the electron mass is no longer equal to one, but rather $Z$. To see what $Z$ actually is at this order in $e^2$, Taylor expand near the pole

$$\Sigma(p) \overset{\text{Taylor}}{=} \Sigma(p = m) + \frac{\partial \Sigma}{\partial p}\big|_{p=m}(p - m) + \cdots$$

$$= \Sigma(p = m_0) + \frac{\partial \Sigma}{\partial p}\big|_{p=m_0}(p - m_0) + \cdots + \mathcal{O}(e^4)$$

So then (1.29) becomes

$$\tilde{G}^{(2)}(p) \overset{p \sim m}{=} \frac{i}{p - m - \frac{\partial \Sigma}{\partial p}\big|_{m_0}(p - m) = \frac{i}{(p - m)\left(1 - \frac{\partial \Sigma}{\partial p}\big|_{m_0}\right)}}$$

So that

$$Z = \frac{1}{1 - \frac{\partial \Sigma}{\partial p}\big|_{m_0}} \simeq 1 + \frac{\partial \Sigma}{\partial p}\big|_{m_0} \equiv 1 + \delta Z$$

and at leading nontrivial order

$$\delta Z = \frac{\partial \Sigma}{\partial p}\big|_{m_0} \overset{(1.27)}{=} \frac{\alpha}{2\pi} \int_0^1 dx \left( -x \ln \frac{x\Lambda^2}{f(x, m_0, \mu)} + (2m_0 - x_0)\frac{-2x(1 - x)}{f(x, m_0, \mu)} \right)$$

$$= -\frac{\alpha}{4\pi} \left( \ln \frac{\Lambda^2}{m_0^2} + \text{finite} \right).$$

Here $f = f(x, m_0, \mu)$ is the same quantity defined in the second line of (1.28). We’ll see below that the cutoff-dependence in $\delta Z$ plays a crucial role in making the $S$ matrix (for example for the $e\mu \rightarrow e\mu$ process we’ve been discussing) cutoff-independent and finite, when written in terms of physical variables.

### 1.6 Big picture interlude

OK, I am having a hard time just pounding away at one-loop QED. Let’s take a break and think about the self-energy corrections in scalar field theory. Then we will step back and think about the general structure of short-distance sensitivity in (relativistic) QFT, before returning to the QED vertex correction and vacuum polarization.

#### 1.6.1 Self-energy in $\phi^4$ theory

[Zee §III.3] Let’s return to the $\phi^4$ theory in $D = 3 + 1$ for a moment. The $\mathcal{M}_{\phi\phi\rightarrow\phi\phi}$ amplitude is not the only place where the cutoff appears.

Above we added a counterterm of the same form as the $\phi^4$ term in the Lagrangian. Now we will see that we need counterterms for everybody:

$$\mathcal{L} = -\frac{1}{2} \left( \phi \Box \phi + m^2 \phi^2 \right) - \frac{g_p}{4!} \phi^4 - \frac{\delta_Z}{4!} \phi^4 - \frac{1}{2} \delta_Z \phi \Box \phi - \frac{1}{2} \delta_{m^2} \phi^2.$$
Here is a way in which \( \phi^4 \) theory is weird: At one loop there is no wavefunction renormalization. That is,

\[
\delta \Sigma_1(k) = -ig \int \frac{d^4 q}{q^2 - m^2 + i\epsilon} = \delta \Sigma_1(k = 0) \sim g \Lambda^2
\]

which is certainly quadratically divergent, but totally independent of the external momentum. This means that when we Taylor expand in \( k \) (as we just did in (1.30)), this diagram only contributes to the mass renormalization. Demanding that the pole in the propagator occurs at \( p^2 = m^2 \), we must set \( \delta m^2 = -\delta \Sigma_1 \).

So let’s see what happens if we keep going:

\[
\delta \Sigma_2(k) = \frac{(-ig)^2}{3!} \int \frac{d^4 p}{p^2 - m^2 + i\epsilon} \int \frac{d^4 q}{q^2 - m^2 + i\epsilon} = I(k^2, m, \Lambda).
\]

Here \( iD_0(p) \equiv \frac{i}{p^2 - m^2 + i\epsilon} \) is the free propagator (the factor of \( i \) is for later convenience), and we’ve defined \( I \) by this expression. The fact that \( I \) depends only on \( k^2 \) is a consequence of Lorentz invariance. Counting powers of the loop momenta, the short-distance bit of this integral is of the schematic form

\[
\int \Lambda d^8 P \, P^6 \sim \Lambda^2,
\]

also quadratically divergent, but this time \( k^2 \)-dependent, so there will be a nonzero \( \delta Z \propto g^2 \). As we just did for the electron self-energy, we should Taylor expand in \( k \). (We’ll learn more about why and when the answer is analytic in \( k^2 \) at \( k = 0 \) later.) The series expansion in \( k^2 \) (let’s do it about \( k^2 = 0 \sim m^2 \) to look at the UV behavior) is

\[
\delta \Sigma_2(k^2) = A_0 + k^2 A_1 + k^4 A_2 + \cdots
\]

where \( A_0 = I(k^2 = 0) \sim \Lambda^2 \). In contrast, dimensional analysis says \( A_1 = \frac{\partial}{\partial k^2} I|_{k^2=0} \sim \int \frac{d^8 P}{p^2} \sim \Lambda^{0^+} \sim \ln \Lambda \) has two fewer powers of the cutoff. After that it’s clear sailing:

\[
A_2 = \left( \frac{\partial}{\partial k^2} \right)^2 I|_{k^2=0} \sim \int \frac{d^8 P}{p^2} \sim \Lambda^{-2} \text{ is finite as we remove the cutoff, and so are all the later coefficients.}
\]

If instead the physical pole were at a nonzero value of the mass, we should Taylor expand about \( k^2 = m_p^2 \) instead:

\[
D^{-1}(k) = D_0^{-1}(k) - \Sigma(k) = k^2 - m_0^2 - (\delta \Sigma_1(m_p^2) + A_0) - (k^2 - m_p^2) A_1 - (k^2 - m_p^2)^2 A_2 + \cdots \equiv a \sim \Lambda^2
\]

where now \( A_n \equiv \frac{1}{n!} \left( \frac{\partial}{\partial k^2} \right)^n \Sigma_2(k^2)|_{k^2=m_p^2} \). The \( \cdots \) here includes both higher orders in \( g \) (\( O(g^3) \)) and higher powers of \( k^2 \), \textit{i.e.} higher derivative terms.
Therefore, the propagator is
\[ D(k) = \frac{1}{(1 - A_1)(k^2 - m_P^2)} + \cdots = \frac{Z}{k^2 - m_P^2} + \cdots \]
with
\[ Z = \frac{1}{1 - A_1}, \quad m_P^2 = m^2 + a \]
where \( a \) was defined in (1.32).

Some points to notice:

• \( \delta Z = A_1 \).

• The contributions \( A_{n \geq 2}(k^2)^n \) can be reproduced by counterterms of the form \( A_n \phi \Box^n \phi \). Had they been cutoff dependent we would have needed to add such (cutoff-dependent) counterterms.

• The mass-squared of the scalar field in \( D = 3 + 1 \) is quadratically divergent, while the mass of the spinor was only log divergent. This UV sensitivity of scalar fields is ubiquitous (see the homework) and is the source of many headaches.

• On the term ‘wavefunction renormalization’: who is \( \phi \)? Also just a theorist’s letter. Sometimes (in condensed matter) it is defined by some relation to observation (like the height of a wave in a mattress), in high energy theory not so much. Classically, we fixed its (multiplicative) normalization by setting the coefficient of \( \phi \Box \phi \) to one. If we want to restore that convention after renormalization, we can make a redefinition of the field \( \phi_R \equiv Z^{-1/2} \phi \). This is the origin of the term ‘wavefunction renormalization’. A slightly better name would be ‘field renormalization’, but even better would be just ‘kinetic term renormalization’.

**Renormalized perturbation theory revisited.** The full story for the renormalized perturbation expansion in \( \phi^4 \) theory is then
\[ \mathcal{L} = \frac{1}{2} (\partial \phi)^2 - \frac{1}{2} m_P^2 \phi^2 - \frac{g_P}{4!} \phi^4 + \mathcal{L}_{ct} \]
with
\[ \mathcal{L}_{ct} = \frac{1}{2} \delta Z (\partial \phi)^2 - \frac{1}{2} \delta m^2 \phi^2 - \frac{\delta g}{4!} \phi^4. \]

Here are the instructions for using it: The Feynman rules are as before: the coupling and propagator are
\[ \begin{align*}
\begin{array}{c}
\begin{array}{c}
\phi
\end{array}
\end{array}
\end{align*} = -ig_P, \quad \begin{array}{c}
\begin{array}{c}
\phi
\end{array}
\end{array} = \frac{i}{k^2 - m_P^2 + i\epsilon} \quad (1.33)
\end{align*} \]

\(^7\text{At least for most regulators. We’ll see that dim reg is special.}\)
but the terms in $L_{ct}$ (the counterterms) are treated as new vertices, and treated perturbatively:

$$\begin{align*}
-\delta g & = -i\delta g, \\
-\delta Z & = -i(\delta Zk^2 + \delta m^2).
\end{align*}$$

All integrals are regulated, in the same way (whatever it is). The counterterm couplings $\delta g, \delta Z, \delta m^2$ are determined iteratively, as follows: given the $\delta_{N-1}$s up to $O(g^N_P)$, we fix each one $\delta = \delta_{N-1} + g^N_P \Delta \delta_N + O(g^{N+1}_P)$ by demanding that (1.33) are actually true up to $O(g^{N+1}_P)$. This pushes the cutoff dependence back into the muck a bit further.

I say this is the full story, but wait: we didn’t try to compute amplitudes with more than four $\phi$s (such as $3 \leftarrow 3$ scattering of $\phi$ quanta). How do we know those don’t require new counterterms (like a $\phi^6$ term, for example)?

### 1.6.2 Where is the UV sensitivity?

[still Zee §III.3, Peskin ch. 10. We’ll follow Zee’s discussion pretty closely for a bit.] Given some process in a relativistic, perturbative QFT, how do we know if it will depend on the cutoff? We’d like to be able answer this question for a theory with scalars, spinors, vectors. Here’s how: First, look at each diagram $A$ (order by order in the loop expansion). Define the ‘superficial’ degree of divergence of $A$ to be $D_A \equiv \langle A \rangle$, just its engineering dimension. In the limit that $\Lambda \gg$ all other scales, we must then have $A \sim \Lambda^{D_A}$ (in the absence of cancellations). A log divergent amplitude has $D_A = 0$ (sometimes it’s called $D_A = 0^+$).

