A Direction of Time in
Time-Symmetric Electrodynamics

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In grateful memory of my mentor, Dr. John M. J. Madey.
This thesis introduces a recent analytical verification which is of significance to the philosophical debate on the direction of time in the case of electromagnetic radiation. I give an overview of the problem of the direction of time in thermodynamics, as well as how it is solved with the Past Hypothesis, a hypothesis that the macrostate of the universe at the moment of the Big Bang was an extremely low-entropy state. I also describe the standard accepted textbook solution to the radiation problem, as well as an alternative time-symmetric theory presented by Feynman and Wheeler that had historically been considered less favorable to physicists. Analytical verification supports that time-symmetric accounts of radiation such as Feynman and Wheeler’s theory are needed for radiation fields to comply with energy conservation and the fundamental equations of electromagnetism. I describe two other philosophical accounts of the direction of time in radiation theory, and then argue that proposed experiments based on this recent analytical result can help us rule out some of the alternative philosophical proposals on the origin of the direction of time in radiation theory. I also suggest that if the proposed experiment does not yield the hypothesized result, physicists could move forward by modifying the fundamental laws of electrodynamics. I conclude with a suggestion for a hypothetical experiment that could potentially stop time in an isolated macroscopic system, and help determine the physical origin of the direction of time.
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Chapter 1

Introduction

1.1 Time Symmetry in the Laws of Physics

Shortly after developing a quantum theory of light, Einstein turned his attention to another problem in understanding electromagnetism. In his 1909 paper with Walter Ritz, "The Present Status of the Radiation Problem," he disagrees with Ritz that the observed irreversibility of electromagnetic radiation should be a feature of the fundamental equations of electromagnetic radiation (Ritz and Einstein, 1909). Einstein instead argues that the irreversibility of electromagnetic radiation originates not in fundamental laws of electromagnetism, but in the probabilistic nature of physical phenomena (Einstein, 1909).

The laws of electromagnetism are time-symmetric, meaning that the laws themselves allow processes to evolve in time either from the past toward the future, or from the future toward the past, but when we observe electromagnetic radiation, we only see radiation emitted from charged particles. The time-reverse of radiation would be absorption of incoming light, but this doesn’t happen when you reverse processes that lead to emission of radiation. It only happens when external radiation is incoming to the system in question. The laws of electromagnetism don’t account for the irreversibility of electromagnetic radiation because they are time-symmetric, and allow for radiation occurring both forward and backward in time.

Time-symmetric laws of motion are not unique to electrodynamics. Newton’s laws can be used to describe the world of human experience, such as the motions of baseballs and cars. Just like the equations for electromagnetic
fields, the equations of motion for baseballs are also time-symmetric. This feature of the world can easily be observed by playing a video of a baseball being tossed in the air in reverse: it will look as if the baseball was dropped instead of tossed upward, with its maximum height in the air as its end point instead as its starting point. Both scenarios are physically possible, and both trajectories are realized in the actual world. Newton’s laws aim to give the trajectories of point particles or collections of point particles, and they succeed at describing phenomena at the physical scale of everyday human life. This leads one to wonder about how it is that we observe a direction of time.

For example, Newton’s laws can describe a trajectory of an egg as it falls off the counter, and the trajectory of all the flecks of the egg shell as it breaks apart upon hitting the floor. Just like the case of the baseball, we can play a video of this in reverse, and watch the egg uncrack and land whole again onto the counter. All of those trajectories of those fractured chips of egg shell are still following physically allowable paths when played in reverse. Why don’t we ever see an egg uncracking then? Why don’t the pieces ever spontaneously collect themselves off the floor and combine into an egg that lands on the counter in one piece? The laws of physics allow for this to occur, just as the laws allow for a baseball to follow a trajectory that is in the opposite direction, something we do see whenever a baseball is tossed up into the air and falls back down.

Something else in addition our currently accepted physical laws is needed to explain why we experience a direction of time. This something else is usually probability, as suggested by Einstein. Unless our currently accepted physical laws are wrong and the dynamical laws of motion themselves are inherently stochastic in such a way that the probabilities can be fully explained by the stochastic laws of physics (Albert, 2000, p. 151), we need, in addition to the laws of physics, a postulate about probability to explain the direction of time.
The goal of this thesis is to incorporate new analytical results in classical electromagnetic theory and a proposed experiment into the philosophical debate on the direction of time in radiation theory. In the remainder of this chapter I will describe thermodynamics and how philosophers understand the origin of the direction of time in thermal systems. The explanation of the direction of time that I present in this chapter is used in some philosophical accounts of the observed time-asymmetry in electromagnetic theory, which I analyze in Chapters 3 and 4. In Chapter 2, I describe classical electromagnetic theory, as this is essential to understanding alternative philosophical accounts of radiation and the new analytical result in electrodynamics presented in Chapter 3. In Chapter 4, I argue that one of the philosophical accounts of radiation can be refuted experimentally by the new proposed experiment, and that another philosophical account is already refuted by the new analytical result. I also suggest to physicists that if their experiment does not yield the hypothesized result, they should consider modifying the fundamental equations of electromagnetism. In Chapter 5, I conclude with a suggestion for a hypothetical experiment, though not currently technologically achievable, that could experimentally probe a long-debated philosophical question about whether the direction of time that we experience is the result of yet-unknown time-asymmetries in the fundamental laws of physics, or the result of thermodynamic irreversibilities that apply only to large collections of fundamental particles.

1.2 Thermodynamics

The development of thermodynamics began primarily with the work of engineers who studied the effects of pressure, volume, temperature, and mechanical work on steam engines and related systems during the Industrial Revolution. Temperature is a measure of the heat content of a body, where
heat is understood as a form of energy. The laws of thermodynamics describe the behavior of closed, thermally isolated systems, meaning they do not exchange heat or other forms of energy with the environment.

For some thermodynamic processes, reversing all the steps of the experiment after the system has reached its final state will bring it back to its initial state. In other cases, reversing the steps will not bring the system back to the original state. An example of an irreversible process is releasing a gas that is compressed onto one side of a chamber by lifting a removable wall separating the gas from vacuum on the other side. As you remove the partition wall that separates the chamber, the gas will spontaneously expand to fill the whole box. This process is irreversible; putting a partition wall back into the chamber of gas will not cause the gas to spontaneously condense on one side of the chamber again. The gas occupies a larger volume, and will be at a lower pressure when expanded, and it will stay this way as long as the chamber goes untouched and remains thermally isolated from its environment.

A heated up box of gas will increase in pressure as the temperature increases if the volume stays fixed, but, if there is a piston in place, the pressure of the gas will result in mechanical work done on the environment by the gas pushing on the piston as it expands in volume. This is an example of a reversible process: if you push the piston in after the gas stops expanding, the pressure and temperature of the gas will rise to its initial state when it reaches its initial volume. Heat became understood as a type of energy from these kinds of experiments, since the heat of the gas is the source of energy for the mechanical motion of the piston. This is encapsulated in the first law of thermodynamics, which states the conservation of energy for thermal systems, where energy can take the form of heat and mechanical work, and can be exchanged between the system and its environment.
1.2. Thermodynamics

The zeroeth law of thermodynamics defines thermal equilibrium and provides a theoretical base for temperature measurements, stating that any two bodies in thermal equilibrium in thermal contact with a third body will also be in thermal equilibrium with the third body, meaning that they are all at the same temperature. The second law of thermodynamics explains why objects in thermal contact will reach thermal equilibrium. A common irreversible thermodynamic phenomenon is the cooling of a hot object placed near a cold one: separating the objects will not cause their temperatures to go back to their original value. By being in thermal contact, the objects will reach the same temperature after a long enough time has elapsed, but removing them from thermal contact will not change their temperatures back to what it was before they were in contact. Heat always flows from hotter objects to cooler ones, never the other way around. It is these irreversible processes that give us reason to connect thermodynamics with the direction of time that we observe in our everyday lives.

