Chapter 1: The Physical Problem of Light and Matter

Quantum electrodynamics begins with a familiar world: charged particles attract or repel, light travels, atoms emit spectral lines, and matter responds to electromagnetic fields. Its difficulty is not that these phenomena are exotic. Its difficulty is that they sit at the intersection of three principles that cannot be consistently combined by ordinary nonrelativistic quantum mechanics alone:

1. Quantum mechanics: energy, momentum, angular momentum, and measurement outcomes are represented probabilistically by quantum states and operators.
2. Special relativity: no inertial frame is physically preferred, and signals cannot propagate faster than light.
3. Electromagnetism: electric charge produces and responds to electromagnetic fields, whose classical dynamics are described by Maxwell’s theory (Maxwell 1873).

Quantum electrodynamics, or QED, is the quantum field theory that results when these three demands are made simultaneously. In its standard form it describes the interaction of the Dirac field, whose quanta are electrons and positrons, with the electromagnetic field, whose quanta are photons. The word quantum field is important. A field assigns physical degrees of freedom to every point of spacetime; a quantum field is a field whose excitations behave as particles and whose measurable predictions are governed by quantum probability amplitudes.

At the end of this chapter, the goal is not yet to compute a scattering cross section or a loop correction. The goal is to understand the problem QED solves and the principles that make the theory so constrained: Lorentz invariance, gauge symmetry, locality, unitarity, and the operational meaning of measurement.

1.1 The starting point: classical light and charged matter

Classically, electromagnetism is described by electric and magnetic fields, usually denoted

$$\mathbf{E}(t, \mathbf{x}), \qquad \mathbf{B}(t, \mathbf{x}).$$

These fields exert forces on a particle of charge q. In relativistic notation, the electromagnetic field is packaged into the antisymmetric tensor

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu,$$

where Aμ is the electromagnetic four-potential. The index μ runs over spacetime components 0,1,2,3, and ∂μ denotes differentiation with respect to spacetime coordinates.

The potential Aμ is not itself unique. The same electromagnetic fields are obtained if we transform

$$A_\mu(x) \longrightarrow A_\mu(x) + \partial_\mu \alpha(x),$$

where α(x) is any sufficiently smooth function of spacetime. This non-uniqueness is called gauge redundancy. It is not an ordinary physical symmetry relating two different physical states; rather, it is a redundancy in our description. Many mathematical representatives correspond to the same physical electromagnetic field.

A useful analogy is a map with coordinates. The same city can be described using different coordinate systems. The coordinates may change, but the streets do not. Similarly, the potential Aμ may change under a gauge transformation, while the physical fields E and B, or equivalently $F_{(\mu\text{nu})}$, remain unchanged.

The classical electromagnetic field has its own dynamics. In modern relativistic form, the free electromagnetic field is described by the Lagrangian density

$$\mathcal{L}_{\text{EM}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}.$$

A Lagrangian density is a function of fields and their derivatives from which equations of motion are derived by the principle of stationary action. This formulation will become central in later chapters because quantum field theory is most naturally organized through Lagrangians and symmetries.

Classical electrodynamics is already relativistic. Maxwell’s equations imply electromagnetic waves moving at a fixed speed, and Einstein’s special relativity clarified that this speed is the invariant speed c shared by all inertial observers (Einstein 1905a). In units commonly used in QED, we set

$$\hbar = c = 1.$$

This is not a physical assumption. It is a choice of units. Setting c=1 measures time and distance in compatible units, and setting hbar=1 measures action as dimensionless.

1.2 The quantum problem appears

Classical electromagnetism treats light as a wave. Yet several phenomena require a quantum description of radiation and matter. Planck's treatment of black-body radiation introduced energy quantization in the context of thermal radiation (Planck 1901). Einstein then argued that light itself behaves in interactions as if it consists of localized quanta of energy, now called photons, in his explanation of the photoelectric effect (Einstein 1905b). Compton scattering later gave direct evidence that X-rays exchange energy and momentum with electrons in a particle-like way (Compton 1923).