Let’s start simple, and study the $\phi^4$ theory in $D = 4$. Consider a connected diagram $A$ with $B_E$ external scalar lines. I claim that $D_A = 4 - B_E$.

Why doesn’t it (explicitly) depend on any other data of the diagram, such as

- $B_I \equiv \#$ of internal scalar lines (i.e., propagators)
- $V \equiv \#$ of $\phi^4$ vertices
- $L \equiv \#$ of loops

We can understand this better using two facts of graph theory and some power counting. I recommend checking my claims below with an example, such as the one at right.

**Graph theory fact #1:** These quantities are not all independent. For a connected
Math proof\textsuperscript{8}: Imagine placing the vertices on the page and adding the propagators one at a time. You need $V - 1$ internal lines just to connect up all $V$ vertices. After that, each \textit{internal} line you add necessarily adds one more loop.

Another way to think about this fact makes clear that $L = \#$ of loops = \# of momentum integrals. Before imposing momentum conservation at the vertices, each internal line has a momentum which we must integrate: $\prod_{\alpha=1}^{B_I} \int d^D q_\alpha$. We then stick a $\delta^{(D)}(\sum q)$ for each vertex, but one of these gives the overall momentum conservation $\delta^{(D)}(k_T)$, so we have $V - 1$ fewer momentum integrals. For the example above, (1.34) says $4 = 8 - (5 - 1)$.

\textbf{Graph theory fact \#2:} Each external line comes out of one vertex. Each internal line connects two vertices. Altogether, the number of ends of lines sticking out of vertices is

$$B_E + 2B_I = 4V$$

where the RHS comes from noting that each vertex has four lines coming out of it (in $\phi^4$ theory). In the example, this is $4 + 2 \cdot 8 = 4 \cdot 5$. So we can eliminate

$$B_I = 2V - B_E/2.$$  \hfill (1.35)

Now we count powers of momenta:

$$\mathcal{A} \sim \prod_{a=1}^{L} \int^{A} d^D k_a \prod_{\alpha=1}^{B_I} \frac{1}{k_a^2}.$$  

Since we are interested in the UV structure, I’ve set the mass to zero, as well as all the external momenta. The only scale left in the problem is the cutoff, so the dimensions of $\mathcal{A}$ must be made up by the cutoff:

$$D_A = [\mathcal{A}] = DL - 2B_I \stackrel{(1.34)}{=} B_I(D - 2) - D(V - 1) \stackrel{(1.35)}{=} D + \frac{2 - D}{2}B_E + V(D - 4).$$

If we set $D = 3 + 1 = 4$, we get $D_A = 4 - B_E$, as claimed. Notice that with $B_E = 2$ we indeed reproduce $D_A = 2$, the quadratic divergence in the mass renormalization, and with $B_E = 4$ we get $D_A = 0$, the log divergence in the $2 \leftrightarrow 2$ scattering. This pattern continues: with more than four external legs, $D_A = 4 - B_E < 0$, which means

\textsuperscript{8}I learned this one from my class-mate M.B. Schulz.
the cutoff dependence must go away when $\Lambda \to 0$. This is illustrated by the following diagram with $B_E = 6$:

$$\sim \int_{\Lambda}^\infty \frac{d^4p}{p^6} \sim \Lambda^{-2}.$$ 

So indeed we don’t need more counterterms for higher-point interactions in this theory.

Why is the answer independent of $V$ in $D = 4$? This has the dramatic consequence that once we fix up the cutoff dependence in the one-loop diagrams, the higher orders have to work out, i.e. it strongly suggests that the theory is renormalizable.

Before we answer this, let’s explore the pattern a bit more. Suppose we include also a fermion field $\psi$ in our field theory, and suppose we couple it to our scalar by a Yukawa interaction:

$$S_{\text{bare}}[\phi, \psi] = -\int d^Dx \left( \frac{1}{2} \phi (\Box + m_\phi^2) \phi + \bar{\psi} (-\partial + m_\psi) \psi + y\phi \bar{\psi} \psi \right) + \frac{g}{4!} \phi^4.$$ 

To find the degree of divergence in an amplitude in this model, we have to independently keep track of the number fermion lines $F_E, F_I$, since a fermion propagator has dimension $\frac{1}{p} = -1$, so that $D_A = [\mathcal{A}] = DL - 2B_I - F_I$. The number of ends-of-fermion-lines is $2V_y = 2F_E + F_I$ and the number of ends-of-boson-lines is $V_y + 4V_g = B_E + 2B_I$. The number of loops is $L = B_I + F_I - (V_y + V_g - 1)$. Putting these together (I used Mathematica) we get

$$D_A = D + (D - 4) \left( V_g + \frac{1}{2} V_y \right) + B_E \left( \frac{2 - D}{2} \right) + F_E \left( \frac{1 - D}{2} \right).$$ 

Again in $D = 4$ the answer is independent of the number of vertices! Is there something special about four spacetime dimensions?

To temper your enthusiasm, consider adding a four-fermion interaction: $G(\bar{\psi} \gamma^\mu \psi)(\bar{\psi} \gamma^\mu \psi)$ (or maybe $G_V(\bar{\psi} \gamma^\mu \gamma^5 \psi)(\bar{\psi} \gamma^\mu \gamma^5 \psi)$ or $G_A(\bar{\psi} \gamma^\mu \gamma^5 \psi)(\bar{\psi} \gamma^\mu \gamma^5 \psi)$ or any other pile of gamma matrices in between, with the indices contracted). When you redo this calculation on

$$\mathcal{I} = \int_{\Lambda}^\infty \frac{d^4p}{(p^2 + m^2)^5} \int_{\Lambda}^\infty d^4k.$$ 

According to our method of counting, we would say $D_\mathcal{I} = 4 + 4 - 10 = -2$ and declare this finite and cutoff-independent. On the other hand, it certainly does depend on the physics at the cutoff. (I bet it is possible to come up with more pathological examples.) The rest of the work involving ‘nested divergences’ and forests is in showing that the extra structure in the problem prevents things like $\mathcal{I}$ from being Feynman amplitudes.
the homework, you’ll find that in $D = 4$ a diagram (for simplicity, one with no $\phi^4$ or Yukawa interactions) has

$$D_A = 4 - (1)B_E - \left(\frac{3}{2}\right)F_E + 2V_G,$$

where $V_G$ is the number of insertions of the 4-fermion term. This dependence on the number of four-fermi vertices means that there are worse and worse divergences as we look at higher-order corrections to a given process. Even worse, it means that for any number of external lines $F_E$ no matter how big, there is a large enough order in perturbation theory in $G$ where the cutoff will appear! This means we need $\delta_n(\bar{\psi}\psi)^n$ counterterms for every $n$, which we’ll need to fix with physical input. This is a bit unappetizing, and such an interaction is called “non-renormalizable”. However, when we remember that we only need to make predictions to a given precision (so that we only need to go to a finite order in this process) we will see that such theories are nevertheless quite useful.

So why were those other examples independent of $V$? It’s because the couplings were dimensionless. Those theories were classically scale invariant (except for the mass terms).

1.6.3 Naive scale invariance in field theory

[Halpern] Consider a field theory of a scalar field $\phi$ in $D$ spacetime dimensions, with an action of the form

$$S[\phi] = \int d^Dx \left(\frac{1}{2}\partial_{\mu}\phi\partial^{\mu}\phi - g\phi^p\right)$$

for some constants $p,g$. Which value of $p$ makes this scale invariant? (That is: when is $g$ dimensionless, and hence possibly the coupling for a renormalizable interaction.)

Naive dimensions:

$$[S] = [\hbar] = 0, \quad [x] \equiv -1, \quad [d^Dx] = -D, \quad [\partial] = 1$$

The kinetic term tells us the engineering dimensions of $\phi$:

$$0 = [S_{\text{kinetic}}] = -D + 2 + 2[\phi] \implies [\phi] = \frac{D - 2}{2}.$$

Notice that the $D = 1$ case agrees with our quantum mechanics counting from §1.1. Quantum field theory in $D = 1$ spacetime dimensions is quantum mechanics.

Then the self-interaction term has dimensions

$$0 = [S_{\text{interaction}}] = -D + [g] + p[\phi] \implies [g] = D - p[\phi] = D + p\frac{2 - D}{2}.$$
We expect scale invariance when \([g] = 0\) which happens when 

\[
p = p_D \equiv \frac{2D}{D-2},
\]

i.e. the scale invariant scalar-field self-interaction in \(D\) spacetime dimensions is \(\phi^{\frac{2D}{D-2}}\).

<table>
<thead>
<tr>
<th>(D)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>(D)</th>
<th>(\infty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>([\phi])</td>
<td>(-\frac{1}{2})</td>
<td>0</td>
<td>(\frac{1}{2})</td>
<td>1</td>
<td>3/2</td>
<td>2</td>
<td>(\frac{D-2}{2})</td>
<td>(\infty)</td>
</tr>
<tr>
<td>scale-inv’t (p \equiv p_D)</td>
<td>(-2)</td>
<td>(\infty)</td>
<td>6</td>
<td>4</td>
<td>10/3</td>
<td>3</td>
<td>(\frac{2D}{D-2})</td>
<td>2</td>
</tr>
</tbody>
</table>

\* What is happening in \(D = 2\)? The field is dimensionless, and so any power of \(\phi\) is naively scale invariant, as are more complicated interactions like \(g_{ij}(\phi)\partial_\mu \phi^i \partial^\mu \phi^j\), where the coupling \(g(\phi)\) is a function of \(\phi\). This allows for scale-invariant non-linear sigma models, where the fields are coordinates on a curved manifold with metric \(ds^2 = g_{ij}d\phi^id\phi^j\).

In dimensions where we get fractional powers, this isn’t so nice.

Notice that the mass term \(\Delta S = \int d^Dx \frac{m^2}{2} \phi^2\) gives

\[
0 = -D + 2[m] + 2[\phi] \implies [m] = 1 \quad \forall D < \infty
\]

– it’s a mass, yay.