1.2.1 Time Asymmetry and the Second Law

The second law of thermodynamics specifically deals with irreversible processes that give rise to the direction of time. The second law of thermodynamics was originally stated in terms of heat flowing from hotter bodies to cooler ones, and never in reverse, but was reworded over time to become more general as the theory of statistical mechanics developed. While the laws of thermodynamics originated from engineering experiments with pressurized gases and heat engines, the theory of statistical mechanics provides a microscopic picture of what is happening in these experiments.

The laws of thermodynamics don’t hold the status of fundamental physical laws (Schroeder, 2000, p. 59). Thermodynamic laws are like the laws of
the other special sciences, such as biology: they describe regularities in cer-
tain complex systems, but the behavior of these complex systems can also be
reduced solely to physical laws.

Thermodynamic conditions such as temperature, volume, and pressure
are referred to as macroconditions of a system, while the microscopic ar-
rangements and the quantum mechanical states of particles in the system
are referred to as the microconditions. I also refer to the macroscopic state
of the system as its macrostate, and the microscopic state of the system as
its microstate. Human scale objects such as a coffee mug or an ice cube are
the macrostates, but the precise underlying arrangement of the fundamental
particles that compose these objects are the microstates. There are many pos-
sible microconditions that can produce a given macrocondition. For example,
there are vastly many possible ways that the atoms of a coffee mug could be
arranged such that we would say it is a coffee mug, or the ways that water
molecules could be arranged such that we could say that there is an ice cube.
Since an ice cube has a crystal structure, which puts some constraints on how
the molecules can be arranged, a puddle of water, without such constraints,
is a macrostate with even more possible microstates than the ice cube.

The microconditions are governed by the laws of physics. In a determin-
istic physical theory of the world such as Newtonian mechanics, the micro-
conditions of the whole history of the universe are fully determined. Given a
list of particles in the universe, their inherent properties, all their positions at
a certain point in time, and how their positions are changing (their instanta-
neous velocity at that time), the entire history of the universe can be known
precisely (Albert, 2000, p. 2).

However, the exact microcondition of any system, which would be the ex-
act arrangement of the subatomic particles that compose the whole system,
is not easily accessible. We don’t have any experimental methods to reveal
the quantum state and exact arrangement of the atoms that compose human-scale objects. For this reason, we usually only have access to the macrostate of a system. The macrocondition, the condition of the system at human scales, is easy to control in experiments, as was done by the industrial engineers that developed thermodynamics. Consider again the box of gas: there is a huge number of precise arrangements of all the particles that make up the gas for which we would say that it is at a certain pressure, volume, and temperature. This brings us to the concept of entropy, a quantity vaguely defined in some introductory textbooks and practical manuals on thermal systems as a measure of disorder within a system.

In the case of the ice cube and the puddle of water above, the ice cube is a lower-entropy system than the puddle of water. This is because, as mentioned above, there are more possible microstates such that we would say that the water molecules can be arranged and we would still say it is a puddle of water. The water molecules are more disordered in the puddle, whereas they are more ordered in the ice cube, where they are fixed into a crystal arrangement. Another example of a low-entropy system is a precisely ordered set of pages that constitutes a book, whereas a scrambled set of those pages is a high entropy system; there is only one page arrangement that makes the book a novel, and many arrangements that would suffice to make the pages scrambled out of order. Similarly, an egg on a counter has a much lower entropy than a scrambled egg and flecks of egg shell on the floor after it falls.

The second law of thermodynamics states that the entropy of a closed system will either remain constant or increase, but never decrease. Statistical mechanics and the kinetic theory of gases relate temperature to the average kinetic energy of the particles that constitute the macroscopic object or fluid. The faster the particles are jostling around inside a container, the hotter the gas will be. This is also true for solid objects: the atoms and molecules that compose the object will be jostling around much more when it is hot than
when it is cold. A temperature of absolute zero (much farther below zero on
the familiar Fahrenheit or Celsius scales) is defined when there is no motion
of the particles at all, and has never been achieved in a laboratory.

How does entropy relate to temperatures, pressures, volumes, and other
thermodynamic quantities? Consider a hot object brought in contact with a
cold one. An object will have a higher entropy when it is hot than when it is
cold because there are more possible arrangements of the composite particles
for the object to be hot. Even though the object might not have expanded
in size, there are more particles that can be in motion over a wider range
of velocities than when it is cold. Discussions of entropy of systems often
make reference to phase space, an abstract space that is the space of possible
coordinate values of positions and velocities in the three-dimensional space
available to all the particles in the system.

While in the box of gas, there are more particle positions and velocities
available when the gas expands to a higher-entropy state, a hot solid object of
fixed size will have more possible particle velocities available than when it is
cold. This is why the concept of entropy is powerful: it generalizes the time-
directedness of thermal systems, making them about the size of the abstract
phase space that the constituent particles can occupy, instead of about heat
flow between objects at higher and lower temperatures. The second law of
thermodynamics can now be phrased entirely in terms of entropy: the total
entropy of an isolated system can only either remain constant or increase over
time. The entropy remains constant in reversible processes, and increases in
irreversible ones.

The second law of thermodynamics explains the irreversibility of the ex-
pansion of gas inside a box once a partition is removed that separates the
gas from vacuum, even though there is no flow of heat in the system. This
is because there are now more possible arrangements that the gas particles
could take when they are free to occupy a larger volume; there are more possible ways for the particles to be arranged but still to fill the whole box at that volume and pressure. Assuming each microstate is equally probable, macrostates that are compatible with more microstates are more likely to occur than macrostates compatible with a fewer number of microstates. When the gas is compressed to one side of the box, the gas is at a lower entropy than when it fills the box, because there are fewer possible ways for the particles to all arrange themselves in the smaller volume. There are many possible trajectories that the microscopic particles could take that would describe the evolution of the initial macrostate to its final one.

Thermal systems always tend toward a stable condition called thermal equilibrium. For two hot and cold objects in contact with each other, thermal equilibrium is reached when the two objects reach the same temperature. For the box of gas, thermal equilibrium is reached when the gas is fully diffused inside the chamber and stops spreading out. In both of these examples, the system spontaneously evolves toward thermal equilibrium when the macroscopic constraints on the system change, toward their state of maximal entropy given those constraints. The equilibrium condition is the highest entropy state for these systems. Before it is reached, the system is in an unstable, lower entropy state, and it does not stop spontaneously evolving until its entropy is maximized.

1.2.2 Statistical Mechanics and Probability

The theory of statistical mechanics quantifies the concept of entropy in terms of the size of the phase space available. Higher entropy systems correspond to larger volumes of this abstract space of possible position and velocity coordinates. In systems of higher entropy, there are more microstates that are compatible with the macrostate in question than there are for systems in
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A lower entropy state.

The dynamical laws of physics are concerned with the exact trajectories of the particles that compose macroscopic systems, and statistical mechanics aims to explain how it is that we can arrive at the laws of thermodynamics, including the second law, from our deterministic, time-symmetric physical laws. We expect this to be possible, because macroscopic systems are collections of microscopic particles. It happens to be a feature of our universe that there are observable regularities at the level of macroscopic systems that allow for a scientific theory of thermodynamics.

A philosophical problem emerges when one considers how it is that the second law of thermodynamics can arise. The laws of physics are time symmetric, but the second law of thermodynamics is not, even though the second law describes the behavior of collections of particles that follow the time-symmetric laws. Ludwig Boltzmann, one of the founders of statistical mechanics, invoked probability to explain the direction of time encompassed in the second law. Consider a gas initially compressed in a small region of an empty chamber. The number of microstates that are compatible with the macrostate of the gas increases at every point in time as it expands. As the gas gradually occupies larger regions of physical space, the region of phase space that it occupies also increases, because the larger region of physical space is compatible with more positions and velocities of the gas particles. If we assume that there is an equal probability that any of the future microstates compatible with the macrostate of the gas are equally likely to occur, there is then a high probability that the particles will end up in thermal equilibrium.

If the number of possible microscopic particle arrangements is higher in certain macrostates, and the probability of being in any possible arrangement is equally likely, then it is most probable that systems will be in a macrostate that is compatible with the largest number of microstates. The point at which
this occurs, that the system is in a state that occupies the largest possible volume of phase space available, is thermal equilibrium. By postulating that any possible future microstate compatible with the final macroscopic constraints of the system is equally likely to occur, it is most probable that systems will evolve toward thermal equilibrium (Albert, 2000, p. 52).

