

Chapter 1

Theory

1.1 Classical Electrodynamics

Introduction stuff, cite Eisenberg and Greiner (1978) and Jackson (1999).

We will begin with Maxwell's equations in free space

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \quad (1.1a)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (1.1b)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (1.1c)$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}, \quad (1.1d)$$

which relate the electromagnetic field to sources, which must satisfy an additional equation to ensure charge conservation

$$\nabla \cdot \mathbf{j}(\mathbf{r}, t) + \frac{\partial \rho(\mathbf{r}, t)}{\partial t} = 0. \quad (1.2)$$

As we can see above, equations (1.1c) and (1.1b) do not involve sources and thus they state the dynamical properties of the fields. Since equations (1.1a) and (1.1d) describe how the sources influence the fields, we need an additional equation to describe how the fields affect the sources

$$\mathbf{F} = \int d\mathbf{r}' \rho(\mathbf{r}', t) \mathbf{E}(\mathbf{r}', t) + \frac{1}{c} \int d\mathbf{r}' \mathbf{j}(\mathbf{r}', t) \times \mathbf{B}(\mathbf{r}', t).$$

Maxwell's equations (1.1) relate six field quantities (\mathbf{E} and \mathbf{B}) to four source quantities (ρ and \mathbf{j}). This implies that there are some restrictions on the six quantities. This suggests that we can find a less redundant way to express the fields, and indeed the four quantities given by the vector potential \mathbf{A} and scalar potential ϕ provide this representation. Equation (1.1b) implies the existence of a vector potential

$$\mathbf{B}(\mathbf{r}, t) = \nabla \times \mathbf{A}(\mathbf{r}, t). \quad (1.3)$$

Substituting (1.3) in (1.1c) we obtain

$$\nabla \times \left(\mathbf{E} + \frac{\partial \mathbf{A}}{\partial t} \right) = 0 \quad (1.4)$$

and thus the quantity in the paranthesis can always be expressed as the gradient of a scalar field, namely the scalar potential

$$\nabla \phi(\mathbf{r}, t) = -\mathbf{E}(\mathbf{r}, t) - \frac{\partial \mathbf{A}}{\partial t}.$$

With these considerations (1.1a) becomes

$$\nabla \cdot \left(\nabla \phi + \frac{\partial \mathbf{A}}{\partial t} \right) = -\frac{\rho}{\varepsilon_0}$$

or

$$\nabla^2 \phi + \frac{\partial}{\partial t} \nabla \cdot \mathbf{A} = -\frac{\rho}{\varepsilon_0} \quad (1.5)$$

and (1.1d)

$$\nabla \times (\nabla \times \mathbf{A}) = \mu_0 \mathbf{j} - \frac{1}{c^2} \frac{\partial}{\partial t} \left(\nabla \phi + \frac{\partial \mathbf{A}}{\partial t} \right). \quad (1.6)$$

Using the following vector identity

$$\nabla \times (\nabla \times \mathbf{A}) = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A} \quad (1.7)$$

eq. (1.6) becomes

$$\nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A} = \mu_0 \mathbf{j} - \frac{1}{c^2} \left(\nabla \frac{\partial \phi}{\partial t} + \frac{\partial^2 \mathbf{A}}{\partial t^2} \right)$$

or

$$\nabla^2 \mathbf{A} - \frac{1}{c^2} \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu_0 \mathbf{j} + \nabla \left(\nabla \cdot \mathbf{A} + \frac{1}{c^2} \frac{\partial \phi}{\partial t} \right). \quad (1.8)$$

Equations (1.5) and (1.8) were obtained by substituting the potentials obtained from the source-less equations, (1.1b) and (1.1c), into the ones with sources, (1.1a) and (1.1d). They are thus fully equivalent with Maxwell's equations (1.1) and, as we can observe, relate the four quantities given by the potentials to the four quantities for the sources. They also preserve the invariance under Lorentz transformations, with the scalar potential ϕ as the time-like component.