What are the consequences of this engineering dimensions calculation in QFT? For \(D > 2\), an interaction of the form \(g\phi^p\) has

\[
[g] = D \cdot \frac{pD - p}{p_D} \begin{cases}
< 0 \text{ when } p > p_D, & \text{non-renormalizable or irrelevant} \\
= 0 \text{ when } p = p_D, & \text{renormalizable or marginal} \\
> 0 \text{ when } p < p_D, & \text{super-renormalizable or relevant}.
\end{cases}
\]

Consider the ‘non-renormalizable’ case. Suppose we calculate in QFT some quantity \(f\) with \([f]\) as its naive dimension, in perturbation theory in \(g\), e.g. by Feynman diagrams. We’ll get:

\[
f = \sum_{n=0}^{\infty} g^n c_n
\]

with \(c_n\) independent of \(g\). So

\[
[f] = n[g] + [c_n] \implies [c_n] = [f] - n[g]
\]

So if \([g] < 0\), \(c_n\) must have more and more powers of some mass (inverse length) as \(n\) increases. What dimensionful quantity makes up the difference? Sometimes it is
masses or external momenta. But generically, it gets made up by UV divergences (if everything is infinite, dimensional analysis can fail, nothing is real, I am the walrus). More usefully, in a meaningful theory with a UV cutoff, \( \Lambda_{UV} \), the dimensions get made up by the UV cutoff, which has \([\Lambda_{UV}] = 1\). Generically: \( c_n = \tilde{c}_n (\Lambda_{UV})^{-n[g]} \), where \( \tilde{c}_n \) is dimensionless, and \( n[g] < 0 \) – it’s higher and higher powers of the cutoff.

Consider the renormalizable (classically scale invariant) case: \([c_n] = [f]\), since \([g] = 0\). But in fact, what you’ll get is something like

\[
c_n = \tilde{c}_n \log^{\nu(n)} \left( \frac{\Lambda_{UV}}{\Lambda_{IR}} \right),
\]

where \( \Lambda_{IR} \) is an infrared cutoff or a mass or external momentum, \([\Lambda_{IR}] = 1\). Some classically scale invariant examples (so that \( m = 0 \) and the bare propagator is \( 1/k^2 \)) where you can see that we get logs from loop amplitudes:

\( \phi^4 \) in \( D = 4 \):

\[
\phi^6 \text{ in } D = 3:
\]

\( \phi^3 \) in \( D = 6 \):

In \( D = 2 \), even the propagator for a massless scalar field has logs:

\[
\langle \phi(x)\phi(0) \rangle = \int d^2k \frac{e^{-ikx}}{k^2} \sim \log \frac{|x|}{\Lambda_{UV}}.
\]

The terms involving ‘renormalizable’ in (1.37) are somewhat old-fashioned and come from a high-energy physics point of view where the short-distance physics is unknown, and we want to get as far as we can in that direction with our limited knowledge (in which case the condition ‘renormalizability’ lets us get away with this indefinitely – it lets us imagine we know everything). The latter terms are natural in the opposite situation (like condensed matter physics) where we know some basically correct microscopic description but want to know what happens at low energies. Then an operator like \( \frac{1}{\Lambda_{IR}^2} \phi^{28} \) whose coefficient is suppressed by some large mass scale \( M \) is irrelevant for physics at energies far below that scale. Inversely, an operator like \( m^2\phi^2 \) gives a mass to the \( \phi \) particles, and matters very much (is relevant) at energies \( E < m \). In the marginal case, the quantum corrections have a chance to make a big difference.

[End of Lecture 5]
1.7 Vertex correction in QED

[Peskin chapter 6, Schwartz chapter 17, Zee chapter III.6] Back to work on QED. The vertex correction has some great physics payoffs:

- We’ll cancel the cutoff dependence we found in the $S$ matrix from $\delta Z$.
- We’ll compute $g - 2$ (the anomalous magnetic moment) of the electron, the locus of some of the most precise agreement between theory and experiment. (Actually the agreement is so good that it’s used as the definition of the fine structure constant. But a similar calculation gives the leading anomalous magnetic moment of the muon.)
- We’ll see that the exclusive differential cross section $(d\sigma/d\Omega)_{e\mu \to e\mu}$ that we’ve been considering is not really an observable. Actually it is infinity! The key word here is ‘exclusive,’ which means that we demand that the final state is exactly one electron and one muon and absolutely nothing else. Think for a moment about how you might do that measurement.

This is an example of an IR divergence. While UV divergences mean you’re overstepping your bounds (by taking too seriously your Lagrangian parameters or your knowledge of short distances), IR divergences mean you are asking the wrong question.

To get started, consider the following class of diagrams.

\[ \equiv i\mathcal{M} = ie^2 (\bar{u}(p')\Gamma^\mu(p,p')u(p)) \frac{1}{q^2} \bar{u}(K')\gamma_\mu u(K) \]  

(1.38)

The shaded blob is the vertex function $\Gamma$. The role of the light blue factors is just to make and propagate the photon which hits our electron; let’s forget about them. Denote the photon momentum by $q = p' - p$. We’ll assume that the electron momenta $p, p'$ are on-shell, but $q^\mu$ is not, as in the $e\mu$ scattering process. Then $q^2 = 2m^2 - 2p' \cdot p$.

---

10More accurately, the exclusive cross section is zero; the one-loop correction is minus infinity, which is perturbation theory’s clumsy attempt to correct the finite tree level answer to make it zero.
Before calculating the leading correction to the vertex $\Gamma^\mu = \gamma^\mu + \mathcal{O}(e^2)$, let’s think about what the answer can be. It is a vector made from $p, p', \gamma^\mu$ and $m, e$ and numbers. It can’t have any $\gamma^5$ or $\epsilon_{\mu\nu\rho\sigma}$ by parity symmetry of QED. So on general grounds we can organize it as

$$\Gamma^\mu(p, p') = A\gamma^\mu + B(p + p')^\mu + C(p - p')^\mu$$

(1.39)

where $A, B, C$ are Lorentz-invariant functions of $p^2 = (p')^2 = m^2$, $p \cdot p'$, $\not\!p, \not\!p'$. But, for example, $\not\!p\gamma^\mu u(p) = (m\gamma^\mu - p^\mu)u(p)$ which just mixes up the terms; really $A, B, C$ are just functions of the momentum transfer $q^2$. Gauge invariance, in the form of the Ward identity, says that contracting the photon line with the photon momentum should give zero:

$$0 \overset{\text{Ward}}{=} q_\mu \bar{u}(p')\Gamma^\mu u(p) \overset{(1.39)}{=} \bar{u}(p') \begin{pmatrix} A & \frac{q}{m^2 - m_m^2 = 0} & u(p) \\ & +B(p + p') \cdot (p - p') + Cq^2 & u(p) \end{pmatrix}$$

Therefore $0 = Cq^2 \bar{u}(p')u(p)$ for general $q^2$ and general spinors, so $C = 0$. This is the moment for the Gordon identity to shine:

$$\bar{u}(p')\gamma^\mu u(p) = \bar{u}(p') \left( \frac{p^\mu + p'^\mu}{2m} + \frac{i\sigma_{\mu\nu}q_\nu}{2m} \right) u(p)$$

(where $\sigma_{\mu\nu} \equiv \frac{i}{2}[\gamma^\mu, \gamma^\nu]$) can be used to eliminate the $p + p'$ term. The Gordon identity shows that the QED interaction vertex $\bar{u}(p')\gamma^\mu u(p)A_\mu$ contains a magnetic moment bit in addition to the $p + p'$ term (which is there for a charged scalar field).

It is then convenient (and conventional) to parametrize the vertex in terms of the two form factors $F_{1,2}$:

$$\Gamma^\mu(p, p') = \gamma^\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q_\nu}{2m} F_2(q^2).$$

(1.40)

This little monstrosity has the complete information about the coupling of the electron to the electromagnetic field, such as for example a background electromagnetic field. It is a parametrization of the matrix elements of the current between two one-electron states, incorporating the fact of gauge invariance.

11 Actually this is why we didn’t include a $\sigma_{\mu\nu}$ term. You could ask: what about a term like $\sigma_{\mu\nu}(p + p')^\nu$? Well, there’s another Gordon identity that relates that to things we’ve already included:

$$\bar{u}_2\sigma_{\mu\nu}(p_1 + p_2)^\nu u_1 = i\bar{u}_2(q_\mu - (m_1 - m_2)\gamma_\mu) u_1.$$ 

It is proved the same way: just use the Dirac equation $\not\!p_1 u_1 = m_1 u_1, \bar{u}_2\not\!p_2 = \bar{u}_2m_2$ and the Clifford algebra. We are interested here in the case where $m_1 = m_2$. 

44
The first term at zero momentum $eF_1(q^2 = 0)$ is the electric charge of the electron (if you don’t believe it, use the vertex (1.40) to calculate the Coulomb field of the electron; there are some details on page 186 of Peskin). Since the tree-level bit of $F_1$ is 1, if by the letter $e$ here we mean the actual charge, then we’d better include counterterms ($\mathcal{L}_{ct} \ni \bar{\psi} \delta_e \gamma^\mu A_\mu \psi$) to make sure it isn’t corrected: $F_1(0) = 1$.

The magnetic moment of the electron is the coefficient $\vec{\mu}$ of $\vec{V}(q) = -\vec{\mu} \cdot \vec{B}(q) + ...$ in the non-relativistic effective potential. Comparing the non-relativistic limit of $\bar{u}(p')\Gamma^i u(p)A_i(q) = -\vec{\mu} \cdot \vec{B}(q) + ...$, (see the homework) shows that (see Peskin p. 187)

$$\vec{\mu} = g \frac{e}{2m} \vec{S},$$

where $\vec{S} \equiv \xi \sigma \xi^\dagger$ is the electron spin. Comparing with the vertex function, this says that the $g$ factor is

$$g = 2(F_1(0) + F_2(0)) = 2 + 2F_2(0) = 2 + \mathcal{O}(\alpha).$$

We see that the anomalous magnetic moment of the electron is $2F_2(q^2 = 0)$.

Now that we have some expectation about the form of the answer, and some ideas about what it’s for, we sketch the evaluation of the one-loop QED vertex correction:

$$= -ie^3 \int d^4k \bar{u}(p')\gamma^\nu \frac{k' + m_e}{(k')^2 - m_e^2} \gamma^\mu \frac{k^2}{k^2 - m_e^2} \gamma^\rho u(p) \cdot \eta_{\nu\rho} \frac{\eta_{\nu\rho}}{(p-k)^2 - m_\gamma^2}$$

with $k' \equiv k + q$.