Of course, if the laws of physics are deterministic, as in Newtonian mechanics, all trajectories, while unknown to experimenters, are already fully determined. Statements about the probability that particles can take certain trajectories are then epistemic statements about our knowledge of such systems, not objective statements about the systems themselves. How can these statements about probabilities be used to make predictions about physical systems, if they tell us only about our knowledge of those systems? Philosophers of physics evade this problem by treating the probability distribution over microstates for a given macrostate as a law of nature. Like other scientific laws, the probability distribution is a simple and informative statement that helps us to make predictions (Loewer, 2001, p. 617).

However, this postulate about probability alone does not suffice to explain the time-asymmetry in the second law of thermodynamics. Given that the fundamental laws of physics are time-symmetric, the same argument about microstates evolving toward macrostates that take up a larger volume of phase space in the future can be applied in reverse. The overwhelming majority of trajectories passing through a non-equilibrium macrocondition in phase space evolve toward a higher entropy macrocondition in the future. But since the time-reverse of all of these trajectories are also physically possible, this also implies that systems are just as overwhelmingly likely to be decreasing in entropy as they are increasing in entropy, in direct contradiction with our experience. The time-reverse of any trajectory (the trajectory that has the same position values but with the direction of the velocities is reversed) belongs to the same macrostate as the trajectories that are
going forward in time. Because of the time-reversal symmetry of the laws of physics, the overwhelming majority of time-reversed trajectories passing through a non-equilibrium macrocondition in phase space evolve toward a higher entropy macrocondition in the past. It implies that entropy was higher in the past as well as the future: for example, that an ice cube was melting at the time when it was actually still in the freezer. This deeply concerned the founders of statistical mechanics such as Boltzmann.

### 1.2.3 The Past Hypothesis

Postulating that there is an equal probability for any trajectory passing through a non-equilibrium macrostate to be realized is insufficient to explain why there is a direction of time. Physics textbooks on thermodynamics and statistical mechanics often ignore this crucial problem in the theory, but many suggestions have been put forth in the physics literature to solve the problem (Albert, 2000, p. 85). One of the most successful and agreed upon is referred to as the Past Hypothesis, which claims that the direction of time is a result of the microstate of the universe at its very inception, the moment of the Big Bang (Albert, 2000, p. 96). Most importantly, the microstate of the universe at its conception is hypothesized to be compatible with a very low-entropy macrostate.

To see how this hypothesis, in addition to the statistical postulate, can solve the problem, imagine what happens when you apply only the statistical postulate and the time-reversal symmetric laws of physics to everyday situations. Imagine an ice cube sitting on a kitchen counter that melts completely in 5 minutes. If you apply the statistical postulate to the unmelted ice cube, given the postulate that any trajectory toward any future microstate of the ice cube is equally probable, there is an overwhelming probability that in 5 minutes the ice cube will become a small puddle of water, because there are
so many more microstates that are compatible with a puddle of water than are compatible with an unmelted or partially melted chunk of ice.

This seems to solve the problem: this is what we experience. But since the laws of physics are time-symmetric, these arguments also apply for trajectories that go from the future toward the past (essentially, plug in negative time values into the dynamical equations, instead of positive ones). There will be an overwhelming number of trajectories toward that past that correspond to a puddle of water rather than an ice cube 5 minutes beforehand. This is the case no matter how the ice cube got there, contrary to our experience, and contrary to the memory of the person who put the ice cube on the counter. At whatever point in time we decide to apply the statistical postulate, to say that all trajectories that pass through the current microstate of the system are equally likely to occur, that point in time will be an entropy minimum. There will be an equally overwhelming number of particle trajectories that evolve toward a state of higher entropy both toward the future and the past.

Should we try applying the statistical postulate 5 minutes before the ice cube is sitting on the counter about to melt? If we did, we would run into the same problem again, only for earlier points in time. Any point in time that you apply the statistical postulate will be at an entropy minimum, meaning entropy will be increasing both toward the future and the past.

Should we just ignore the solutions that go from future to past? That won’t solve the problem, because we are trying to explain how thermodynamics comes about from the laws of physics. However, S. Leeds suggest that we do exactly that, and ignore the solutions that don’t match up with our experience. He suggests that we are asking questions that the theory can’t answer when we ask why time-reversal symmetry in the dynamical laws predicts that entropy has been increasing toward the past (Leeds, 2012, p. 361). He doesn’t see this as a problem, but rather as something new we learned about what types of questions the theory can answer. For those who
want an answer to this question, the theory seems to be telling us something about the state of universe at the moment of the Big Bang.

There is only one point in time when we can ignore the behavior of trajectories that go toward the past, and that is at the exact moment of the Big Bang, the temporal origin of the universe. If we apply the statistical postulate to the exact microstate of the universe at the moment of the Big Bang, then, since the whole universe is essentially one very large, thermally isolated system, we know that the system and all of its subsystems have an enormously high probability of evolving toward a state of maximal entropy. It is not that the laws of physics don’t allow for systems to evolve toward states of lower entropy, but that is so unlikely that it has not been observed.

The Past Hypothesis, unlike other scientific hypotheses, can’t be experimentally tested. David Albert suggests that it be understood as a law of nature, though not a dynamical law such as Newtonian laws or electromagnetic laws referenced above. Albert argues that our grounds for believing that the universe started out in a incredibly low-entropy state are inductive. We have reason to believe it because we repeatedly see empirical evidence of it. Like any scientific law, it is a general statement that allows us to make a variety of empirical predictions. While we often think of hypotheses as ideas that can be scientifically tested and later understood as empirical facts, Albert’s interpretation of the Past Hypothesis helps us to explain patterns in nature, just like other scientific laws (Albert, 2000).

With the Past Hypothesis and the statistical postulate, the postulate that all future states of a system are equally likely, we can explain how it is that we experience a direction of time even though microscopically, all of the particles that compose complex systems are governed by time-symmetric laws of physics. The reason eggs don’t uncrack is not because it is physically impossible, but rather, that there is an overwhelming probability that this will not occur. There would have to be the right amount of heat energy in the
floor at the locations of the egg shells that converts to their kinetic energy, gives them an impulse that sends them back along their initial trajectory to recombine as a whole egg. It’s not impossible, but the effort needed to create a thermal arrangement where this would occur spontaneously would be enormous: for all practical matters, impossible.

We also see evidence of the Past Hypothesis by our ability to remember the past and to make and find records of the past. For example, when we see a trail of footprints in the sand when walking along the beach, we understand that this means that, in the past, someone had strolled along the beach and left those impressions in the sand. The footprints are a record of the past. However, they are only a record because we can also assume that there is an extremely low chance (essentially, impossible) that sand particles spontaneously arranged themselves to form a trail of footprints. Rather, we infer that farther in the past, before someone strolled on the beach and left footprint, the sand was in a state where it was ready to make the record that we see at the present time. For example, we infer that the sand was smooth and undisturbed before and after the person walked there and left the footprints. For every record of the past that we come across, we need to be able to assume that the system was in a state such that is was ready to make a recording of future events (Loewer, 2012, p. 126). We need to be able to assume that at some point in the past, even though we have no record of it, before any records were made, that the macrocondition of the universe was such that it was possible for traces of the past to be recorded.
Chapter 2

Electromagnetic Radiation

2.1 Maxwell’s Equations

Before delving into different philosophical accounts of electromagnetic radiation and the observed direction of time, this chapter outlines the current classical model of electrodynamics and the accepted classical theory of electromagnetic radiation. For centuries, physicists studied electricity, magnetism, and light as entirely unrelated phenomena. Experiments eventually began to reveal that they are intrinsically related: moving electrically-charged particles produced magnetic fields, changing magnetic fields produced electric fields, and electric and magnetic fields could induce each other even if no charges, moving or stationary, were present.