Equations (1.5) and (1.8) can be simplified by decoupling the potentials. This is possible due to the fact that potentials are not unique. To illustrate this point consider

$$\mathbf{A}'(\mathbf{r}, t) = \mathbf{A}(\mathbf{r}, t) + \nabla \Lambda(\mathbf{r}, t).$$

This vector potential gives rise to a magnetic field

$$\nabla \times \mathbf{A}' = \nabla \times \mathbf{A} + \nabla \times (\nabla \Lambda) = \nabla \times \mathbf{A} = \mathbf{B}$$

equal with the original one since $\nabla \times (\nabla \varphi) = 0$.

Similarly, for a scalar potential

$$\phi'(\mathbf{r}, t) = \phi(\mathbf{r}, t) - \frac{\partial \Lambda(\mathbf{r}, t)}{\partial t}$$

and the corresponding electric field will be

$$-\nabla \phi' - \frac{\partial \mathbf{A}'}{\partial t} = -\nabla \phi + \nabla \frac{\partial \Lambda}{\partial t} - \frac{\partial \mathbf{A}}{\partial t} - \frac{\partial}{\partial t} \nabla \Lambda = -\nabla \phi - \frac{\partial \mathbf{A}}{\partial t} = \mathbf{E},$$

since the spatial and temporal derivatives commute. These kinds of transformations are called gauge transformations.

1.1.1 Gauge transformations

The freedom of choosing the gauge leads to the following condition satisfied by the scalar and vector potentials

$$\nabla \cdot \mathbf{A} + \frac{1}{c^2} \frac{\partial \phi}{\partial t} = 0,$$

called the Lorenz condition.

Indeed, if we consider a set of potentials \mathbf{A} and ϕ that don't satisfy the condition

$$\nabla \cdot \mathbf{A} + \frac{1}{c^2} \frac{\partial \phi}{\partial t} \neq 0 = f(\mathbf{r}, t),$$

then we can always carry out a gauge transformation to a new set of potentials \mathbf{A}' and ϕ' that satisfy the Lorenz condition, such that

$$\begin{aligned} \nabla \cdot \mathbf{A} + \frac{1}{c^2} \frac{\partial \phi}{\partial t} &= \nabla \cdot (\mathbf{A}' - \nabla \Lambda) + \frac{1}{c^2} \frac{\partial}{\partial t} \left(\phi' + \frac{\partial \Lambda}{\partial t} \right) \\ &= \nabla \cdot \mathbf{A}' - \nabla^2 \Lambda + \frac{1}{c^2} \frac{\partial \phi'}{\partial t} + \frac{1}{c^2} \frac{\partial^2 \Lambda}{\partial t^2} = f(\mathbf{r}, t) \end{aligned}$$

or

$$\nabla \cdot \mathbf{A} + \frac{1}{c^2} \frac{\partial \phi}{\partial t} = \square \Lambda \equiv \frac{1}{c^2} \frac{\partial^2 \Lambda}{\partial t^2} - \nabla^2 \Lambda = f(\mathbf{r}, t),$$

where the d'Alembertian operator is defined as

$$\square \equiv \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2$$

when choosing the Minkowski metric $(+, -, -, -)$ and

$$\nabla \cdot \mathbf{A}' + \frac{1}{c^2} \frac{\partial \phi'}{\partial t} = 0,$$

since they satisfy the Lorenz condition. The transformation we need is thus defined by the solution of $\square \Lambda = f$.

Imposing the Lorenz condition on equations (1.5) and (1.4) decouples the potentials

$$\begin{aligned}\nabla^2 \phi - \frac{\partial}{\partial t} \frac{1}{c^2} \frac{\partial \phi}{\partial t} &= -\frac{\rho}{\varepsilon_0} \\ \nabla^2 \mathbf{A} - \frac{1}{c^2} \frac{\partial^2 \mathbf{A}}{\partial t^2} &= -\mu_0 \mathbf{j}\end{aligned}$$

yielding the simplified form of Maxwell's equations

$$\begin{aligned}\square \phi &= \frac{\rho}{\varepsilon_0} \\ \square \mathbf{A} &= \mu_0 \mathbf{j}.\end{aligned}$$

This form of Maxwell's equations preserves Lorentz invariance, as the Lorenz gauge condition can be expressed in a covariant way as the contraction of the four-vector $A \equiv (\frac{\phi}{c}, \mathbf{A})$ with the four-gradient $(\frac{1}{c} \frac{\partial}{\partial t}, -\nabla)$.