A photon is the quantum excitation of the electromagnetic field. This statement is more precise than saying “light is made of particles” in a classical sense. A photon is not a tiny billiard ball moving along a definite trajectory. It is an excitation of a quantum field, and its observed particle-like behavior appears in events such as absorption, emission, and scattering.

Matter also becomes problematic if treated as a fixed number of particles. In nonrelativistic quantum mechanics, one often begins with a wavefunction

$$\psi(\mathbf{x}, t)$$

for one particle, or

$$\psi(\mathbf{x}_1, \ldots, \mathbf{x}_N, t)$$

for N particles. But special relativity allows energy to be converted into particle-antiparticle pairs. A sufficiently energetic photon near a nucleus can produce an electron and a positron. Conversely, an electron and positron can annihilate into photons. Therefore, a relativistic theory of charged matter cannot keep the number of particles fixed.

This is one of the deepest reasons QED must be a field theory. Fields can create and destroy quanta. A quantum field theory has a state space large enough to include

$$|e^-\rangle, \qquad |e^-e^+\rangle, \qquad |e^-e^+\gamma\rangle, \qquad |2\gamma\rangle,$$

and many other possibilities. Here e^- denotes an electron, e^+ a positron, and γ a photon.

Dirac's relativistic equation for the electron successfully incorporated spin-frac12 and led naturally to the interpretation of antiparticles (Dirac 1928). The positron was later observed experimentally by Anderson (Anderson 1933). In QED, the electron and positron are not described by unrelated fields. They are particle and antiparticle excitations of the same Dirac field.

1.3 What QED must explain

QED is not merely a formal construction. It is built to explain measured phenomena involving light and electrically charged matter. Its empirical targets include both qualitative facts and extremely precise numerical predictions.

One basic target is scattering. In a scattering experiment, particles are prepared far apart in an initial state, allowed to interact, and then detected far apart in a final state. Examples include

$$e^-\mu^- \to e^-\mu^-,$$

electron-muon scattering,

$$e^-e^+ \to \gamma\gamma,$$

electron-positron annihilation, and

$$e^-\gamma \to e^-\gamma,$$

Compton scattering.

A second target is atomic structure. At leading order, the electromagnetic attraction between an electron and a proton produces the Coulomb potential and explains the broad structure of hydrogen-like atoms. But more refined measurements reveal smaller effects: fine structure, hyperfine structure, and radiative shifts. The Lamb shift, observed by Lamb and Retherford, showed that levels predicted to be degenerate by the simplest Dirac-Coulomb analysis are actually separated (Lamb and Retherford 1947). QED explains such shifts through the interaction of the electron with quantized electromagnetic fluctuations.

A third target is the magnetic moment of the electron. A charged spinning particle behaves partly like a tiny magnet. The Dirac equation predicts a gyromagnetic factor g=2 for a pointlike spin-frac12 charged particle at tree level. QED predicts a small correction, called the anomalous magnetic moment,

$$a_e = \frac{g-2}{2}.$$

Schwinger's famous leading-order result is

$$a_e = \frac{\alpha}{2\pi} + \cdots ,$$

where

$$\alpha = \frac{e^2}{4\pi}$$

in natural Heaviside-Lorentz units is the fine-structure constant (Schwinger 1948). The dots represent higher-order quantum corrections. This is one of the earliest and most celebrated examples of a radiative correction: a contribution caused by virtual quantum processes not present in the simplest classical or tree-level picture.

These examples already show the scope of QED. It is a theory of scattering, spectra, radiation, pair creation, annihilation, and precision measurement. The modern perturbative framework used to compute these phenomena was developed in covariant form by Tomonaga, Schwinger, Feynman, and Dyson, with Feynman diagrams becoming one of the central calculational languages of the subject (Feynman 1949; Dyson 1949).

1.4 The basic fields of QED

The minimal QED Lagrangian for electrons, positrons, and photons is

$$\mathcal{L}_{\text{QED}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi.$$

This expression contains much of the book in compressed form. Let us unpack only the essential meanings for now.