Step (1) Feynman parameters again. The one we showed before can be rewritten more symmetrically as:

$$\frac{1}{AB} = \int_0^1 dx \int_0^1 dy \frac{\delta(x + y - 1)}{(xA + yB)^2}$$
Now how can you resist the generalization\textsuperscript{12}: 

\[
\frac{1}{ABC} = \int_0^1 dx \int_0^1 dy \int_0^1 dz \, \delta(x + y + z - 1) \frac{2}{(xA + yB + zC)^3}.
\]

So, set \( A = (k')^2 - m_e^2, B = k^2 - m_e^2, C = (p - k)^2 - m_e^2 \) (with the appropriate is), so that the integral we have to do is

\[
\int \frac{d^4kN^\mu}{(k^2 + k \cdot (\ldots) + \ldots)^5}.
\]

Step (2) Complete the square, \( \ell = k - zp + xq \) to get

\[
\Delta = -xyq^2 + (1 - z)^2m^2 + zm^2 \gamma.
\]

The \( \ell \)-dependence in the numerator is either 1 or \( \ell^\mu \) or \( \ell^\nu \ell^\nu \). In the integral over \( \ell \), the second averages to zero, and the third averages to \( \eta^\mu\nu \ell^\mu \ell^\nu \). As a result, the momentum integrals we need are just

\[
\int \frac{d^D\ell}{(\ell^2 - \Delta)^m} \quad \text{and} \quad \int \frac{d^D\ell \, \ell^2}{(\ell^2 - \Delta)^m}.
\]

Right now we only need \( D = 4 \) and \( m = 3 \), but it turns out to be quite useful to think about them all at once. Like in our discussion of the electron self-energy diagram, we

\textsuperscript{12}Peskin outlines a proof by induction of the whole family of such identities on page 190. But here’s a simpler proof using Schwinger parameters. You’ll agree that

\[
\frac{1}{A} = \int_0^\infty ds \, e^{-sA}.
\]

Applying this identity to each factor gives

\[
\frac{1}{A_1A_2\cdots A_n} = \int_0^\infty ds_1 \cdots \int_0^\infty ds_n \, e^{-\sum_{i=1}^n s_i A_i}.
\]

Now use scaling to set \( \tau = \sum_{i=1}^n s_n \), and \( x_i \equiv s_i/\tau \). Then

\[
\frac{1}{A_1A_2\cdots A_n} = \int_0^\infty d\tau \tau^{n-1} \prod_{i=1}^n \int_0^1 dx_i \delta \left( \sum_{i=1}^n x_i - 1 \right) \, e^{-\tau \sum_{i=1}^n x_i A_i}.
\]

Now do the integral over \( \tau \), using \( \int_0^\infty d\tau \tau^{n-1} e^{-\tau X} = \frac{(n-1)!}{X^n} \) (differentiate (1.41) wrt \( A \)), to arrive at

\[
\frac{1}{A_1A_2\cdots A_n} = \prod_{i=1}^n \int_0^1 dx_i \delta \left( \sum_{i=1}^n x_i - 1 \right) \frac{(n-1)!}{(\sum_i x_i A_i)^n}.
\]
can evaluate them by Wick rotating (which changes the denominator to $\ell^2 E + \Delta$) and going to polar coordinates. This gives:

$$\int \frac{d^D \ell}{(\ell^2 - \Delta)^m} = (-1)^m \frac{i}{(4\pi)^{D/2}} \frac{\Gamma(m - \frac{D}{2})}{\Gamma(m)} \left(\frac{1}{\Delta}\right)^{m-\frac{D}{2}}. \quad (1.43)$$

$$\int \frac{d^D \ell^2}{(\ell^2 - \Delta)^m} = (-1)^{m-1} \frac{D}{2} \frac{i}{(4\pi)^{D/2}} \frac{\Gamma(m - \frac{D}{2} - 1)}{\Gamma(m)} \left(\frac{1}{\Delta}\right)^{m-\frac{D}{2}-1}. \quad (1.44)$$

Notice that these integrals are not equal to infinity when the parameter $D$ is not an integer. This is the idea behind dimensional regularization.

Step (0) But for now let’s persist in using the Pauli Villars regulator. (I call this step (0) instead of (3) because it should have been there all along.) Here this means we subtract from the amplitude the same quantity with $m$ replaced by $\Lambda^2$. The dangerous bit comes from the $\ell^2$ term we just mentioned, since $m - D/2 - 1 = 3 - 4/2 - 1 = 0$ means logs.

The numerator is

$$N^\mu = \bar{u}(p') \gamma^\mu (k + q + m_e) \gamma^\nu (k + m_e) \gamma_\nu u(p)$$

$$= -2 (A \bar{u}(p') \gamma^\mu u(p) + B \bar{u}(p') \gamma^\mu q_\nu u(p) + C \bar{u}(p') q^\mu u(p)) \quad (1.45)$$

where

$$A = -\frac{1}{2} \ell^2 + (1 - x)(1 - y)q^2 + (1 - 4z + z^2)m^2$$

$$B = imz(1 - z)$$

$$C = m(z - 2)(y - x). \quad (1.46)$$

The blood of many men was spilled to arrive at these simple expressions (actually most of the algebra is done explicitly on page 319 of Schwartz). Now you say: but you promised there would be no term like $C$ because of the Ward identity. Indeed I did and indeed there isn’t because $C$ is odd in $x \leftrightarrow y$ while everything else is even, so this term integrates to zero.

The first term (with $A$) is a correction to the charge of the electron and will be UV divergent. More explicitly, we get, using Pauli-Villars,

$$\int d^4 \ell \left( \frac{\ell^2}{(\ell^2 - \Delta_m)^3} - \frac{\ell^2}{(\ell^2 - \Delta)^3} \right) = \frac{i}{(4\pi)^2} \ln \frac{\Delta}{\Delta_m}. \quad \Delta_m$$

The other bits are finite, and we ignore the terms that go like negative powers of $\Lambda$. More on this cutoff dependence soon. But first something wonderful:
1.7.1 Anomalous magnetic moment

The second term $B$ contains the anomalous magnetic moment:

$$F_2(q^2) = \frac{2m}{e} \cdot (\text{the term with } B)$$

$$= \frac{2m}{e} 4e^3 i m \int dx dy dz \delta(x + y + z - 1) (1 - z) \int \frac{d^4 \ell}{(\ell^2 - \Delta)^3}$$

$$= \frac{\alpha}{\pi} m^2 \int dx dy dz \delta(x + y + z - 1) \frac{z(1 - z)}{(1 - z)^2 m^2 - xyq^2}. \quad (1.47)$$

The correction to the magnetic moment is the long-wavelength bit of this:

$$F_2(q^2 = 0) = \frac{\alpha}{\pi} m^2 \int_0^1 dz \int_0^{1-z} dy \frac{z}{(1 - z)m^2} = \frac{\alpha}{2\pi}.$$  

$$g = 2 + \frac{\alpha}{\pi} + O(\alpha^2).$$

A rare opportunity for me to plug in numbers: $g = 2.00232$.

1.7.2 IR divergences mean wrong questions.

There is a term in the numerator from the $A_{\gamma^\mu}$ bit

$$\int \frac{d^4 \ell}{(\ell^2 - \Delta)^3} = c \frac{1}{\Delta}$$

(with $c = -\frac{1}{32\pi^2}$ again), but without the factor of $z(1 - z)$ we had in the magnetic moment calculation. It looks like we’ve gotten away without having to introduce a UV regulator here, too (so far). But now look at what happens when we try to do the Feynman parameter integrals. For example, at $q^2 = 0$, we get (if we had set $m_{\gamma} = 0$)

$$\int dx dy dz \delta(x + y + z - 1) \frac{m^2(1 - 4z + z^2)}{\Delta} = m^2 \int_0^1 dz \int_0^{1-z} dy \frac{-2 + 2(1 - z) + (1 - z)^2}{(1 - z)^2 m^2}$$

$$= \int_0^1 dz \frac{-2}{(1 - z)} + \text{finite}, \quad (1.48)$$

which diverges at the upper limit of integration. In fact it’s divergent even when $q^2 \neq 0$.

This is a place where we actually need to include the photon mass, $m_{\gamma}$, for our own safety. The fact that restoring $m_{\gamma} \neq 0$ in (1.42) regulates this divergence is one way to see that it is indeed an IR divergence.  

[End of Lecture 6]
The (IR singular bit of the) vertex (to $O(\alpha)$) is of the form

$$\Gamma^\mu = i^\mu \left( 1 - \frac{\alpha}{2\pi} f_{IR}(q^2) \ln \left( \frac{-q^2}{m^2_\gamma} \right) \right) + \text{stuff which is finite as } m_\gamma \to 0. \quad (1.49)$$

Notice that the IR divergent stuff depends on the electron momenta $p, p'$ only through $q$, the momentum of the photon. So it looks like we are led to conclude

$$\left( \frac{d\sigma}{d\Omega} \right)_{\mu e \to \mu e} = \left( \frac{d\sigma}{d\Omega} \right)_{Mott} \left( 1 - \frac{\alpha}{\pi} f_{IR}(q^2) \ln \left( \frac{-q^2}{m^2_\gamma} \right) \right) + \mathcal{O}(\alpha^2)$$

which blows up when we remove the fake photon mass $m_\gamma \to 0$. Notice that the one-loop correction is not only infinite, but negative infinity, which simply cannot happen from the definition of the cross section. This is perturbation theory’s way of telling us that the answer is $1 - \alpha \cdot \infty + \mathcal{O}(\alpha^2) \simeq 0$ – the putatively small corrections from radiative effects are actually trying to make the answer zero.

[Schwartz §20.1] I wanted to just quote the above result for (1.49) but I lost my nerve, so here is a bit more detail leading to it. The IR dangerous bit comes from the second term in $A$ above. That is,

$$F_1(q^2) = 1 + f(q^2) + \delta_1 + \mathcal{O}(\alpha^2)$$

with

$$f(q^2) = \frac{e^2}{8\pi^2} \int_0^1 dx dy dz \delta(x+y+z-1) \left( \ln \frac{z\Lambda^2}{\Delta} + \frac{q^2(1-x)(1-y) + m^2_e(1-4z+z^2)}{\Delta} \right).$$

$\delta_1$ here is a counterterm for the $\Psi \gamma^\mu A^\mu \Psi$ vertex.