Since the Lorenz condition doesn't fix the gauge, but only restricts us to transformations with $\square \Lambda = 0$, we can impose further conditions in order to fix the gauge, but in general those will not be covariant. One such condition is given by the Coulomb gauge

$$\nabla \cdot \mathbf{A} = 0. \quad (1.9)$$

In this gauge eq. (1.5) becomes a Poisson equation for the scalar potential

$$\nabla^2 \phi = -\frac{\rho}{\varepsilon_0} \quad (1.10)$$

with the solution given by the instantaneous Coulomb potential of the charge density in the domain $\rho(\mathbf{r}, t)$

$$\phi(\mathbf{r}, t) = \frac{1}{4\pi\varepsilon_0} \int \frac{\rho(\mathbf{r}', t)}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}', \quad (1.11)$$

explaining the name of the condition (1.9).

An apparent violation of special relativity shows up in the above result which states that the scalar potential (at time t) is given by the instantaneous Coulomb interactions between charges (also at time t). The contradiction is only apparent and stems from the fact that the Coulomb gauge is not Lorentz invariant.

In order to resolve the contradiction we first note that we can only observe the electric field

$$\mathbf{E}(\mathbf{r}, t) = -\nabla \phi(\mathbf{r}, t) - \frac{\partial \mathbf{A}(\mathbf{r}, t)}{\partial t}.$$

Thus, the instantaneous propagation is removed by the time derivative of the vector potential.

In the Coulomb gauge, the vector potential is given by

$$\square \mathbf{A} = \mu_0 \mathbf{j} - \frac{1}{c^2} \nabla \frac{\partial \phi}{\partial t}. \quad (1.12)$$

Considering the continuity equation (1.2) and the form of the scalar potential in eq. (1.11), the second term in eq. (1.12) becomes

$$\nabla \frac{\partial \phi}{\partial t} = \nabla \frac{1}{4\pi\epsilon_0} \int \frac{\frac{\partial \rho}{\partial t}}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}' = -\frac{1}{4\pi\epsilon_0} \nabla \int \frac{\nabla' \cdot \mathbf{j}(\mathbf{r}', t)}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}', \quad (1.13)$$

where ∇' denotes the derivatives with respect to \mathbf{r}' . Using the Helmholtz decomposition we can write any sufficiently well behaved vector (the current density in this particular case) as the sum of a divergence-free (transversal) component and a curl-free (longitudinal) one:

$$\mathbf{j} = \mathbf{j}^t + \mathbf{j}^l,$$

where

$$\begin{aligned} \nabla \cdot \mathbf{j}^t &= 0 \\ \nabla \times \mathbf{j}^l &= 0. \end{aligned}$$

Using the vector identity (1.7) and

$$\nabla^2 \frac{1}{|\mathbf{r} - \mathbf{r}'|} = -4\pi\delta(\mathbf{r} - \mathbf{r}')$$

we can write the current density as follows

$$\begin{aligned} \nabla^2(\mathbf{j}^t + \mathbf{j}^l) &= \nabla(\nabla \cdot \mathbf{j}^l) - \nabla \times (\nabla \times \mathbf{j}^t) \\ \int \frac{\nabla^2 \mathbf{j}}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r} &= \int \frac{\nabla(\nabla \cdot \mathbf{j}^l)}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}' - \int \frac{\nabla \times (\nabla \times \mathbf{j}^t)}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}' \\ -4\pi\mathbf{j} &= \nabla \int \frac{\nabla \cdot \mathbf{j}^l}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}' - \nabla \times \nabla \times \int \frac{\mathbf{j}^t}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}' \end{aligned}$$

and thus we obtain the two components as

$$\begin{aligned} \mathbf{j}^t &= \frac{1}{4\pi} \nabla \times \nabla \times \int \frac{\mathbf{j}(\mathbf{r}', t)}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}' \\ \mathbf{j}^l &= -\frac{1}{4\pi} \nabla \int \frac{\nabla' \cdot \mathbf{j}(\mathbf{r}', t)}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}'. \end{aligned}$$