The symbol ψ(x) is the Dirac field. It is not an ordinary complex scalar function; it has spinor components. A spinor is an object that transforms under Lorentz transformations in the way appropriate for spin-frac12 particles. The conjugate field is

$$\bar{\psi} = \psi^\dagger\gamma^0.$$

The matrices γ^μ, called gamma matrices, encode the relativistic spinor structure and satisfy the Clifford algebra

$$\{\gamma^\mu, \gamma^\nu\} = 2\eta^{\mu\nu}.$$

Here A,B\=AB+BA is the anticommutator, and η⁽μnu⁾ is the Minkowski metric.

The symbol Dμ is the gauge-covariant derivative,

$$D_\mu = \partial_\mu + ieA_\mu.$$

It replaces the ordinary derivative ∂μ when a charged field interacts with the electromagnetic potential. The parameter e is the magnitude of the electron charge in the convention where the electron has charge -e or e depending on the sign convention used for the field transformation. What matters physically is the coupling strength, measured by α.

The QED interaction is contained in the term

$$\bar{\psi}i\gamma^\mu(ieA_\mu)\psi = -e\bar{\psi}\gamma^\mu A_\mu\psi$$

up to sign conventions. This term says that the electromagnetic field couples to the Dirac current

$$j^\mu = \bar{\psi}\gamma^\mu\psi.$$

In words: charged matter acts as a source for the electromagnetic field, and the electromagnetic field acts on charged matter.

This is the simplest possible local coupling between a spin-frac12 charged field and the electromagnetic field that respects Lorentz invariance and gauge symmetry. Later chapters will derive this statement carefully rather than assume it.

1.5 Lorentz invariance: no preferred inertial observer

A physical law is Lorentz invariant if it has the same form in every inertial frame related by a Lorentz transformation. A Lorentz transformation is a change of spacetime coordinates that preserves the spacetime interval

$$s^2 = t^2 - \mathbf{x}^2$$

in units where c=1, up to the sign convention for the metric.

This principle is not optional in relativistic quantum theory. If two laboratories move at constant velocity relative to one another, they may assign different energies and momenta to the same process, but they must agree on invariant physical predictions such as total probabilities, decay rates expressed appropriately, and cross sections.

For example, consider electron-muon scattering,

$$e^-(p_1) + \mu^-(p_2) \to e^-(p_3) + \mu^-(p_4).$$

The four-momenta p_i^μ depend on the observer’s frame. But the amplitude can be written in terms of Lorentz-invariant combinations such as

$$s = (p_1 + p_2)^2, \qquad t = (p_1 - p_3)^2, \qquad u = (p_1 - p_4)^2.$$

These are called Mandelstam variables. They will become standard tools in scattering calculations.

Lorentz invariance is also restrictive. It controls what kinds of terms may appear in the Lagrangian. A term such as

$$\bar{\psi}\psi$$

is a Lorentz scalar and may appear as a mass term. A term with an uncontracted spacetime index would not be Lorentz invariant unless it is paired with another object carrying the matching index.

In quantum field theory, Lorentz invariance is tied to the structure of particles themselves. Particles are classified by mass and spin through the representations of the Poincaré group, the group of spacetime translations and Lorentz transformations. This classification is one of the conceptual foundations of relativistic quantum theory (Weinberg 1995).

1.6 Gauge symmetry: redundancy with consequences

Gauge symmetry is often introduced with the phrase “local phase invariance.” Let us build that slowly.

In ordinary quantum mechanics, multiplying a state vector by a constant phase,

$$|\psi\rangle \to e^{i\theta}|\psi\rangle,$$

does not change measurement probabilities. A phase is an angle appearing in a complex exponential. Probabilities depend on squared magnitudes, so an overall constant phase is not observable.

For a charged field, QED allows a stronger statement: the phase may depend on spacetime,

$$\psi(x) \to e^{ie\alpha(x)}\psi(x).$$

This is called a local U(1) transformation. The group U(1) is the group of complex phases of unit magnitude. The word “local” means the transformation can vary from point to point.