These self-inducing fields propagated as electromagnetic waves, and it was discovered that their speed of propagation was the experimentally confirmed speed of light. All of these profound experimental and theoretical insights carried out by many physicists throughout history are summarized by the Maxwell equations, written down by James Clerk Maxwell in the 1800s. The four Maxwell equations are written below:

\[
\begin{align*}
\nabla \cdot \vec{E} &= \frac{\rho}{\varepsilon_0} \\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\nabla \times \vec{B} &= \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \\
\nabla \cdot \vec{B} &= 0,
\end{align*}
\]

where \(\vec{E}\) and \(\vec{B}\) are the electric and magnetic fields, respectively, \(\rho\) is the stationary charge density that produces the electric field, and \(\vec{J}\) is the current.
density that produces the magnetic field. The symbol $\vec{H}$ is used to represent the magnetic field strength, which can appear in these equations instead of the magnetic field $\vec{B}$, because the field strength takes account of magnetization in a material, which is often more relevant in physical systems.

Besides these equations, the Lorentz force law, $\vec{F} = q(\vec{E} + (\vec{v} \times \vec{B}))$, which relates the force on a charged particle due to external electric and magnetic fields, encompasses all electromagnetic phenomena. The equations of motion of the charged particles can be calculated from the Lorentz force law, and the fields used to calculate the force can be calculated using the Maxwell equations, given the sources of the charges that produce the fields. Electromagnetic fields and their sources are related by these powerful equations, which continue to be experimentally confirmed. The wave equation, which describes electromagnetic waves, is derived from the Maxwell equations, and governs how the waves are related to their sources. The wave equation can also be used to describe electromagnetic waves propagating in regions of spaces where there are no sources, simply by setting the sources terms, $\rho$ and $\vec{J}$, equal to zero.

Algebraic manipulation of the Maxwell equations yield the wave equations:

$$\frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} - \nabla^2 \vec{E} = -\nabla \left(\frac{\rho}{\epsilon_0}\right) - \mu_0 \frac{\partial \vec{J}}{\partial t}$$

$$\frac{1}{c^2} \frac{\partial^2 \vec{B}}{\partial t^2} - \nabla^2 \vec{B} = \mu_0 (\nabla \times \vec{J})$$

Electromagnetic radiation is electromagnetic waves emitted by an accelerating charged particle, and hence is described by these wave equations. Because these equations are linear, sums of solutions are also solutions. When waves are summed, their field values can add either constructively, increasing in amplitude, or destructively, interfering and canceling each other out.
2.2 

Radiation

Just as physics textbooks often neglect to mention that the Past Hypothesis is needed to explain the second law of thermodynamics, textbooks often quickly brush away the problem of time-asymmetry in radiation. It is usually not posed as a philosophical problem that radiation is only observed as waves outgoing from their source. While the wave equation allows incoming and outgoing waves as mathematical solutions, physicists routinely neglect mathematical solutions because they are unphysical. The current classical model of radiation relies on the Sommerfeld radiation condition, a condition introduced by Arnold Sommerfeld in the 1940s stating that energy can radiate away from a source out to infinity, but cannot arrive from infinity to the radiating source.

The physics of accelerating charged particles is different than that of non-electrically charged particles. This is because the charged particles are surrounded by an electromagnetic field that propagates at a finite speed, namely, the speed of light. Centuries ago, the force between stationary electric charges was discovered to depend on the inverse square of the distance between them, known as Coulomb’s law. However, when you consider accelerating charges, the distance between the charges that must be used to calculate the force is not the distance separating the particles at the time the force from one charge on another is felt.

The electromagnetic force is not instantaneous. The force will only be felt once the time that it takes for light waves to travel the distance separating the charges has elapsed. This means that the force depends on the position of the charge at the time that the electromagnetic wave of the charge was emitted, known as the retarded time. The advanced time is defined in terms of this same distance, except that it corresponds to the distance the field will travel in the future.
The radiation problem is to calculate the fields of the radiating particle at a distant point, called the field point. The field propagates at the speed of light, not instantaneously, so you have to use the time at which the radiation was emitted minus the time it takes for the radiation to travel from the source point to the field point at the speed of light, \( \frac{r}{c} \), to calculate the strength of the field at the field point. This fits with our intuitive causal picture of causality: the radiating particle produced the field at the source point. Even though advanced solutions, where the time used to calculate the field strength at the field point is the time of emission plus the time it takes for the radiation to travel from the source point to the field point at the speed of light, gives the correct answer as well, it does not match with our causal picture of the world.

\[
\begin{align*}
t_{\text{ret}} &= t - \frac{r}{c} \\
t_{\text{adv}} &= t + \frac{r}{c}
\end{align*}
\]

The advanced solution is the mathematical representation of electromagnetic fields propagating backwards in time, from their detection point to their source. The advanced fields can still be used to solve the radiation problem, just as well as the retarded solutions. Instead of the fields depending on the charge and current distributions in the past, the present fields depend on the distributions of charges and currents in the future. Griffiths argues that this means that the advanced potentials have no physical significance, because they imply that the cause precedes the effect in time (Griffiths, 1981, p. 425). Arnold Sommerfeld originally concluded that for radiation entering into free, unbounded space, the advanced fields should be neglected outside the region of space where the charges and currents that produced the radiation fields exist. However, the radiation condition often was used in all regions of space, excluding the advanced field solutions near the region of charges as well (Smith, 2015, p. 2). Ascribing reality to only the retarded solutions is referred to as the Sommerfeld radiation condition.
The Sommerfeld condition may sound convincing at first, because it matches with our intuitive picture of causes and effects in nature. However, there are arguments in the philosophy of science that do not require us to accept scientific explanations as being a matter of causes and effects. David Hume suggests that there is only constant conjunction of events, and no real cause. For example, it could be that the effect can occur without the perceived cause, but it just so happens that we always see the perceived cause occurring beforehand.

We can think of physical laws as describing patterns of events in nature, without committing to the idea of causes to effects, and the sorts of counterfactuals needed to define what we mean by cause and effect. The Humean picture of the world, of events occurring in certain consistent patterns but without causes and effects, makes it hard to accept Griffiths’ account of why we should abandon the advanced solutions for the radiation problem (Gasper, 1991, p. 290). The advanced solutions describe this pattern in nature just as well as the retarded solution. If both solutions equivalently describe reality, why should we only accept one of them as real? (Frisch, 2009, p. 15).

Humean views of causality aside, arguments about causality don’t usually appear in physics textbooks. The laws of physics are expressed as mathematical equations that relate physical quantities. It should be possible to describe radiation, a fundamental physical process, solely by the laws of physics as well, and not by both the laws of physics and arguments about causality.
2.3 The Radiation Reaction Force

While there are debates about the mechanisms of radiation, and how to mathematically describe the radiation fields, all proposed theories must explain the experimentally observed emitted electromagnetic fields, as well as the observed deceleration that the particle experiences when it radiates. The philosophical accounts described in the following chapters often debate the physical origin of the force that causes the radiating particle to decelerate, known as the radiation reaction force.

Accelerating charged particles produce electromagnetic radiation, but in turn, the particles themselves lose energy. Neutral particles, ones without electric charge, will accelerate more than charged particles if subjected to and influenced by the same force. Given Newton’s laws, this implies that there is a force directed opposite to the force that is causing the acceleration. Griffiths describes this force as a recoil force, similar to the recoil force of a gun. This radiation reaction force, as it is known, can be calculated by considering conservation of energy, setting the power lost by the particle, $\vec{F}_{rad} \cdot \vec{v}$, equivalent to the power radiated out to infinity.

Electromagnetic radiation is sometimes referred to as the acceleration fields, since it is the electromagnetic fields that result from the acceleration of a particle. There is also energy that gets stored in electromagnetic fields that are not radiated out to infinity. These are referred to as the velocity fields, and this derivation of the radiation reaction force does not include the energy stored in these fields. Neglecting the velocity fields is only valid for oscillatory systems, if you do the calculation for a time interval equal to the period of oscillation. While not very general, this yields the Abraham-Lorentz formula for the radiation reaction force (Panofsky and Phillips, 1990, p. 386):

$$\vec{F}_{rad} = \frac{q^2 \ddot{a}}{6\pi\epsilon_0 c^3}$$
Griffiths shows that this equation for the radiation reaction force can also be derived from considering a fuzz-ball model of a charged particle. Instead of charged particles being considered points of zero size, of the charge being located at a radial distance of zero from the particle’s center, it is assumed that the charge of the particle is spread out in space. Griffiths simplifies this model even further and assumes two internal points of charge inside the particle that are in a dipole configuration and calculates the force of one point of charge on the other when the particle is accelerating.

