The History of Modern Physics

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Chapter 1

Classical World Pictures

1.1 The Scientific Revolution

The Copernican Revolution combined with Gallileo's innovation of a new telescope jumpstarted astronomy and allowed for a reconstruction of the heavens with a newfound motivation for mathematics in mind.

1.2 Newtonian Mechanics

Newton brought the new math of calculus to particle (terrestrial) mechanics together with celestial mechanics to formulate what became known as Newtonian mechanics.

The two key features of Newtonian mechanics are

1. Kinematics (trajectory)

2. Dynamics (forces, causes)

These two key features tied in very well with the traditional values of natural philosophy: the study of change and its causation.

In addition to the physics for which he was well known, Newton spent much of his time investigating theology and alchemy, which he considered to be valid natural philosophical pursuits.

1.2.1 *Principia*

Newton's *Principia* detailed his laws of motion, which assume absolute time and space. His uniform gravitation force law was used to derive the elliptical orbits of planets previously found.

A problem of classical mechanics that remains unsolved even today is the three-body problem: what is the mechanical fate of a sun, planet, and moon when gravity is considered? Though there are approximations to the answer found in "perturbation theory," physicists have long labored to use Newton's pure mathematics to derive an exact answer.

There were a number of other problems the *Principia* touched on but did not provide solutions to. Among them are fluid dynamics and the mechanics of continuous matter rather than particles.

1.2.2 *Opticks*

Newton's *Opticks* detailed experimental setup and results for his examinations of light, which he tried to explain in mechanical terms.

He proved the decomposability of white light into its component colors, and proved these colors can not be transformed to others.

Though not as well-known now, the work was extremely influential at the time of publication.

1.2.3 Mechanical Philosophy

There are four key components to the tradition of physics that Newton established:

1. All phenomena are matter in motion subject to forces
2. Mathematical evaluation of data
3. Reductive: explains large phenomena as small particles, or corpuscles
4. Abstract: indirect explanations, manipulations of sensory observations

1.2.4 "I frame no hypotheses"

Though Newton had no idea as to the true nature of what caused gravity, he was nonetheless very speculative of causes in both his major works. True to the ideal of natural philosophy, Newton felt he and other physicists must go beyond description and provide a reason for phenomena.

1.3 The Influence of Newton

The philosopher Immanuel Kant (1724-1804) used Newton as the basis for much of his work, assuming the absolute time and space that Newton postulated in his *Principia*.

1.3.1 Post-Newtonian Programs

There were two principal schools of thought — idealogies of how to approach the science — of physics in the late eighteenth century: Laplacian physics and rational mechanics (Table 1.1).

1.3.2 Refraction

Both Laplacian physics and rational mechanics attempted to explain refraction, the phenomena of light bending through glass that is explained by Snell's Law.

The Laplacians hypothesized that interactions between light and glass microparticles at the interface of the two substances caused the bending of light. They postulated a force law of these microparticles and used it to derive Snell's Law.

Rational mechanicians had a general solution that could determine the minimal path required to traverse a distance, and applied it to this problem. Their result was also a derivation of Snell's Law.

1.3.3 Heat

Heat was another pressing phenomena that begged scientific explanation, and both disciplines tackled the problem.

Laplacians saw heat as a subtle fluid called "caloric" which could penetrate bodies, thus endowing them with heat. An example of a realization of this theory is in the primitive steam engine, where heat moves from the fire to the water to the steam. Later, some Laplacians postulated an alternate explanation of heat as a motion of invisible particles.

Laplacian Physics	**Rational Mechanics**
• Derive specific observed phenomena from micro postulated hypotheses about 1. Basic constituents of matter — particles or subtle/imponderable fluids — which were massless and flowing through all things 2. Force laws that operate between those basic constituents • Metric to gauge correctness of theory was if natural observations could be derived from suppositions • Determinism, or complete prediction of future events, *a la* Laplace, emerged from these initial ideas • Paradigmatic example: capillary action • Entirely a French movement in Paris under Laplace	• Generate very general, very abstract ways of handling entire classes of problems and ignore the whole question of the micro substrate • No interest in postulating basic components — a de-emphasis on hypothesis • Ignored forces, and causation • Heavily kinematic • Paradigmatic example: wave motion, fluid flow, and elasticity were all specific cases of one rational mechanics problem solving tool • At first a French movement that eventually took hold in Britain

Table 1.1: Characteristics of Laplacian physics and rational mechanics, two post-Newtonian paradigms in physics.