We can be more explicit if we consider $-q^2 \gg m^2_e$ so that we can ignore the electron mass everywhere. Then we would choose the counterterm $\delta_1$ so that

$$1 = F_1(0) \implies \delta_1 = -f(0) \left. \right|_{m_e/q^2 \to 0} \to -\frac{e^2}{8\pi^2} \frac{1}{2} \ln \frac{\Lambda^2}{m^2_\gamma}.$$

And the form of $f(q^2)$ is

$$f(q^2) \big|_{m_e=0} = \frac{e^2}{8\pi^2} \int dx dy dz \delta(x+y+z-1) \left( \ln \frac{(1-x-y)\Lambda^2}{\Delta} + \frac{q^2(1-x)(1-y)}{-xyq^2 + (1-x-y)m^2_\gamma} \right)$$

$$F_1(q^2) \big|_{m_e=0} = 1 - \frac{e^2}{16\pi^2} \left( \ln^2 \frac{-q^2}{m^2_\gamma} + 3 \ln \frac{-q^2}{m^2_\gamma} \right) + \text{finite}.$$ 

In doing the integrals, we had to remember the $i\epsilon$ in the propagators, which can be reproduced by the replacement $q^2 \to q^2 + i\epsilon$. This $\ln^2(q^2/m_\gamma)$ is called a *Sudakov double logarithm*. Notice that taking differences of these at different $q^2$ will not make it finite.

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**Diversity and inclusion to the rescue.** Before you throw up your hands in despair, I would like to bring to your attention another consequence of the masslessness of the photon: It means real (as opposed to virtual) photons can be made with arbitrarily low energy. But a detector has a minimum triggering energy: the detector works by particles doing some physical something to stuff in the detector, and it has a finite energy resolution – it takes a finite amount of energy $E_c$ for those particles to do the stuff. This means that a process with exactly one $e$ and one $\mu$ in the final state cannot be distinguished from a process ending in $e\mu$ plus a photon of arbitrarily small energy, such as would result from (final-state radiation) or (initial-state radiation). This ambiguity is present for any process with external charged particles.

Being more inclusive, then, we cannot distinguish amplitudes of the form

$$\bar{u}(p')M_0(p', p)u(p) \equiv -i\left(\begin{array}{ccc}
\end{array}\right),$$

from more inclusive amplitudes like

$$-i\left(\begin{array}{ccc}
\end{array}\right) + \left(\begin{array}{ccc}
\end{array}\right) = \bar{u}(p')\gamma^\mu\frac{\epsilon}{p' + \gamma - m_e}M_0(p', p)\gamma^\mu u(p)\epsilon^*(k) + \bar{u}(p')M_0(p', p)\frac{\epsilon}{p - \gamma - m_e}\gamma^\mu u(p)\epsilon^*(k).$$

Now, by assumption the extra outgoing photon is real ($k^2=0$) and it is soft, in the sense that $k^0 < E_c$, the detector cutoff. So we can approximate the numerator of the second term as

$$(p - \gamma + m_e)\gamma^\mu u(p) \simeq (p + m_e)\gamma^\mu u(p) \overset{\text{Clifford}}{=} (2p^\mu + \gamma^\mu (-p + m_e))u(p) = 2p^\mu u(p).$$

In the denominator we have e.g. $(p - \gamma)^2 - m_e^2 = p^2 - m_e^2 - 2p \cdot k + k^2 \sim -2p \cdot k$ since the electron is on shell $p^2 = m_e^2$ and so is the photon $k^2 = 0$. Therefore

$$\mathcal{M}(e\mu + \text{one soft } \gamma \leftarrow e\mu) = e\bar{u}(p')M_0(p', p)u(p)\left(\frac{p' \cdot \epsilon^*}{p' \cdot k + i\epsilon} - \frac{p \cdot \epsilon^*}{p \cdot k - i\epsilon}\right) \quad (1.50)$$

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This is bremsstrahlung. Before we continue this calculation to find the inclusive amplitude which a real detector actually measures, let’s pause to relate the previous expression to some physics we know. Where have we seen this kind of expression before? Notice that the $i\epsilon$ are different because one comes from final state and one from initial. Well, this object is the Fourier transform $\tilde{j}^\mu(k) = \int d^4x \: e^{i k \cdot x} j^\mu(x)$ of the current

$$j^\mu(x) = e \int d\tau \frac{d j^\mu(x)}{d\tau} \delta^{(4)}(x - y(\tau))$$

associated with a particle which executes a piecewise linear motion

$$y^\mu(\tau) = \begin{cases} \frac{p^\mu}{m} \tau, & \tau < 0 \\ \frac{p'^\mu}{m} \tau, & \tau > 0 \end{cases}.$$  

This is a good approximation to the motion a free particle which experiences a sudden acceleration; sudden means that the duration of the pulse is short compared to $\omega^{-1}$ for any frequency we’re going to measure. The electromagnetic radiation that such an accelerating charge produces is given classically by Maxwell’s equation: $\tilde{A}^\mu(k) = -\frac{1}{k^2} \tilde{j}^\mu(k)$.

I claim further that the factor $f_{IR}(q^2) = \frac{q}{\pi} \ln \left( \frac{-q^2}{m^2} \right)$ (which entered our lives in (1.49)) arises classically as the number of soft photons produced by such a process in each decade of wavenumber. You can figure this out by plugging $\tilde{A}^\mu(k) = -\frac{1}{k^2} \tilde{j}^\mu(k)$ into the electromagnetic energy

$$\frac{1}{2} \int d^3x \: (E^2 + B^2) = \int d^3k \: \hbar \omega_k n_k.$$  

(Note that the integral over $k$ here actually diverges; this is an artifact of the approximation that the momentum change is instantaneous.) See Peskin §6.1 for help.

\[
\left( \frac{d\sigma}{d\Omega} \right)_{\mu e \gamma \mu e}^{E_\gamma < E_e} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}}^{\gamma p} \int_0^{E_e} \int_0^{E_k} \frac{d^3k}{k^3} \left| \frac{p \cdot e^*}{p \cdot k} - \frac{p' \cdot e^*}{p' \cdot k} \right|^2 e^{i \frac{p \cdot e^*}{2 E_k} + i \frac{p' \cdot e^*}{2 E_k}} \sim \int_0^{E_k} \frac{d^3k}{k^3} = \infty.
\]

Check it:

$$\int d^4x j^\mu(x) e^{i k \cdot x} = e \int d\tau \frac{dy^\mu(\tau)}{d\tau} e^{i k \cdot y(\tau)} = e \int_0^\infty d\tau \frac{p^\mu}{m} e^{i\left(\frac{k \cdot p}{m} + i \tau\right)} + e \int_0^\infty d\tau \frac{p'^\mu}{m} e^{i\left(\frac{k \cdot p'}{m} - i \tau\right)} = \tilde{j}^\mu(k).$$  

Notice that the $i\epsilon$ are convergence factors in the Fourier transforms.
This is another IR divergence. (One divergence is bad news, but two is an opportunity for hope.) Just like we must stick to our UV regulators like religious zealots, we must cleave tightly to the consistency of our IR regulators: we need to put back the photon mass:

$$E_k = \sqrt{k^2 + m_\gamma^2}$$

which means that the lower limit of the $k$ integral gets cut off at $m_\gamma$:

$$\int_0^{E_c} \frac{dk}{E_k} = \left( \int_0^{m_\gamma} + \int_{m_\gamma}^{E_c} \right) \frac{dk}{\sqrt{k^2 + m_\gamma^2}} \sim \int_0^{m_\gamma} \frac{dk}{m_\gamma} + \int_{m_\gamma}^{E_c} \frac{dk}{\ln \frac{E_c}{m_\gamma}}$$

Being careful about the factors, the actual cross section measured by a detector with energy resolution $E_c$ is\(^\text{14}\)

$$\left( \frac{d\sigma}{d\Omega} \right)_{\text{observed}} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{e}^+\mu^-\text{e}^-} + \left( \frac{d\sigma}{d\Omega} \right)_{\text{e}^+\mu^-\text{soft}+\text{e}^-} + \mathcal{O}(\alpha^3)$$

$$= \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \left( 1 - \frac{\alpha}{\pi} f_{IR}(q^2) \ln \left( \frac{-q^2}{m_\gamma^2} \right) + \alpha \left( \frac{f_{IR}(q^2) \ln \left( \frac{E_c^2}{m_\gamma^2} \right)}{\text{vertex correction}} + \text{soft photons} \right) \right)$$

The thing we can actually measure is independent of the IR regulator photon mass $m_\gamma$, and finite when we remove it. On the other hand, it depends on the detector resolution.

Like in the plot of some kind of Disney movie, an apparently minor character whom you may have been tempted to regard as an ugly detail has saved the day.

I didn’t show explicitly that the coefficient of the log is the same function $f_{IR}(q^2)$. In fact this function is $f_{IR}(q^2) = \frac{1}{2} \log(-q^2/m_\gamma^2)$, so the product $f_{IR} \ln q^2 \sim \ln^2 q^2$ is the Sudakov double logarithm. A benefit of the calculation which shows that the same $f_{IR}$ appears in both places (Peskin chapter 6.5) is that it also shows that this pattern persists at higher order in $\alpha$: there is a $\ln^2(q^2/m_\gamma^2)$ dependence in the two-loop vertex correction, and a matching $-\ln^2(E_c^2/m_\gamma^2)$ term in the amplitude to emit two soft

\(^{14}\)Notice that we add the cross-sections, not the amplitudes, for these processes with different final states. Here’s why: even though we don’t measure the existence of the photon, something does: it gets absorbed by some part of the apparatus or the rest of the world and therefore becomes entangled with some of its degrees of freedom; when we fail to distinguish between those states, we trace over them, and this erases the interference terms we would get if we summed the amplitudes.
photons. There is a $\frac{1}{2}$ from Bose statistics of these photons. The result exponentiates, and we get

$$e^{-\frac{\alpha f}{\pi} \ln(-q^2/m^2_\gamma)} e^{-\frac{\alpha f}{2}(E^2_c/m^2_\gamma)} = e^{-\frac{\alpha f}{\pi} \ln(-q^2/E^2_c)}.$$  

You may be bothered that I’ve made all this discussion about the corrections from the electron line, but said nothing about the muon line. But the theory should make sense even if the electron and muon charges $Q_e, Q_m$ were different, so the calculation should make sense term-by-term in an expansion in $Q_m$.

Some relevant names for future reference: The name for the guarantee that this always works in QED is the Bloch-Nordsieck theorem. Closely-related but more serious issues arise in QCD, the theory of quarks and gluons; this is the beginning of the story of jets (a jet is some IR-cutoff dependent notion of a QCD-charged particle plus the cloud of stuff it carries with it) and parton distribution functions.