The result matches the Abraham-Lorentz force, and Griffiths concludes that this shows that the radiation reaction force is fundamentally the result of a "self-force" of electromagnetic repulsion of points of charge within the charged particle. Essentially, when accelerated, Newton’s third law no longer applies to the particle. There is not an equal and opposite force for every force on the internal points of charge within the particle. The radiation reaction force is the net force, which is always directed opposite the acceleration. This calculation explicitly excludes the advanced radiation fields, using only the retarded time.
Chapter 3

Alternatives to the Origin of the Radiation Reaction Force

3.1 Feynman and Wheeler’s Infinite Absorber Theory of Radiation

Standard physics textbooks, such as Griffiths referenced above, use Sommerfeld’s radiation condition, choosing to neglect the advanced solutions of the wave equation because they seem to contradict our intuitive picture of the world, that causes precede their effects in time. The theory that the radiation reaction force arises from the self-force of the radiating charged particle is the accepted picture of what is microscopically occurring during the radiation process, but in the 1940s Richard Feynman and John Wheeler challenged this theory of the physical origin of the observed radiation reaction force, ascribing it to radiation fields traveling backwards in time from an absorbing boundary, instead of the self-force of the charge. Their theory is empirically equivalent to the retarded-only theory, but more complex, which is likely why it did not become part of standard physics textbooks on the subject. New analytical analysis shows that the Feynman and Wheeler theory can be empirically tested, and it is possible that experiments could someday make the Feynman-Wheeler theory the standard accepted theory in the future.

In their 1945 paper, Feynman and Wheeler aimed to provide a physical account of the observed radiation reaction force by appealing to arguments first posed by Hugo Tetrode. Tetrode asked whether or not radiation would
be emitted if there were nothing to observe it, no absorbing boundary off in the distance. Essentially, would stars still shine if there were no one and nothing to see them? As vague as this question sounds, Feynman and Wheeler made a mathematically rigorous theory assuming that light would not shine without a distant material object that absorbed the light’s energy.

Ritz, in his debate with Einstein, suggested that electromagnetic laws contain a fundamental time-asymmetry, which itself could be used in an explanation for the thermodynamic time-asymmetry (Ritz and Einstein, 1909). Systems often reach thermal equilibrium by losing heat in the form of electromagnetic radiation. Ritz had calculated electromagnetic fields from thermal radiation emitted inside a cavity, and had argued that neglecting the advanced fields and using only the retarded fields could be used to derive the observed blackbody radiation spectrum (Lacki, 2011). The quantum mechanical nature of light was in its early stages of development when Ritz had suggested that blackbody radiation could be explained if one assumed only retarded fields. However, blackbody radiation can only be explained with quantum mechanics, not with classical electrodynamics, even with restriction to retarded-only fields. It was with the example thermal radiation in mind of that Ritz disagreed with Einstein, and suggested that thermal irreversibilities could arise from a fundamental time-asymmetry in electrodynamics. Feynman and Wheeler instead aim to provide a fundamentally time-symmetric account of radiation and the physical origin of the observed radiation reaction force, with the direction of time arising from thermodynamics.

The radiation reaction force is physically observable as a damping force or recoil force on the accelerating charges, as can be observed by energy lost when particles are deflected (accelerated) near atomic nuclei, or when glowing, light-emitting objects cool down. The idea of a self-force as the physical
origin of the force is a bit contrived, considering that electrodynamics theory otherwise exclusively describes the effects on a charge from the fields of external sources of charge, not a charge’s own field on itself. In the rest of classical electromagnetic theory, charged particles are always assumed to be points with no spatial extent that cannot exert forces on themselves; only in the case of accelerating particles is it assumed that charged particles have spatial extent and experience internal forces. To create the concept of a self-force, Abraham and Lorentz imagined elementary charges as fuzz balls of charge rather than point particles, which can make the force difficult to translate into quantum mechanics theories, which treat elementary charged particles as points.

Dirac made an attempt to treat electromagnetic radiation differently mathematically, without raising any suggestions for the physical origin of his new mathematical description. He postulated that the field responsible for the observed radiation reaction force, which he called the radiation reaction field, is equal to one half of the retarded field minus one half of the advanced field. This theory treated the radiating particle as a point charge instead of postulating a self-charge of a finite-sized particle.

$$\text{Dirac radiation reaction field} = \frac{1}{2} (F_{\text{ret}} - F_{\text{adv}})$$

This field gives the correct force at the location of the charge for the examples that Dirac investigated. While this succeeds in making correct experimental predictions, it is just a mathematical instruction with no physical picture in mind (Wheeler and Feynman, 1949, p. 159).

Feynman and Wheeler followed the picture presented by Tetrode, interpreting radiation fundamentally as an interaction between a radiating source and a distant absorber, with no notion of self-fields of fuzz-ball charges. Simply stated, a point charge in free space, without the presence of an absorbing, thermally dissipative boundary would not radiate at all, even if it were to
be accelerated. On this theory, there is no such thing as radiation into "unbounded space," since if there is radiation, that means there is an absorbing boundary surrounding it, even if the actual location of the boundary is unknown and very distant.

While it is time-symmetric, the fact that the theory seemed to invent a distant absorbing boundary in far reaches of the universe made it originally unfavorable compared to using the Sommerfeld condition. This theory is fundamentally non-local, which means that there is an intrinsic, instantaneous connection between the state of one physical system and another, no matter how far apart those systems are located in space. Any changes in one system are reflected in changes in the other system, even though there is no causal process that mediates these changes, and no time elapsed between the two distant systems' correlated evolutions. Dirac's radiation reaction field, in its use of advanced fields, also assumes non-local interactions, but there is no physical picture behind his equation. In the Feynman-Wheeler theory, the advanced fields come from the boundary that absorbs the radiation emitted by the accelerating charge.

Non-locality is contradictory to our intuitive picture of the world, where there is a causal chain of physical interactions that occur between objects that are physically adjacent to each other in space, or where a field propagates through space, linking them. For example, the flicking on of a light switch on a wall might seem to instantaneously turn on a ceiling lamp, but upon closer inspection there is a causal chain of events that lead to the light bulb turning on: the flow of electrons between the closed switch and the light bulb takes time, even if its such a short time interval that it is barely noticeable when you enter a room.

Another example of a non-local physical theory would be Newton's theory of gravity, in which the gravitational force between objects is related to the masses of the objects and their distance. Changes in the masses or
distance between them instantaneously change the amount of gravitational force they experience and exert. However, with the introduction of general relativity by Einstein, gravity became a local theory, where the force between massive objects is due to the continuous curvature of space-time that connects the objects. Non-locality means that the physical state of one system depends on the physical state of distant, disconnected regions of the universe instantaneously.

In the Feynman-Wheeler absorber theory of radiation, the instant that light is emitted from a radiating source, passively oscillating particles in a distant absorber feel the oscillation of the radiating charge (the source) instantaneously. The particles in the absorber generate a field that is equal to half the retarded field plus half the advanced field.

\[ \frac{1}{2} (F_{\text{ret}} + F_{\text{adv}}) \]

There needs to be enough particles in the absorber to completely absorb the radiation from the source, but the physical properties of the absorbing material are otherwise irrelevant. The advanced fields from the distant absorbing particles are present near the source particle at the time it radiates and are what determines the observed deceleration of the particle during radiation. These advanced fields from the absorber exert a finite force simultaneously on the charge at the time it accelerates, whose magnitude and direction match our observations of energy loss to accelerating charges.