Comparing with (1.13) we see that

$$\frac{1}{c^2} \nabla \frac{\partial \phi}{\partial t} = \frac{\epsilon_0}{c^2} \mathbf{j}^l = \mu_0 \mathbf{j}^l$$

and thus the source term in eq. (1.12) can be expressed as function of the transverse current:

$$\square \mathbf{A} = \mu_0(\mathbf{j} - \mathbf{j}^l) = \mu_0 \mathbf{j}^t$$

and this also why the Coulomb gauge is also called the transverse gauge. This gauge is useful when no sources are present. In this case $\phi = 0$, \mathbf{A} satisfies the

homogeneous wave equation and the fields can be expressed only as function of the vector potential

$$\begin{aligned}\mathbf{E} &= -\frac{\partial \mathbf{A}}{\partial t} \\ \mathbf{B} &= \nabla \times \mathbf{A} .\end{aligned}$$

1.1.2 The Poynting theorem

In order to complete the description of the interaction between fields and sources, we will now focus on how the fields affect the particles. We begin by considering the force acting on a charge q

$$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B} .$$

The corresponding infinitesimal variation of the force is given by

$$\delta \mathbf{F} = \rho \mathbf{E} \delta V + \mathbf{j} \times \mathbf{B} \delta V = (\rho \mathbf{E} + \mathbf{j} \times \mathbf{B}) \delta V \equiv f \delta V ,$$

where $f = \rho \mathbf{E} + \mathbf{j} \times \mathbf{B}$ is the Lorentz force density. We can now consider a uniform charge distribution characterized by ρ . For an infinitesimal volume δV of this charge distribution, the rate of change of the work, or the power given by the fields is given by

$$\mathbf{v} \cdot \mathbf{F} = \rho \mathbf{v} \cdot \mathbf{E} + \frac{\mathbf{j}}{q} \cdot (\mathbf{j} \times \mathbf{B}) = \rho \mathbf{v} \cdot \mathbf{E} .$$

As we can see above, the magnetic force doesn't contribute to the work done by the fields. Thus, the power transferred from the fields to the charges in a finite domain \mathcal{D} is

$$\int_{\mathcal{D}} \mathbf{j} \cdot \mathbf{E} \, d\mathbf{r} .$$

For the energy to conserve, this power must be balanced by a corresponding rate of decrease of energy in the electromagnetic field. Using the Ampère law (1.1d)

$$\int_{\mathcal{D}} \mathbf{j} \cdot \mathbf{E} \, d\mathbf{r} = \int_{\mathcal{D}} \mathbf{E} \cdot \frac{1}{\mu_0} \left(\nabla \times \mathbf{B} - \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} \right) d\mathbf{r} = \frac{1}{\mu_0} \int_{\mathcal{D}} \left[\mathbf{E} \cdot (\nabla \times \mathbf{B}) - \frac{1}{c^2} \mathbf{E} \cdot \frac{\partial \mathbf{E}}{\partial t} \right] d\mathbf{r}$$

Using the following vector identity

$$\nabla \cdot (\mathbf{E} \times \mathbf{B}) = \mathbf{B} \cdot (\nabla \times \mathbf{E}) - \mathbf{E} \cdot (\nabla \times \mathbf{B})$$

we can express $\mathbf{E} \cdot (\nabla \times \mathbf{B})$ as

$$\mathbf{E} \cdot (\nabla \times \mathbf{B}) = \mathbf{B} \cdot (\nabla \times \mathbf{E}) - \nabla \cdot (\mathbf{E} \times \mathbf{B}) = -\mathbf{B} \cdot \frac{\partial \mathbf{B}}{\partial t} - \nabla \cdot (\mathbf{E} \times \mathbf{B}) ,$$

where we used (1.1c) for the first term.

Using this result, the power transferred by the fields is given by

$$\int_{\mathcal{D}} \mathbf{j} \cdot \mathbf{E} \, d\mathbf{r} = - \int_{\mathcal{D}} \left[\frac{1}{\mu_0} \nabla \cdot (\mathbf{E} \times \mathbf{B}) + \frac{1}{\mu_0} \mathbf{B} \cdot \frac{\partial \mathbf{B}}{\partial t} + \frac{1}{\mu_0 c^2} \mathbf{E} \cdot \frac{\partial \mathbf{E}}{\partial t} \right] d\mathbf{r}$$