If we used only the ordinary derivative ∂μ, the derivative of the transformed field would produce an extra term involving ∂μα(x). The covariant derivative

$$D_\mu = \partial_\mu + ieA_\mu$$

is designed so that, together with

$$A_\mu(x) \to A_\mu(x) - \partial_\mu \alpha(x),$$

it transforms in the same way as the field itself:

$$D_\mu \psi(x) \to e^{ie\alpha(x)} D_\mu \psi(x).$$

This is the mathematical core of minimal coupling.

Gauge symmetry has two distinct roles that should not be confused.

First, it is a redundancy. Different potentials Aμ can represent the same electromagnetic field $F_{(\mu nu)}$. We must not count gauge-equivalent configurations as different physical states.

Second, it is a constraint on interactions. Once the charged matter field transforms locally, the derivative must become covariant, and the photon field must couple to the conserved electromagnetic current.

A famous reminder that potentials are not merely decorative is the Aharonov-Bohm effect: quantum phases can depend on electromagnetic potentials in regions where the magnetic field vanishes locally, provided the spacetime region has nontrivial global structure (Aharonov and Bohm 1959). This does not mean gauge redundancy is physically observable. It means that gauge-invariant information can be encoded in the potential through quantities such as loop integrals or Wilson phases.

A useful warning is this: gauge-dependent quantities are not directly observable. A photon propagator, for example, depends on the gauge choice. A properly computed cross section does not.

1.7 Locality: interactions happen at spacetime points

A theory is local if interactions are built from fields evaluated at the same spacetime point, or from limits of such expressions. The QED interaction density

$$\mathcal{L}_{\text{int}} = -e\bar{\psi}(x)\gamma^{\mu}A_{\mu}(x)\psi(x)$$

is local because all fields appear at the same point x.

Locality is a physical and mathematical principle. Physically, it reflects the idea that a disturbance cannot act instantaneously at arbitrary distance. Mathematically, relativistic quantum field theory implements this through microcausality: observables associated with spacelike separated regions must commute, so measurements in regions that cannot causally influence one another do not interfere with each other’s outcome statistics. This principle is part of the standard structural framework of relativistic quantum field theory (Weinberg 1995).

A spacelike separation means that two events are separated more by space than by time:

$$(x-y)^2 < 0$$

in the metric convention $x^2=t^2-x^2$. No signal traveling at or below the speed of light can connect such events.

For example, suppose one detector measures an electron-related observable in one laboratory region, and another detector measures a photon-related observable in a spacelike separated region. Relativistic causality demands that the order in which different observers describe those measurements cannot affect the joint physical predictions. Microcausality is the field-theoretic expression of that demand.

Locality also explains why QED interactions are represented by vertices in Feynman diagrams. A vertex is not literally a tiny classical collision point in spacetime, but it encodes a local factor in the interaction Lagrangian. In QED, the basic vertex connects one photon line with two charged fermion lines: an electron can emit or absorb a photon, and the same vertex also represents related processes involving positrons when interpreted with the rules of relativistic quantum theory.

1.8 Unitarity: probabilities must add to one

Quantum theory predicts probabilities. A theory is physically acceptable only if total probability is conserved. The mathematical word for this is unitarity.

If a state evolves from an initial time to a final time by an operator U, unitarity means

$$U^\dagger U = 1.$$

This condition preserves inner products and therefore preserves total probability.

In scattering theory, the central object is the S-matrix, where S stands for scattering. It maps asymptotic incoming states to asymptotic outgoing states:

$$|\text{out}\rangle = S|\text{in}\rangle.$$

“Asymptotic” means very far in the past or future, when particles are separated enough that they can be treated as free for the purpose of defining initial and final states. The S-matrix program became central in the covariant formulation of QED and perturbative quantum field theory (Feynman 1949; Dyson 1949).

Unitarity of the S-matrix means

$$S^\dagger S = 1.$$

This statement has powerful consequences. It relates the imaginary part of forward scattering amplitudes to sums over physical intermediate states, a relation known broadly as the optical theorem. In practical terms, unitarity is one reason loop corrections and real emission processes cannot be considered independently when they contribute at the same order.