There is no radiation reaction self-force in this theory, but the advanced fields of the absorber play the role of the radiation reaction field in explaining the observed deceleration of the accelerating charge at the time it radiates. Feynman and Wheeler show that the advanced field from the boundary at the location of the accelerating charge is equal to the Dirac field, \( F_{\text{adv, absorber}} = \frac{1}{2} (F_{\text{ret, source}} - F_{\text{adv, source}}) \). We have only ever observed retarded radiation in the
Chapter 3. Alternatives to the Origin of the Radiation Reaction Force

lab, in regions far away from the accelerating source particle. The Feynman-Wheeler theory can explain this empirical observation of only seeing retarded fields far from the source particle. The half-advanced field from the source particle destructively interferes with some of the radiation coming from the absorber. The region near the source charge where the advanced fields play a role has not been experimentally probed. The total disturbance of the field far away from the source is the fully retarded field that we observe:

\[
\frac{1}{2}(F_{\text{ret source}} + F_{\text{adv source}}) + \frac{1}{2}(F_{\text{ret source}} - F_{\text{adv source}}) = F_{\text{ret source}}
\]

The above expression is the sum of the advanced field from the absorber with the time-symmetric field of the source, which is equivalent to just the retarded field of the source, consistent with our laboratory observations. The retarded field of the boundary is directed into the rest of space, not toward the accelerating particle. Feynman and Wheeler explain how it is that this process is irreversible in time, even though there is time-reversal symmetry in the microscopic electromagnetic interactions. The process could occur in reverse, where instead of a damping force on the radiating charge, the advanced fields could combine to create a damping force on the absorber particles. In the derivation of their time-symmetric electrodynamics, Feynman and Wheeler assumed that the absorber particles were either at rest or in random motion before the radiating source particle began accelerating. This is the initial condition of the problem, and just as in the case of thermal systems, it is the initial conditions that pick out the observed direction of time, even though the system is allowed to evolve in the reverse of what we observe, given the time-reversal symmetry of the laws of physics.

For the time-reversed scenario, one of the random motions of one of the absorber particles would be such as to induce a disturbance in the rest of the absorber particles such that their collective motion generates a field that converges onto the distant source particle at the moment that it accelerates.
This is highly unlikely, given that there is a very large number of particles assumed to be in the absorber, and of all the possible arrangements of these particles, there are only a few such arrangements that will generate the required disturbance in the rest of the absorber particles. Feynman and Wheeler’s time-symmetric theory of radiation solves the problem of the direction of time in the same way that we account for the thermodynamic asymmetry in time, in agreement with Einstein that the radiation problem is due to matters of probability, not time-asymmetry in the fundamental laws.

### 3.2 The Need for Time Symmetric Radiation Theory

As will be discussed in the Chapter 4, philosophers of physics have challenged the use of the Sommerfeld condition, a retarded-only theory of radiation, because this condition violates the time-symmetry of the Maxwell equations. In a recent physics paper, physicists Pardis Niknejadi, John Madey, and Jeremy Kowalczyk also challenge the Sommerfeld condition, and agree with Feynman and Wheeler that radiation theory needs to be described by time-symmetric equations (Niknejadi, Madey, and Kowalczyk, 2015, p. 2). They show that advanced radiation fields as well as retarded fields must both exist near the accelerating charge at the time it radiates in order to satisfy both Maxwell’s equations and the conservation of energy.

The Maxwell equations can be combined and manipulated, along with the Lorentz force law, to calculate the conservation of energy for an electromagnetic system, presuming there is both mechanical energy of the charges in motion as well as energy stored in the fields. The surface integral of one of these terms in the resulting energy conservation equation, called the Poynting vector, $\frac{1}{\mu_0} \vec{E} \times \vec{H}$, represents the time-averaged energy transferred per
unit time, in or out of the system via electromagnetic radiation. For periodically oscillating charges in free space, the energy conservation relation can be used to relate the time averaged surface integral of the Poynting vector to the time-averaged surface integral of the fields times the current for a steady-state system.

$$\int_{A}^{B} \frac{\mathbf{E} \times \mathbf{H}}{dt} = -\left(\frac{4\pi}{c} \int_{A}^{B} dt \int \mathbf{E} \cdot \mathbf{j} \, dV\right)$$

The above equation doesn’t take into account the possible mechanical or other non-electromagnetic forces on the system, and therefore isn’t necessarily an energy conservation relation, even though it relates flows of energy in the system. Most importantly, Niknejadi realized that these relations can be used as a way to test whether the relations between the fields, and the charges and currents that produced them, are compatible with the Maxwell equations (Niknejadi, Madey, and Kowalczyk, 2015, p. 4). Since this equation is derived directly from Maxwell’s equations assuming only the conservation of energy, if the fields and sources of a system do not satisfy this equation, it means that that system either violates Maxwell’s equations or the conservation of energy. Conservation of energy is one of the most trusted principles of physics. Niknejadi et. al. refer to this equation as the Maxwell energy integral, and also called it the Niknejadi-Madey test (Madey, Niknejadi, and Kowalczyk, 2015, p. 1). If you assume conservation of energy, Maxwell’s energy integral can be used to test whether the fields and sources of the system are compatible with the Maxwell equations, the fundamental equations that govern the relations between fields and their sources.

Maxwell’s energy integral includes all components of the current and the fields from all the sources at the field point at which they are evaluated, including fields due to charges and currents at the boundaries of the system, as well as the fields of a charge or interacting charges in the system. The Niknejadi-Madey test is derived directly from Maxwell’s equations, which
are time-symmetric, and hence makes no assumption about a direction of time. Using this equation for the case of a pair of periodically oscillating charges, we can test whether or not Sommerfeld’s retarded-only condition, or other solutions to the radiation problem, such as the linear combinations of retarded and advanced fields proposed by Dirac or Feynman and Wheeler, are compatible with Maxwell’s equations and the conservation of energy.

All of these formulations can mathematically describe the empirical experience of radiation by accelerating charges in regions far from the accelerating charge, but Niknejadi realized that some of these formulations violate energy conservation. Niknejadi and her collaborators analyzed compliance with Maxwell’s energy integral for the case of coherent radiation from two oscillating charged particles that are oscillating in phase along the direction of their separation, with a separation distance that is on the order of a few wavelengths apart. This length scale can be described with classical electrodynamics, since an oscillation period of less than about 2.8 femtoseconds can only be described by quantum, not classical, electrodynamics.

Niknejadi showed that the Sommerfeld retarded-only theory couldn’t satisfy Maxwell’s energy integral because of the time-asymmetry of the field. Any theory that uses only the retarded time or the advanced time is not symmetric in time. For the case of Dirac’s formulation, neither oscillating charge experiences the self-force of the other, but without the addition of this force in the calculation, the Dirac field also fails the Niknejadi-Madey test. Maxwell’s energy integral is only satisfied in this case if one assumes that the charges are separated by a large distance, larger than the wavelength of the radiation so that interference between the radiation of each charge affects the overall radiated field observed.

Maxwell’s energy integral was satisfied by the approach by Feynman and Wheeler because of the time-symmetry of their theory. The significance of
Niknejadi’s analytical result is that it shows that the standard accepted textbook theories of electromagnetic radiation either do not satisfy Maxwell’s equations, the fundamental equations for all electromagnetic interactions, or do not satisfy energy conservation, one of the most essential tenets of physics. Not only that, but the interpretation of Feynman and Wheeler that has been left out of textbook discussions on philosophical grounds about causality does satisfy the Maxwell’s equations and energy conservation. It is well known that the Sommerfeld condition of restricting to using only retarded fields violates the time-symmetry of the Maxwell equations. However, time-symmetric theories such as Feynman and Wheelers become more appealing when using the Sommerfeld condition is shown to violate conservation of energy.

Niknejadi also proposed an experiment to test for the existence and form of the advanced radiation fields in the near-field region for periodically oscillating charges. This hypothetical experiment may soon be carried out if funding becomes available, since it can be accomplished with currently available experimental technology. This could provide experimental proof that electromagnetic radiation can only be described fundamentally by a time-symmetric theory such as Feynman and Wheeler’s, even though the far-field region can be modeled using the presumption of retarded-only fields.