Considering that

$$\mathbf{E} \cdot \frac{\partial \mathbf{E}}{\partial t} = \frac{1}{2} \frac{\partial \mathbf{E}^2}{\partial t},$$

we obtain

$$\int_{\mathcal{D}} \mathbf{j} \cdot \mathbf{E} \, d\mathbf{r} = - \int_{\mathcal{D}} \left[\frac{1}{2} \frac{\partial}{\partial t} \left(\varepsilon_0 \mathbf{E}^2 + \frac{1}{\mu_0} \mathbf{B}^2 \right) + \frac{1}{\mu_0} \nabla \cdot (\mathbf{E} \times \mathbf{B}) \right] d\mathbf{r}.$$

The total energy density of the electromagnetic field can be denoted with

$$w_{em} = \frac{1}{2} \left(\varepsilon_0 \mathbf{E}^2 + \frac{1}{\mu_0} \mathbf{B}^2 \right)$$

and thus we obtain

$$- \int_{\mathcal{D}} \mathbf{j} \cdot \mathbf{E} \, d\mathbf{r} = \int_{\mathcal{D}} \left[\frac{\partial w_{em}}{\partial t} + \frac{1}{\mu_0} \nabla \cdot (\mathbf{E} \times \mathbf{B}) \right] d\mathbf{r}.$$

Since the domain \mathcal{D} is arbitrary, we can write the above as a differential continuity equation

$$\frac{\partial w_{em}}{\partial t} = - \nabla \cdot \mathbf{S} - \mathbf{j} \cdot \mathbf{E}, \quad (1.14)$$

where

$$\mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B}$$

is the Poynting vector representing the energy flow.

If we consider the domain \mathcal{D} such that no particles will leave it

$$W_{em} = \int_{\mathcal{D}} w_{em} \, d\mathbf{r}$$

is the energy of the electromagnetic field and W_{mech} is the energy of the particles

$$W_{mech} = \int_{\mathcal{D}} w_{mech} \, d\mathbf{r} = \int_{\mathcal{D}} \mathbf{j} \cdot \mathbf{E} \, d\mathbf{r}.$$

By using Gauss' theorem, the energy flux corresponding to the Poynting vector becomes

$$\int_{\mathcal{D}} \nabla \cdot \mathbf{S} = \oint_{\Sigma} \mathbf{n} \cdot \mathbf{S} \, da,$$

where Σ is the surface enclosing the domain \mathcal{D} .

With the above considerations Poynting's theorem gives the conservation of energy for the whole system

$$\frac{dW}{dt} = \frac{d}{dt} (W_{em} + W_{mech}) = - \oint_{\Sigma} \mathbf{n} \cdot \mathbf{S} \, da, \quad (1.15)$$

stating that the rate of change of the energy of the system composed of the charged particles and corresponding fields is given by minus the flux of the Poynting vector through the surface bounding the domain.

Equation (1.14) is the local form for the Poynting theorem.

If we consider the extension of the domain to infinity $\mathcal{D} \rightarrow \mathbb{R}^3$, $\Sigma \rightarrow \Sigma_\infty$, then there is no energy flow through the boundary since electromagnetic waves propagate at a constant finite speed c . Then

$$\frac{dW}{dt} = \frac{d}{dt} (W_{em} + W_{mech}) = 0$$

and the entire energy of the electromagnetic field can be converted into the mechanical energy of the particles interacting with the field.

If we consider \mathcal{D} such that it doesn't enclose any sources, then

$$\frac{d}{dt} W_{em} = - \oint_{\Sigma} \mathbf{n} \cdot \mathbf{S} da ,$$

which shows that the energy of the electromagnetic field in the domain \mathcal{D} can change through the variation of the flux of the Poynting vector on the boundary of the domain, Σ . Thus we can indeed say that the flux of the Poynting vector is the energy flux.

1.2 Electron in a Plane Wave

In this section we will consider the classical dynamics of an electron in a laser pulse following the discussion in Karsch (2018). The starting point is the equation of motion for the electron

$$\frac{d\mathbf{p}}{dt} = -e [\mathbf{E}(\mathbf{r}, t) + \mathbf{v} \times \mathbf{B}(\mathbf{r}, t)] . \quad (1.16)$$

1.2.1 Non-relativistic treatment

1.2.2 Relativistic treatment

1.3 Particle in Cell Method

1.3.1 EPOCH