**Sketch of exponentiation of soft photons.** [Peskin §6.5] In the following we will just keep track of the bits which diverge when $m_\gamma \to 0$. Consider a diagram with $n$ soft external photons, summed over ways of distributing them on an initial and final electron line:

$$\sum_{n_f=1}^n \sum_{n_i=1}^n \prod_{\alpha=1}^n \frac{p' \mu_\alpha}{p' \cdot k_\alpha} \frac{p^\mu_\alpha}{p \cdot k_\alpha} \equiv A_n.$$  

Here the difference in each factor is just as in (1.50), one term from initial and one from final-state emission; expanding the product gives the sum over $n_f = 1 - n_i$, the number coming from the final-state line. From this expression, we can make a diagram with a soft-photon loop by picking an initial line $\alpha$ and a final line $\beta$ setting $k_\alpha = -k_\beta \equiv k$ and tying them together with a propagator and summing over $k$:

$$= A_{n-2} \frac{e^2}{2} \int \frac{d^4 k}{k^2 - m^2_\gamma} \left( \frac{p' \cdot k}{p' \cdot k} - \frac{p \cdot k}{p \cdot k} \right)^\rho \left( \frac{p' \cdot k}{-p' \cdot k} - \frac{p \cdot k}{-p \cdot k} \right)^\sigma.$$  

The factor of $\frac{1}{2}$ accounts for the symmetry under exchange of $\alpha \leftrightarrow \beta$. For the case of $n = 2$, this is the whole story, and this is

$$\bar{u} i M_0 u \cdot X = \begin{pmatrix} \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot 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(where here ‘soft part’ means the part which is singular in \(m_\gamma\)) from which we conclude that

\[
X = -\frac{\alpha}{2\pi} f_{IR}(q^2) \ln \left( \frac{-q^2}{m_\gamma^2} \right) + \text{finite.}
\]

(The integral is done in Peskin, page 201.) Taking the most IR-divergent bit with \(m\) virtual soft photons (order \(\alpha m\)) for each \(m\) gives

\[
M_{\text{virtual soft}} = \sum_{m=0}^{\infty} \left( \frac{1}{m!} \frac{X^m}{e^X} \right)
\]

where the \(1/m!\) is a symmetry factor from interchanging the virtual soft photons. Notice that this verifies my claim that the \(-\infty\) in the one-loop answer is perturbation theory’s way of trying to make the cross-section zero: since \(X \to 0 \to -\infty\), \(d\sigma_{\text{exclusive}} \propto e^{2X} m_\gamma \to 0\).

Now consider the case of one real external soft (\(E \in [m_\gamma, E_c]\)) photon in the final state. The cross section is

\[
d\sigma_{1\gamma} = \int d\Pi \sum_{\text{pols}} e^\mu e^{*\nu} \mathcal{M}_\mu \mathcal{M}_\nu^* \\
= |\bar{u}(p') \mathcal{M}_0 u(p)|^2 \int \frac{d^3k}{2E_k} (-\eta_{\mu\nu}) e^2 \left( \frac{p'}{p' \cdot k} - \frac{p}{p \cdot k} \right)^\mu \left( \frac{p'}{-p' \cdot k} - \frac{p}{-p \cdot k} \right)^\nu
\]

\[
= d\sigma_0 Y, \\
Y = \frac{\alpha}{\pi} f_{IR}(q^2) \ln \left( \frac{E_c^2}{m_\gamma^2} \right).
\]

(This was actually exactly the same integral as in the virtual-photon calculation in (1.51).) Therefore, the exclusive cross section, including contributions of soft real photons gives

\[
\sum_{n=0}^{\infty} d\sigma_{n\gamma} = d\sigma_0 \sum_{n=1}^{\infty} \frac{1}{n!} Y^n = d\sigma_0 e^Y.
\]

Here the \(n!\) is because the final state contains \(n\) identical bosons.

Putting the two effects together gives the promised cancellation of \(m_\gamma\) dependence to all orders in \(\alpha\):

\[
d\sigma = d\sigma_0 e^{2X} e^Y \\
= d\sigma_0 \exp \left( -\frac{\alpha}{\pi} f_{IR}(q^2) \ln \left( \frac{-q^2}{m_\gamma^2} \right) + \frac{\alpha}{\pi} f_{IR}(q^2) \ln \left( \frac{E_c^2}{m_\gamma^2} \right) \right)
\]
\[ d\sigma_0 \exp \left( -\frac{\alpha}{\pi} f_{IR}(q^2) \ln \frac{-q^2}{E_c^2} \right). \]

This might seem pretty fancy, but unpacking the sum we did, the basic statement is that the probability of finding \( n \) photons with energy in a given (low-energy) range \([E_-, E_+]\) is

\[ P_{[E_-, E_+]} = \frac{1}{n!} \lambda^n e^{-\lambda}, \quad \lambda = \frac{\alpha}{\pi} f_{IR}(q^2) \ln \frac{E_+}{E_-} = \langle n \rangle = \langle n^2 \rangle - \langle n \rangle^2 \]

a Poisson distribution. This is just what one finds in a coherent state of the radiation field.

### 1.7.3 Some magic from gauge invariance of QED

We found that the self-energy of the electron gave a wavefunction renormalization factor

\[ Z_2 = 1 + \frac{\partial \Sigma}{\partial p} |_{p=m_0} + O(e^4) = 1 - \frac{\alpha}{4\pi} \ln \frac{\Lambda^2}{m^2} + \text{finite} + O(\alpha^2). \]

We care about this because there is a factor of \( Z_2 \) in the LSZ formula for an \( S \)-matrix element with two external electrons. On the other hand, we found a cutoff-dependent correction to the vertex \( e\gamma^\mu F_1(q^2) \) of the form

\[ F_1(q^2) = 1 + \frac{\alpha}{4\pi} \ln \frac{\Lambda^2}{m^2} + \text{finite} + O(\alpha^2). \]

Combining these together

\[ S_{e\mu\nu-e\mu} = \left( \sqrt{Z_2(e)} \right)^2 \left( \gamma^\nu + \left( \gamma^\nu \cdot \gamma \right) \right) + \cdots \]

\[ = \left( 1 - \frac{\alpha}{4\pi} \ln \frac{\Lambda^2}{m^2} + \cdots \right) e^2 \bar{u}(p') \left( \gamma^\mu \left( 1 + \frac{\alpha}{4\pi} \ln \frac{\Lambda^2}{m^2} + \cdots \right) + \frac{i \sigma^{\mu\nu} q_\nu}{2m} \right) u(p) \]

the UV divergence from the vertex cancels the one in the self-energy. Why did this have to happen? During our discussion of the IR divergences, I mentioned a counterterm \( \delta_1 \) for the vertex. But how many counterterms do we get here? Is there a point of view which makes this cancellation obvious? Notice that the \( \cdots \) multiplying the \( \gamma^\mu \) term still contain the vacuum polarization diagram, which is our next subject, and which may be (is) cutoff dependent. Read on.

### 1.8 Vacuum polarization

[Zee, III.7] We’ve been writing the QED lagrangian as

\[ \mathcal{L} = \bar{\psi} \left( \not{\partial} + ie \not{\mathcal{A}} - m \right) \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}. \]
I’ve put tildes on the photon field because of what’s about to happen: Suppose we rescale the definition of the photon field $e \tilde{A}_\mu \equiv A_\mu, e \tilde{F}_{\mu\nu} \equiv F_{\mu\nu}$. Then the coupling $e$ moves to the photon kinetic term:

$$L = \bar{\psi} \left( \partial \psi + iA - m \right) \psi - \frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu}.$$ 

With this normalization, instead of measuring the coupling between electrons and photons, the coupling constant $e$ measures the difficulty a photon has propagating through space:

$$\langle A_\mu A_\nu \rangle \sim -\frac{i\eta_{\mu\nu}e^2}{q^2}.$$ 

None of the physics is different, since each internal photon line still has two ends on a $\bar{\psi}\gamma^{\mu}A_\mu\psi$ vertex.

But from this point of view it is clear that the magic of the previous subsection is a consequence of gauge invariance, here’s why: the demand of gauge invariance relates the coefficients of the $\bar{\psi}\partial\psi$ and $\bar{\psi}\gamma^{\mu}A_\mu\psi$ terms. Therefore, any counterterm we need for the $\bar{\psi}\partial\psi$ term (which comes from the electron self-energy correction and is traditionally called $\delta Z_2$) must be the same as the counterterm for the $\bar{\psi}\gamma^{\mu}A_\mu\psi$ term (which comes from the vertex correction and is called $\delta Z_1$). No magic, just gauge invariance.

A further virtue of this reshuffling of the factors of $e$ (emphasized by Zee on page 205) arises when we couple more than one species of charged particle to the electromagnetic field, e.g. electrons and muons or, more numerously, protons: once we recognize that charge renormalization is a property of the photon itself, it makes clear that quantum corrections cannot mess with the ratio of the charges. A deviation from $-1$ of the ratio of the charges of electron and proton as a result of interactions might seem plausible given what a mess the proton is, and would be a big deal for atoms. Gauge invariance forbids it.

Just as we defined the electron self-energy (amputated 2-point function) as $\Sigma(p) = -i\Sigma(p)$ (with two spinor indices implied), we define the photon self-energy as

$$+i\Pi_{\mu\nu}(q^2) \equiv \begin{array}{c} \includegraphics[width=0.2\textwidth]{diagram.png} \end{array} = \begin{array}{c} \includegraphics[width=0.2\textwidth]{diagram.png} \end{array} + \mathcal{O}(e^4)$$

(the diagrams on the RHS are amputated). It is a function of $q^2$ by Lorentz symmetry. (The reason for the difference in sign is that the electron propagator is $\frac{i}{p^2-m}$ while the

---

15Notice that the gauge transformation of the rescaled $A_\mu$ is $A_\mu \rightarrow A_\mu + \partial_\mu \lambda(x)$, $\psi(x) \rightarrow e^{iq\lambda(x)}\psi(x)$ so that $D_\mu \psi \equiv (\partial + qA_\mu) \psi \rightarrow e^{iq\lambda} D_\mu \psi$ where $q$ is the charge of the field ($q = -1$ for the electron). This is to be contrasted with the transformation of $\tilde{A}_\mu \rightarrow \tilde{A}_\mu - \partial_\mu \lambda(x)/e$. 

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photon propagator is \( \frac{-i\eta_{\mu\nu}}{q^2} \).