Niknejadi showed that the predicted advanced radiation fields as a function of perpendicular distance from a short dipole antenna system are nearly identical to the advanced radiation fields as a function of perpendicular distance from a single oscillating charge. Her proposed experiment is to measure the power attributed to the fields in the vicinity of the radiating antenna (Niknejadi, Madey, and Kowalczyk, 2015, p. 9). While antennas are human-scale devices, it is not surprising that the radiation from antennas can be described mathematically analogous to the radiation from an oscillating charged particles. Microscopically, a transmitting antenna has an oscillatory
current, composed of charged particles oscillating up and down the length of the antenna. The radiation from the antenna is the radiation produced by these individual oscillating charges. The receiving antenna has a matching oscillatory current induced when the radiation from the transmitting antenna arrives.

Just like in the Feynman and Wheeler theory, calculations that use the advanced fields to describe antenna systems predict that the transmitting antenna will not radiate unless there is thermal dissipation (resistance in the wire) in the receiving antenna, implying also that a transmitting antenna alone in empty space would not radiate at all, just as the Feynman and Wheeler theory predicts for a single accelerating charge alone in the universe.

In order to study the form of the advanced radiation fields described by the Feynman and Wheeler theory, the absorbing boundaries (receiving antenna) surrounding the transmitting antenna must match the boundary conditions used in Feynman and Wheeler’s analysis. Niknejadi used the Feynman-Wheeler model to calculate that the dimensions of the antenna must be at most one-tenth of the wavelength of the radiation fields in order to avoid interference affects of the oscillating particles in the antenna, so that the measured field will be analogous to that of a single oscillating charge. To detect the advanced radiation fields, engineering work must be done to modify currently available electric field probes so that they are sensitive to the phase of the oscillating field. Calculations show that the time-averaged radiated power by a pair of coherently oscillating charges oscillates with their separation, which means that there must be an electric field (the advanced field) that oscillates in phase with the particle velocities to explain this (Niknejadi, Madey, and Kowalczyk, 2015, p. 5).

This experiment will determine whether or not the radiation fields can be described with only outgoing radiation, or if we need to include the advanced fields. If the measured power in the fields near the antenna can
only be explained if you assume the presence of both advanced and retarded fields near the antenna, this will determine the existence of the advanced fields. Furthermore, failure to detect these advanced fields would mean that either Maxwell’s equations or energy conservation is violated in this experiment, since these were assumed to be true in the analysis used to predict the power measurement. Detection of advanced fields would show that we need a time-symmetric theory of electromagnetic radiation such as Feynman and Wheeler’s, though it will not necessarily verify the Feynman-Wheeler theory in particular. It would show that in order to be compatible with both Maxwell’s equations and energy conservation, at the moment a particle radiates into free space, a non-local advanced radiation field is present in the vicinity of the radiating particle.

The need to use a time-symmetric linear combination of advanced and retarded fields within bounded systems has been known within the physics community since cavity quantum electrodynamics experiments done by Serge Haroche (Haroche, 2013). Haroche sent beams of particles known to radiate at certain frequencies into a reflective cavity made of superconducting walls (walls that are entirely reflective, and have no thermal absorption of the light). The particles would not radiate unless the boundaries of the cavity were aligned such that an even number of wavelengths of radiation light could fit inside the cavity. The radiating particle was aware of the boundaries of the cavity before it radiated, and hence before a signal was emitted and reflected back. This showed that advanced fields from the boundary were present at the location of the radiating particle at the time it radiated (or would have radiated). While cavity electrodynamics might have been considered a curious case to the physics community, where advanced fields were

\[1\text{Additional work would need to be done to see if Feynman and Wheeler’s absorber theory can be translated into a quantum mechanical version that is compatible with quantum electrodynamics. Quantum electrodynamics is currently formulated as a time-symmetric theory, but does not posit emitting and absorbing boundaries comparable to Feynman and Wheeler’s theory.}\]
3.2. The Need for Time Symmetric Radiation Theory

play a crucial role in explaining our experimental observations, Niknejadi’s hypothesis concerns radiation into free space, where the boundary can be assumed to be a distant, unknown absorber, as suggested by Feynman and Wheeler. If her hypothesis is confirmed experimentally, there would be evidence that Feynman and Wheeler’s absorber theory cannot be viewed as an alternative philosophical approach to the radiation problem, but rather as one of the best theories we have available.

Even without an experimental test, this analytical result advances the philosophical discussion of the problem of the direction of time in electromagnetic radiation. While the main argument against using time-symmetric formulations of electrodynamics or the use of the advanced fields are that these interpretations violate our picture of causality, Niknejadi showed that if we assume that energy is conserved, time-asymmetric theories of radiation violate Maxwell’s equations, the fundamental equations of electromagnetism.

A local, causal picture of the world is something we might hope to find in our scientific theories, but should be relinquished in the face of experimental evidence. We already have experimental evidence that our world is fundamentally non-local, from quantum mechanics experiments conducted as a test of a hypothesis by John Bell (Maudlin, 2011, p. 21). Bell showed that there are correlations between the states of distant particles that cannot be explained by chance or by local interactions between the particles, and can’t be explained by any hidden mechanism that locally correlates the states of the particles. The Maxwell equations have been confirmed on end to describe all electromagnetic phenomena, and so has energy conservation, which can make it more favorable to accept non-locality in classical electrodynamics rather than rejecting these fundamental equations and principles.
Chapter 4

The arrow of time in radiation theory

One suggestion raised by Mathias Frisch was that the textbook formulation of electrodynamics, using only the retarded solutions of the wave equation, presents no philosophical problems. He sees the problem arising from a desire to have the Maxwell equations alone be the fundamental laws of classical electrodynamics, which alone determine what is physically possible (Frisch, 2000, p. 406). He suggests that we take Sommerfeld’s condition of neglecting the advanced fields as an additional physical law, so that for the case of radiation into free space, the fields satisfy the four Maxwell equations plus the Sommerfeld condition (Frisch, 2000, p. 407). He claims that this should not appear any more problematic than if we had five Maxwell equations instead of four, and that it is just an empirical fact that radiation obeys an extra law that other electromagnetic phenomena does not.

He also claims that it is not a problem that the Maxwell equations and the retardation condition do not imply each other, arguing that we have a prior commitment to Maxwell’s equations as being the only laws of electrodynamics, since their formulation is a great achievement in the history of science, but no real reason to reject the idea that Sommerfeld’s retarded-only condition is also a physical law. He agrees with the textbook formulation of radiation, but for a different reason than given in the textbooks, which rationalize the use of only retarded fields to describe radiation by vaguely referencing causality. Instead of relying on flimsy arguments about causality, Frisch argues that it is an additional law of nature for which we need
to no explanation, because it is simply an empirical fact that radiation from accelerating charges has a direction of time.

Jill North criticized Frisch’s suggestion that there is no philosophical problem that there is a time-asymmetry in radiation theory (North, 2003, p. 1091). Frisch sees the problem being that the laws of electrodynamics, which are time-symmetric, govern radiation and we want an account of why we see a time-asymmetry in this case. He is seeking an account for why radiation from accelerating charges only emits retarded fields instead of advanced fields, even though either of these fields or linear combinations of them are allowed by the time-asymmetry of Maxwell’s equations. He presumes that the retarded-only fields are the only solution that describes radiation experiments. What then is picking out the retarded fields as the only physically realized fields? He suggests that it’s another law of nature. North points out that this suggestion is wrong because his formulation of the problem itself is wrong.

The Maxwell equations relate all of the electromagnetic fields present in the system to their sources, and this means that when we consider radiation from an accelerating charge, the solution to the wave equation, which is derived from Maxwell’s equations for certain sources, will describe both the radiation fields from the accelerating charge as well as whatever background radiation is present in the system. Light from ceiling lamps in a laboratory or the cosmic microwave background radiation, or other such background fields with unspecified sources, contribute to the observed field in addition to the radiation from the accelerating charge.

North notes that in order to describe radiating systems using the advanced fields, you need to add an unnaturally large amount of other radiation from unidentified background sources, referred to as the source-free fields (North, 2003, p. 1091). Since there are multiple mathematical representations of an observed field, each of which ascribes different sources for
different components of the field, there is no way to determine what the background field is based only on empirical evidence, since the mathematical representation of the observed field implicitly has a choice of background source-free radiation.