For example, in electron scattering, a virtual photon loop may contribute to an amplitude. But at the same order in the coupling, the experiment may also allow emission of a soft real photon that escapes detection. If the detector cannot distinguish

$$e^- \mu^- \to e^- \mu^-$$

from

$$e^-\mu^- \to e^-\mu^-\gamma_{\text{soft}},$$

then the physically measured probability must include both. This is not a technical nuisance; it is part of what measurement means in a theory with massless photons. Bloch and Nordsieck showed early on that soft radiation is essential for obtaining physically meaningful infrared behavior in QED (Bloch and Nordsieck 1937).

1.9 Measurement: QED predicts events, not hidden diagrams

A Feynman diagram is a calculational tool. It is not, by itself, a directly observed event. A detector records tracks, energy deposits, timing signals, angular distributions, and counting rates. QED connects the Lagrangian to these observations through probabilities and cross sections.

A cross section measures the effective area for a scattering process. If a beam of particles hits a target, the cross section tells us how likely a given process is, normalized by the incoming flux. Differential cross sections, such as

$$\frac{d\sigma}{d\Omega},$$

describe how scattering probability is distributed over directions.

A decay rate measures the probability per unit time that an unstable state decays into specified final states. Although the electron is stable in QED because charge and energy conservation forbid its decay into lighter charged states, other systems studied with QED methods can decay electromagnetically.

A measurement resolution is the finite precision with which an apparatus distinguishes energies, angles, and particle multiplicities. This matters deeply in QED. Because photons are massless, arbitrarily low-energy photons can be emitted with very little energy cost. A real detector has an energy threshold below which it cannot register photons. Therefore, an actually measured process is usually inclusive over unobserved soft radiation.

For example, when an experiment reports elastic electron scattering, it may really count all events of the form

$$e^- + X \to e^- + X + n\gamma_{\mathrm{soft}},$$

where X is a target and n is any number of photons below the detection threshold. QED must predict such inclusive quantities if it is to match real measurements.

This measurement perspective will become essential when we study infrared divergences. A divergence in an unphysical, perfectly exclusive probability does not necessarily mean the theory is wrong. It may mean the question asked was not experimentally meaningful.

1.10 The hierarchy of descriptions

QED sits between simpler and broader theories.

At low velocities and weak fields, QED reduces to familiar nonrelativistic quantum mechanics with electromagnetic interactions. For example, the Coulomb potential

$$V(r) = -\frac{Z\alpha}{r}$$

is the leading interaction between an electron and a nucleus of charge +Ze. Solving the Schrödinger equation with this potential gives the leading spectrum of hydrogen-like atoms.

At higher precision, relativistic and quantum field effects appear: spin-orbit coupling, Darwin terms, vacuum polarization, self-energy, and radiative corrections. These are not optional decorations; they are required to match high-resolution spectroscopy such as the Lamb shift (Lamb and Retherford 1947).

At still higher energies, QED is embedded in the electroweak sector of the Standard Model. The photon is related to the electroweak gauge fields after symmetry breaking. This book will mostly treat QED as its own theory, but later chapters will return to the modern viewpoint that QED is also an effective low-energy description.

A hierarchy of descriptions means that different theories can be valid at different scales while agreeing where their domains overlap. Newtonian mechanics is not useless because relativity exists; it is an approximation in a certain regime. Similarly, the Schrödinger-Coulomb description of hydrogen is not false; it is the leading approximation to a richer QED description.

1.11 What is actually small in QED?

Perturbative QED works because many processes can be expanded in powers of the fine-structure constant

$$\alpha \approx \frac{1}{137}.$$

A perturbative expansion is an approximation method in which a quantity is written as a series in a small parameter:

$$\mathcal{A} = \mathcal{A}_0 + \alpha\mathcal{A}_1 + \alpha^2\mathcal{A}_2 + \cdots .$$

Here $\mathcal{A}$ may be a scattering amplitude or another observable quantity. The leading term gives the first approximation, and higher powers give corrections.