We can parametrize the answer as

\[
\Pi_{\mu\nu}(q^2) = A(q^2)\eta_{\mu\nu} + B(q^2)q^\mu q^\nu.
\]

The Ward identity says

\[
0 = q_\mu \Pi_{\mu\nu}(q^2) \implies 0 = Aq^\nu + Bq^2 q^\nu \implies B = -A/q^2.
\]

Let \( A \equiv \Pi(q^2) \) so that

\[
\Pi_{\mu\nu}(q^2) = \Pi(q^2)q^2 (\eta_{\mu\nu} - \frac{q^\mu q^\nu}{q^2}).
\]

This object \( \Delta^\mu_T \) is a projector

\[
\Delta_T^\mu \Delta_T^\nu = \Delta_T^\mu \nu
\]

onto modes transverse to \( q^\mu \). Recall that we can take the bare propagator to be

\[
\tilde{G}\sim -i\Delta_T = \frac{-i\Delta_T}{q^2}
\]

without changing any gauge-invariant physics. This is useful because then

\[
G^{(2)}(q) = \frac{-i\Delta_T}{q^2} \left( 1 + i\Pi q^2 \Delta_T \left( -\frac{i\Delta_T}{q^2} \right) + i\Pi q^2 \Delta_T \left( -\frac{i\Delta_T}{q^2} \right) i\Pi q^2 \Delta_T \left( -\frac{i\Delta_T}{q^2} \right) + \cdots \right)
\]

\[
= \Delta_T \frac{-i\Delta_T}{q^2} (1 + \Pi\Delta_T + \Pi^2\Delta_T + \cdots) = \frac{-i\Delta_T}{q^2} \frac{1}{1 - \Pi(q^2)}.
\]

Does the photon get a mass? If the thing I called \( A \) above \( q^2\Pi(q^2) \xrightarrow{q^2 \to 0} A_0 \neq 0 \) (that is, if \( \Pi(q^2) \sim \frac{A_0}{q^2} \) or worse), then \( \tilde{G}\sim \frac{1}{q^2 - A_0} \) does not have a pole at \( q^2 = 0 \). If \( \Pi(q^2) \) is regular at \( q^2 \), then the photon remains massless. In order to get such a singularity in the photon self energy \( \Pi(q^2) \sim \frac{A_0}{q^2} \), we need a process like \( \delta\Pi \sim \frac{1}{q^2} \), where the intermediate state is a massless boson with propagator \( \sim \frac{1}{q^2} \). As I will explain below, this is the Anderson-Higgs mechanism (not the easiest way to understand it).

The Ward identity played an important role here. Why does it work for the vacuum polarization?

\[
q_\mu \Pi^\mu\nu(q^2) = q_\mu \tilde{G} \sim \epsilon^2 \int d^4p tr \frac{1}{p^2 + m^2} \frac{1}{q^2 - m^2} \gamma^\nu.
\]
But here is an identity:

\[
\frac{1}{p + q - m} \frac{1}{p - m} = \frac{1}{p - m} - \frac{1}{p + q - m}.
\]  

(1.54)

Now, if we shift the integration variable \( p \to p + q \) in the second term, the two terms cancel.

Why do I say ‘if’? If the integral depends on the UV limit, this shift is not innocuous. So we have to address the cutoff dependence.

In addition to the (lack of) mass renormalization, we’ve figured out that the electromagnetic field strength renormalization is

\[
Z_\gamma \equiv Z_3 = \frac{1}{1 - \Pi(0)} \sim 1 + \Pi(0) + \mathcal{O}(\epsilon^4).
\]

We need \( Z_\gamma \) for example for the \( S \)-matrix for processes with external photons, like Compton scattering.

Claim: If we do it right\(^\text{16}\), the cutoff dependence looks like\(^\text{17}\):

\[
\Pi_2(q^2) = \frac{\alpha_0}{4\pi} \left( -\frac{2}{3} \ln \Lambda^2 + 2D(q^2)_{\text{finite}} \right)
\]

where \( \Lambda \) is the UV scale of ignorance. The photon propagator gets corrected to

\[
\frac{e_0^2 \Delta_T}{q^2} \sim \frac{Z_3 e_0^2 \Delta_T}{q^2},
\]

and \( Z_3 = \frac{1}{1 - \Pi(0)} \) blows up logarithmically if we try to remove the cutoff. You see that the fine structure constant \( \alpha_0 = \frac{e_0^2}{4\pi} \) has acquired the subscript of deprecation: we can make the photon propagator sensible while removing the cutoff if we are willing to recognize that the letter \( e_0 \) we’ve been carrying around is a fiction, and write everything

---

\(^\text{16}\)What I mean here is: if we do it in a way which respects the gauge invariance and hence the Ward identity. The simple PV regulator we’ve been using does not quite do that. However, an only slightly more involved implementation, explained in Zee page 202-204, does. Alternatively, we could use dimensional regularization everywhere.

\(^\text{17}\)The factor in front of the \( \ln \Lambda \) can be made to look like it does in other textbooks using \( \alpha = \frac{e_0^2}{4\pi} \), so that

\[
\frac{\alpha_0}{4\pi} \left( \frac{2}{3} \ln \Lambda^2 \right) = \frac{e_0^2}{12\pi^2} \ln \Lambda.
\]
In terms of \( e \equiv \sqrt{Z_3} e_0 \) where \( \frac{e^2}{4\pi} = \frac{1}{137} \) is the measured fine structure constant (at low energy). To this order, then, we write

\[
e^2_0 = e^0 \left( 1 + \frac{\alpha_0}{2} \frac{2}{4\pi} \ln \Lambda^2 \right) + \mathcal{O}(\alpha^2). \tag{1.55}
\]

\[
m_0 = m + \mathcal{O}(\alpha_0) = m + \mathcal{O}(\alpha). \tag{1.56}
\]

Since the difference between \( \alpha_0 \) and \( \alpha \) is higher order (in either), our book-keeping is unchanged. Inverting the relationship perturbatively, the renormalized charge is

\[
e^2 = e^2_0 \left( 1 - \frac{\alpha_0}{4\pi} \frac{2}{3} \ln \Lambda^2 + \mathcal{O}(\alpha^2) \right)
\]

— in QED, the quantum fluctuations reduce the charge, as you might expect from the interpretation of this phenomenon as dielectric screening by virtual \( e^+ e^- \) pairs.

In the example case of \( e\mu \leftrightarrow e\mu \) scattering, the full one-loop UV cutoff dependence then looks like

\[
S_{e\mu\leftrightarrow e\mu} = \sqrt{Z_e^2} \left( 1 - \frac{\alpha_0}{2\pi} A(m_0) \right) e^2_0
\]

\[
\times L_\mu \bar{u}(p') \left[ \gamma^\mu \left( 1 + \frac{\alpha_0}{4\pi} \ln \Lambda^2 + \frac{\alpha_0}{2\pi} (B + D) + \frac{\alpha_0}{4\pi} \left( -\frac{2}{3} \ln \Lambda^2 \right) \right) \right] + \frac{i\sigma^{\mu\nu} q_\nu}{2m} \frac{\alpha_0}{2\pi} C(q^2, m_0) \right] u(p) + \mathcal{O}(\alpha^2)
\]

where \( L_\mu \) is the stuff from the muon line, and \( A, B, C, D \) are finite functions of \( m, q^2 \). In the second step, two things happened: (1) we cancelled the UV divergences from the \( Z \)-factor and from the vertex correction: this had to happen because there was no possible counterterm. (2) we used (1.55) and (1.56) to write everything in terms of the measured \( e, m \). This removes the remaining cutoff dependence.

Claim: this works for all processes to order \( \alpha^2 \). For example, Bhabha scattering gets a contribution of the form

\[
\propto e_0 \frac{1}{1 - \Pi(0)} e_0 = e^2.
\]

In order to say what is \( A+B+D \) we need to specify more carefully a renormalization scheme (other combinations of \( A, B, D \) can be changed by gauge transformations and field redefinitions). To do that, I need to give a bit more detail about the integral.

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1.8.1 Under the hood

The vacuum-polarization contribution of a fermion of mass $m$ and charge $e$ at one loop is

$$q_{\mu} \rightarrow q_{\nu} = -\int d^D k \text{tr} \left( (ie\gamma^\mu) \frac{i(k + m)}{k^2 - m^2} (ie\gamma^\nu) \frac{i(q + k + m)}{(q + k)^2 - m^2} \right)$$

The minus sign out front is from the fermion loop. Some boiling, which you can find in Peskin (page 247) or Zee (§III.7), reduces this to something manageable. The steps involved are: (1) a trick to combine the denominators, like the Feynman trick

$$\int_0^1 dx \left( \frac{1}{(1-x)(A+xB)} \right)^2.$$  (2) some Dirac algebra, to turn the numerator into a polynomial in $k, q$. As Zee says, our job in this course is not to train to be professional integrators. The result of this boiling can be written

$$i\Pi_{\mu\nu}(q) = -e^2 \int d^D \ell \int_0^1 dx \frac{N_{\mu\nu}}{(\ell^2 - \Delta)^2}$$

with $\ell = k + xq$ is a new integration variable, $\Delta \equiv m^2 - x(1-x)q^2$, and the numerator is

$$N_{\mu\nu} = 2\ell_{\mu} \ell_{\nu} - \eta_{\mu\nu} \ell^2 - 2x(1-x)q_{\mu} q_{\nu} + \eta_{\mu\nu} (m^2 + x(1-x)q^2) + \text{terms linear in } \ell_{\mu}.$$

At this point I can illustrate explicitly why we can’t use the euclidean momentum cutoff in gauge theory. With a euclidean momentum cutoff, the diagram $\rightarrow \rightarrow$ gives something of the form

$$i\Pi_{\mu\nu} \propto e^2 \int d^D \ell \int_0^\Lambda d\ell_E \frac{\ell_E^2 \eta_{\mu\nu}}{(\ell_E^2 - \Delta)^2} + \ldots \propto e^2 \Lambda^2 \eta_{\mu\nu}$$

This is NOT of the form $\Pi_{\mu\nu} = \Delta_{T,\mu\nu} \Pi(p^2)$; rather it produces a correction to the photon mass proportional to the cutoff. What happened? Our cutoff was not gauge invariant. Oops.\footnote{Two points: How could we have predicted that the cutoff on euclidean momentum $\ell_E^2 < \Lambda^2$ would break gauge invariance? Its violation of the Ward identity here is a proof, but involved some work. The idea is that the momentum of a charged field shifts under a gauge transformation. Second: it is possible to construct a gauge invariant regulator with an explicit UV cutoff, using a lattice. The price, however, is that the gauge field enters only via the link variables $U(x, \hat{e}) = e^{i \int_{x}^{x+\hat{e}} A}$ where $x$ is a site in the lattice and $\hat{e}$ is the direction to a neighboring site in the lattice. For more, look up ‘lattice gauge theory’ in Zee’s index. More on this later.}

**Fancier PV regularization.** [Zee page 202] We can fix the problem by adding also heavy Pauli-Villars electron ghosts. Suppose we add a bunch of them with masses
\( m_a \) and couplings \( \sqrt{e_a} e \) to the photon. Then the vacuum polarization is that of the electron itself plus

\[
- \sum_a c_a \int d^D k \text{tr} \left( \left( i e \gamma^\mu \right) \frac{i}{q + k - m_a} \left( i e \gamma^\nu \right) \frac{i}{q - m_a} \right) \sim \int d^4 k \left( \sum_a c_a \frac{k^2}{k^4} + \sum_a c_a m_a^2 \right).
\]

So, if we take \( \sum_a c_a = -1 \) we cancel the \( \Lambda^2 \) term, and if we take \( \sum_a c_a m_a^2 = -m^2 \), we also cancel the \( \ln \Lambda \) term. This requires at least two PV electron fields, but so what? Once we do this, the momentum integral converges, and the Ward identity applies, so the answer will be of the promised form \( \Pi^{\mu\nu} = q^2 \Pi^{\mu\nu}_T \). After some more boiling, the answer is

\[
\Pi_2(q^2) = \frac{1}{2\pi^2} \int dxx (1-x) \ln \frac{M^2}{m^2 - x(1-x)q^2}
\]

where \( \ln M^2 \equiv -\sum_a c_a \ln m_a^2 \). This \( M \) plays the role of the UV scale of ignorance thenceforth.