The source-free fields could be chosen to be zero for simplicity. While choosing the simplest form of the background fields leads to the textbook use of the retarded fields, our empirical observations do not pick this out as the correct mathematical description; it is merely a theoretical choice that we are free to make. The use of advanced fields with zero source-free background yields a different observable field than the use of retarded fields with zero source-free background, but you can still find an equivalent physical description using the advanced fields with another choice of background radiation. In reality, there is a certain amount of background radiation, and while we can’t know it precisely with the observed field, the retarded fields have a realistic source-free term, while the description with advanced fields doesn’t.

The philosophical problem cannot be brushed away by stating that advanced fields are mathematically possible but not physically possible, and make it a law of nature that only retarded solutions are physical, as Frisch tried to do. The Maxwell equations relate electromagnetic fields and sources in any region in space, and radiation from accelerating charges is no exception. Niknejadi’s theoretical developments also explicitly show that the retardation condition and its use of a radiation reaction field is inconsistent with Maxwell’s equations and energy conservation. Not only that, but she shows that only time-symmetric fields, such as those suggested by Feynman and Wheeler, satisfy Maxwell’s equations and energy conservation.
4.1 An Alternative Thermodynamic Explanation of the Arrow of Time in Radiation

In addition to arguing against Frisch, North presented another way for there to be fundamental time-asymmetry in radiation besides the Feynman and Wheeler theory. She suggested that the philosophical problem of how there exists an arrow of time for the radiation of accelerating charges can be resolved by considering the initial state of the universe at the time of the Big Bang (North, 2003, p. 1094). The dynamical laws are time-reversal invariant, but asymmetry can be introduced in the boundary conditions. David Albert presents the Past Hypothesis, the hypothesis that the universe started out in a low-entropy state, as a solution to the thermodynamic arrow of time. North expands upon this idea to suggest that we see a direction of time in radiation.

When matter began to clump in the early universe, the universe went out of thermal equilibrium. In order to go back toward equilibrium, accelerating charged particles in the hot clumps of matter would emit radiation into surrounding space. Given the low-entropy initial conditions, the probability of radiating toward the future instead of the past was overwhelmingly likely, since this is the direction for progression toward thermal equilibrium, where there is a much higher number of available quantum states. The particle could radiate toward the past, since this is allowed by Maxwell’s equations, but it is overwhelmingly unlikely to occur, if the universe was in thermal equilibrium in the past.

Just as it is physically possible but extremely unlikely for an egg to un-crack from off the floor, it is physically possible for accelerating charges to emit radiation toward the past, but extremely unlikely. For this reason we still only see future-directed, retarded radiation instead of radiation toward the past, just as was true in the early universe.

North’s suggestion provides an alternative view to Feynman and Wheeler
in attributing the arrow of time in radiation theory to thermal and statistical origins. However, on her theory, the fields near radiating charges are not presumed to be time-symmetric, as they are in the Feynman and Wheeler theory, which attributes the observed arrow of time in radiation theory to thermal dissipation in the boundaries of the system. While in North’s conception the state of the universe at the moment of the Big Bang determines the direction of time for radiation just as it does for the universe’s tendency towards maximal entropy, Feynman and Wheeler presume that for radiation into free space, advanced radiation from the boundary is always present near the source charge. The thermodynamic arrow of time determines the behavior of particles in the absorbing boundary, which can be very far away or at an unknown distance, but must exist for radiation to occur.

4.2 Experiments to End a Philosophical Debate?

North’s suggestion still has fundamental time-asymmetries in the near-field region of the charge, in that it is physically possible for charges to radiate towards the future or towards the past, but that for every instance of radiation, the charge emits a radiation field that either goes forward in time or backwards in time. In order to pass the Niknejadi-Madey test, the fields that exist in the region of interest need to be time-symmetric. While North’s theory seems a more plausible account for why we see retarded radiation fields than the textbook account or Frisch’s suggestion, it can also be ruled out by the Niknejadi-Madey test, because on her picture, microscopically, at the moment of radiation in the near-field region of the radiating charge, the radiation fields have a direction of time. Frisch’s hypothesis has already been ruled out by Niknejadi’s analytical result, because the Sommerfeld condition does not satisfy the Niknejadi-Madey test.
If experiments were to refute Niknejadi’s hypothesis, this would show that compliance with Maxwell’s equations or energy conservation is not true for all electromagnetic fields and sources. If non-controversial experimental results indicate that Maxwell’s energy integral is violated, Frisch’s idea of modifying or adding additional fundamental laws of electrodynamics might be worth taking seriously. The conservation of energy has been used so broadly and successfully in physics that such a result would be a better indicator that our current fundamental laws (Maxwell’s equations) don’t explain the experimental result. North’s argument against Frisch is that he isn’t taking into account the fact that all the fields in a region of interest must satisfy Maxwell’s equations. Niknejadi now has a proposed experiment that could prove whether or not this is true, at least if we want to retain energy conservation.

If Niknejadi’s hypothesis is confirmed experimentally, experiments will show that advanced and retarded fields must be present in the near-field region of a radiating charge. Niknejadi’s proposed experiments can help to rule out North’s suggestion, because we will be able to determine whether or not advanced fields exist near radiating charges, and what their functional form is. Additional theoretical calculations by Stephen Smith also show that the advanced components of radiation fields in antenna systems are attenuated due to interference more gradually than assumed by Feynman and Wheeler (Smith, 2015, p. 6). Experiments to confirm the existence of advanced field components may not necessarily confirm the Feynman and Wheeler theory, but they would show the need to adopt a time-symmetric theory of radiation. Regardless, this proposed experiment will advance the philosophical discussion on the arrow of time in electromagnetic radiation theory tremendously.
Chapter 5

Conclusions

What really is the source of the direction of time? Is it electromagnetic in origin fundamentally, or does it have to do with thermal dissipation? Will we ever be able to bring these debates out of philosophy discussions and into physics laboratories? Perhaps. The proposal by Pardis Niknejadi to determine the existence and form of the advanced radiation fields would be a monumental step in advancing electrodynamics and our philosophical picture of the world, and this could be carried out with presently available laboratory techniques. While this the proposed experiment would not shed any light on the origin of the direction of time, experimental studies such as this of the role and nature of advanced fields, light traveling backwards in time, can help us shape our philosophical accounts of the observed direction of time.

However, if technology becomes available, we could devise an experiment to study whether the origin of the direction of time is due to thermal dissipation in absorbing boundaries, as suggested by Feynman and Wheeler, or due to a time-asymmetry in the fundamental laws of physics. It is not possible to do experiments on a charged particle in unbounded space, but we could still in principle experimentally simulate a particle in a space without absorbing boundaries.

Superconductors have no resistance or thermal dissipation, which we can use in experiments to simulate unbounded space. As was shown in his Nobel Prize-winning experiment, Haroche determined that radiating particles would not radiate inside a superconducting cavity unless the frequency of the radiation was compatible with the reflective boundaries (Haroche,
The particles that Haroche used in his experiment radiate at regular time intervals; the presence of the superconducting boundary essentially stopped time for these particles when their radiation was incompatible with the boundaries.

A more ambitious version of this experiment was suggested to me by John Madey. Would a complex system, such as an amoeba or other small life form, develop as usual without a thermally dissipative boundary? Would an amoeba still age inside a chamber of entirely superconducting walls? Or would time stand still for this organism? While this tantalizing hypothesis is currently experimentally out of reach, since we don’t have the means to create a purely superconducting boundary and study something inside it, this hypothesis does show the importance for physics, not just the philosophy of time, to consider these philosophical questions about the direction of time in radiation theory. Experiments in the near future could confirm the existence of advanced radiation field components, forcing us to discard standard textbook accounts of radiation, and opening up the possibility for technological applications of advanced fields. Niknejadi’s recent discovery has opened up a new direction of inquiry into this philosophical debate, moving us forward toward a better understanding of the direction of time.
Bibliography