However, the smallness of α does not make every QED problem easy. Several complications remain:

- Loop integrals can be ultraviolet divergent and require renormalization.
- Massless photons produce infrared sensitivity.
- Bound states require methods beyond ordinary scattering perturbation theory.
- Strong external fields can invalidate simple expansions in photon exchange.
- Very high orders may involve many diagrams and subtle cancellations.

Thus QED is both simple and difficult. Its Lagrangian is compact, but its consequences are deep.

1.12 A first picture of the QED vertex

The interaction term

$$-e\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

contains the basic process: charged matter emits or absorbs a photon. In Feynman diagram language, this is represented by a vertex connecting two fermion lines and one photon line.

At first glance, one might say:

> An electron emits a photon.

But the full field-theoretic meaning is broader. The same vertex contributes to several related processes:

$$e^{-} \to e^{-} + \gamma,$$

$$e^{+} + \gamma \to e^{+},$$

$$e^{-} + e^{+} \to \gamma,$$

and many others, depending on which lines are interpreted as incoming or outgoing particles. In actual free space, some of these simple one-vertex processes may be forbidden by energy-momentum conservation for on-shell particles. For example, a free electron cannot emit a single real photon and remain a free on-shell electron while conserving four-momentum. But the vertex still appears inside larger allowed processes, such as scattering in an external field or emission during acceleration.

The phrase on shell means that a particle's energy and momentum satisfy its physical mass relation:

$$p^2 = m^2$$

for a massive particle in the metric convention $p^2=E^2-p^2$. A virtual particle is an internal line in a perturbative diagram whose momentum generally does not satisfy this relation. Virtual particles are not directly detected particles; they are elements of the mathematical expansion used to compute amplitudes.

This distinction prevents a common misconception. A virtual photon exchanged between two electrons is not a tiny observed object flying between them. It is part of the internal bookkeeping of a quantum amplitude. The observable result is the scattering probability.

1.13 The five guiding principles

We can now state the chapter's central organizing principles.

Lorentz invariance means the theory respects the spacetime structure of special relativity. Predictions cannot depend on a preferred inertial frame.

Gauge symmetry means the electromagnetic potential contains redundancy, and physical quantities must be invariant under local phase transformations. It also fixes the form of the coupling between charged matter and the photon field.

Locality means the fundamental interactions are built from fields at the same spacetime point, consistent with relativistic causality.

Unitarity means total probability is conserved. In scattering language, the S-matrix must be unitary.

Measurement means QED must ultimately predict detector-level probabilities, cross sections, decay rates, and spectra, not merely formal amplitudes or individual diagrams.

These principles are mutually reinforcing. Gauge symmetry removes unphysical photon polarizations. Lorentz invariance organizes spin and momentum. Locality makes causal propagation possible. Unitarity makes probabilities meaningful. Measurement tells us which theoretical quantities correspond to experiments.

The rest of the book develops these ideas in increasing technical detail. We will begin by examining relativistic wave equations and why they force us beyond fixed-particle-number quantum mechanics. Then we will build classical field theory, quantize free fields, construct QED, derive Feynman rules, compute scattering processes, and confront loops, divergences, renormalization, and precision tests.

QED is therefore not just a theory of electrons and photons. It is a model example of how modern physics turns symmetry, locality, and measurement into numerical predictions.

1.14 Chapter checkpoint

Before moving on, you should be able to explain the following in your own words:

1. Why relativistic quantum theory requires fields rather than a fixed number of particles.
2. What it means for the photon to be a quantum of the electromagnetic field.
3. Why gauge transformations describe redundancy rather than ordinary physical change.
4. How Lorentz invariance constrains the form of physical laws.
5. Why locality is connected to relativistic causality.
6. What unitarity means for probabilities and scattering.
7. Why real measurements in QED often require inclusive descriptions involving unobserved soft photons.
8. How the compact QED Lagrangian encodes electrons, positrons, photons, and their interaction.

If these points are clear, you are ready to study why relativistic single-particle quantum mechanics is not enough.

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