Notice that this is perfectly consistent with our other two one-loop PV calculations: in those, the extra PV electrons never get a chance to run. At higher loops, we would have to make sure to be consistent.

**Dimensional regularization.** A regulator which is more automatically gauge invariant is dimensional regularization (dim reg). I have already been writing many of the integrals in \( D \) dimensions. One small difference when we are considering this as a regulator for an integral of fixed dimension is that we don’t want to violate dimensional analysis, so we should really replace

\[
\int d^4 \ell \quad \longrightarrow \quad \int d^{4-\epsilon} \ell \frac{\ell^\epsilon}{\bar{\mu}^{-\epsilon}}
\]

where \( D = 4 - \epsilon \) and \( \bar{\mu} \) is an arbitrary mass scale which will appear in the regulated answers, which we put here to preserve dim’l analysis – *i.e.* the couplings in dim reg will have the same engineering dimensions they had in the unregulated theory (dimensionless couplings remain dimensionless). \( \bar{\mu} \) will parametrize our RG, *i.e.* play the role of the RG scale. (It is often called \( \mu \) at this step and then suddenly replaced by something also called \( \mu \); I will instead call this \( \bar{\mu} \) and relate it to the thing that ends up being called \( \mu \).)

[Zinn-Justin 4th ed page 233] Dimensionally regularized integrals can be defined systematically with a few axioms indicating how the \( D \)-dimensional integrals behave under

1. translations \( \int d^D p f(p + q) = \int d^D p f(p) \)

\[^{19}\text{Note that this rule fails for the euclidean momentum cutoff. Also note that this is the property we needed to demonstrate the Ward identity for the vertex correction using (1.54).}\]
2. scaling \( \int d^D p f(s p) = |s|^{-D} \int d^D p f(p) \)

3. factorization \( \int d^D p \int d^D q f(p) g(q) = \int d^D p f(p) \int d^D q g(q) \)

The (obvious?) third axiom implies the following formula for the sphere volume as a continuous function of \( D \):

\[
(\frac{\pi}{a})^{D/2} = \int d^D x e^{-ax^2} = \Omega_{D-1} \int_0^\infty x^{D-1} dx e^{-ax^2} = \frac{1}{2} a^{\frac{D}{2}} \Gamma \left( \frac{D}{2} \right) \Omega_{D-1} .
\]  

(1.58)

This defines \( \Omega_{D-1} \) for general \( D \).

In dim reg, the one-loop vacuum polarization correction \textit{does} satisfy the gauge-invariance Ward identity \( \Pi^{\mu\nu} = \Delta^{\mu\nu} q^2 \Pi_2(q^2) \). A peek at the tables of dim reg integrals shows that \( \Pi_2 \) is:

\[
\Pi_2(q^2)_{\text{Peskin p. 252}} = -\frac{8e^2}{(4\pi)^{D/2}} \int_0^1 dx x(1-x) \frac{\Gamma(2-\frac{D}{2})}{\Delta^{2-D/2}} \bar{\mu}^\epsilon
\]

\[
D \rightarrow 4 \quad -\frac{e^2}{2\pi^2} \int_0^1 dx x(1-x) \left( \frac{2}{\epsilon} - \log \left( \frac{\Delta}{\mu^2} \right) \right)
\]

(1.59)

where we have introduced the heralded \( \mu \):

\[
\mu^2 \equiv 4\pi\mu^2 e^{-\gamma_E}
\]

where \( \gamma_E \) is the Euler-Mascheroni constant, which appears in the Taylor expansion of the Euler gamma function; we define \( \mu \) in this way so that, like Rosencrantz and Guildenstern in Hamlet, \( \gamma_E \) both appears and disappears from the discussion in this one scene.

In the second line of (1.59), we expanded the \( \Gamma \)-function about \( D = 4 \). Notice that what was a log divergence, becomes a \( \frac{1}{\epsilon} \) pole in dim reg. There are other singularities of this function at other integer dimensions. It is an interesting question to ponder why the integrals have such nice behavior as a function of \( D \). That is: they only have simple poles. A partial answer is that in order to have worse (\textit{e.g.} essential) singularities at some \( D \), the perturbative field theory would have to somehow fail to make sense at larger \( D \).

Now we are in a position to choose a renormalization condition (also known as a \textit{renormalization scheme}), which will specify how much of the finite bit of \( \Pi \) gets subtracted by the counterterm. One possibility is to demand that the photon propagator is not corrected at \( q = 0 \), \textit{i.e.} demand \( Z_\gamma = 1 \). Then the resulting one-loop shift is

\[
\delta \Pi_2(q^2) \equiv \Pi_2(q^2) - \Pi_2(0) = \frac{e^2}{2\pi^2} \int_0^1 dx x(1-x) \log \left( \frac{m^2 - x(1-x)q^2}{m^2} \right).
\]
We’ll use this choice below.

Another popular choice, about which more later, is called the $\overline{\text{MS}}$ scheme, in which $\Pi$ is defined by the rule that we subtract the $1/\epsilon$ pole. This means that the counterterm is

$$\delta^{(\overline{\text{MS}})}_{\Pi_2} = -\frac{e^2}{2\pi^2} \frac{2}{\epsilon} \int_0^1 dx x (1 - x).$$

(Confession: I don’t know how to state this in terms of a simple renormalization condition on $\Pi_2$. Also: the bar in $\overline{\text{MS}}$ refers to the (not so important) distinction between $\bar{\mu}$ and $\mu$.) The resulting vacuum polarization function is

$$\delta\Pi^{(\overline{\text{MS}})}_2(q^2) = \frac{e^2}{2\pi^2} \int_0^1 dx x (1 - x) \log \left( \frac{m^2 - x(1-x)q^2}{\mu^2} \right).$$

1.8.2 Physics from vacuum polarization

One class of physical effects of vacuum polarization arise from attaching the corrected photon propagator to a static delta-function charge source. The resulting effective Coulomb potential is the fourier transform of

$$\tilde{V}(q) = \frac{1}{q^2} e^2 \frac{2}{1 - \Pi(q^2)} \equiv \frac{e^2_{\text{eff}}(q)}{q^2}. \quad (1.60)$$

This has consequences in both IR and UV.

**IR:** In the IR ($q^2 \ll m^2$), it affects the spectra of atoms. The leading correction is

$$\delta\Pi_2(q) = \frac{e^2}{2\pi^2} \int dx x (1-x) \ln \left( 1 - \frac{q^2}{m^2} x(1-x) \right) \approx \frac{e^2}{2\pi^2} \int dx x (1-x) \left( -\frac{q^2}{m^2} x(1-x) \right) = -\frac{q^2}{60\pi^2 m^2}$$

which means

$$\tilde{V}(q) \underset{q^2 \ll m^2}{\approx} \frac{e^2}{q^2} + \frac{e^4}{q^2} \left( -\frac{q^2}{30m^2} \right) + \cdots$$

and hence

$$V(r) = -\frac{e^2}{4\pi r^2} - \frac{e^4}{60\pi^2 m^2} \delta(r) + \cdots \equiv V + \Delta V.$$

This shifts the energy levels of hydrogen $s$-orbitals (the ones with support at the origin) by $\Delta E_s = \langle s|\Delta V|s \rangle$ which contributes to lowering the $2S$ state relative to the $2P$ state (the Lamb shift).
This delta function is actually a long-wavelength approximation to what is called the Uehling potential; its actual range is \( 1/m_e \), which is the scale on which \( \Pi_2 \) varies. The delta function approximation is a good idea for atomic physics, since \( \frac{1}{m_e} \ll a_0 = \frac{1}{\alpha m_e} \), the Bohr radius. See Schwartz p. 311 for a bit more on this.

**UV:** In the UV limit \( (q^2 \gg m^2) \), we can approximate \( \ln \left( 1 - \frac{q^2}{m^2} x(1-x) \right) \simeq \ln \left( -\frac{q^2}{m^2} \right) \) to get\(^{20}\)

\[
\Pi_2(q^2) = \frac{e^2}{2\pi^2} \int_0^1 dx x(1-x) \ln \left( 1 - \frac{q^2}{m^2} x(1-x) \right) \simeq \frac{e^2}{2\pi^2} \int_0^1 dx x(1-x) \ln \left( -\frac{q^2}{m^2} \right) = \frac{e^2}{12\pi^2} \ln \left( -\frac{q^2}{m^2} \right).
\]

Therefore, the effective charge in (1.60) at high momentum exchange is

\[
e_{eff}(q^2) \simeq \frac{e^2}{1 - \frac{e^2}{12\pi^2} \ln \left( -\frac{q^2}{m^2} \right)}. \tag{1.61}
\]

(Remember that \( q^2 < 0 \) for t-channel exchange, as in the static potential, so the argument of the log is positive and this is real.)

Two things: if we make \( q^2 \) big enough, we can make the loop correction as big as the 1. This requires \( |q| \sim 10^{286} \text{ eV} \). Good luck with that. This is called a Landau pole. The second thing is: this perspective of a scale-dependent coupling is very valuable, and is a crucial ingredient in the renormalization group. The value \( \alpha = \frac{1}{137} \) is the extreme IR value, for \( q \ll m_e \).

\(^{20}\)The last step is safe since the \( x(1-x) \) suppresses the contributions of the endpoints of the \( x \) integral, so we can treat \( x(1-x) \) as finite.

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2 Consequences of Unitarity

3 Wilsonian perspective on renormalization

4 Gauge theory

5 Effective field theory