Rational mechanics put forward their traditional view that the nature of heat is itself uninteresting but that we can mathematically characterize heat as a continuous fluid, as Fourier did.

Count Rumford, famous for the invention of the drop coffee maker and some cannons, postulated that it was possible to generate an indefinite amount of heat by friction. He saw this as evidence to disprove the caloric theory of heat.

Joule's (1818-1889) experimental apparatus for heat transformed mechanical motion to heat with a paddle wheel around a liquid. The increase in temperature of the liquid could then be measured and the heat quantified. Since his family raised him in the tradition of the brewers since a child, Joule was extraordinarily skilled at reading a thermometer. He claimed to be able to discern 1/200ths of a degree Fahrenheit, a skill he used to get precise measurements of the heat of mechanical energy.

1.4 Evolution of Thermodynamics

1.4.1 Joule's Statement of Equivalence

By showing the factor in the equivalence relation for heat and mechanical work was constant with respect to fluid, Joule was able to assert that there existed some fundamental natural relation between heat and work.

1.4.2 Heat and Newtonian Mechanics Fuse

Interest in the equivalence of heat and work was motivated by the industrial work with engines of the eighteenth century.

Terms such as "work" became well-defined because of work with machines. The term "force" also had a specific Newtonian definition, but Joule was using it for a specific, different meaning.

What Joule was really getting at was "energy," a concept whose term was later coined by Helmholtz. Energy served as the basis for Newtonian mechanics problem solving and as a basis for extensions to Newton and further research.

1.4.3 Conservation of Energy

Conservation of energy was a concept that crystallized in the mid-nineteenth century out of a flux of ideas concerning heat, work, and other energy forms. It acknowledged:

1. The umbrella concept of energy which recognized many varied phenomena as cases of a larger, overarching order to the universe
2. Forms of energy are not fixed but actually interconvertible

An immediate consequence of this theory is the many possible forms for energy, which made it applicable to many fields of research and therefore became strikingly popular across physics. One extreme example is Dr. Robert Myer, a German physician who used energy to explain how food intake relates to body heat production.

That's not to say that there did not exist opponents to the theory. They were prevalent especially as reactionaries to the romantic connotations of the energy theory.

A precursor to energy is the earlier postulated analog more specifically for kinetic energy, *vis viva*.

1.4.4 Origin of Energy

The interest in understanding work and interconversion of natural "forces" contributed to the formulation of energy theory.

Also, the particular form of natural philosophy in England and Germany at the time, called *naturphilosophie*, which investigated nature as an energized holistic system, contributed to the formulation of energy.

Even the English authors Wordsworth and Coleridge can be seen as a part of the movement toward a energy-driven, romantic (in its ideals) system of physics and philosophy.

1.4.5 Helmholtz's First Law

The Imperial Chancellor of German Physics Hermann von Helmholtz (1821-1894) reigned supreme in championing the energy theory to a newly-unified Germany in the 1850s. Though he initially refers to the interconvertible characteristic of nature as "force," Helmholtz is quick to correct himself and shows that the quantity which is conserved is distinct from force.

Before publication of his landmark paper in 1847, Helmholtz was a relatively unknown scientist that loomed on the outside of major natural philosophical circles. His mathematical and medical education allowed him to propel himself to the forefront with his breakthrough research on the conservation of energy, which later became the *first law of thermodynamics*.

A highly epistemological work, his paper states that if we can describe everything in the world as forces then everything worth knowing about nature could be known. Again, the romantic nature of the physics of the day is apparent since energy theory can be seen as the logical destination, or pinnacle of progress, of physics thus far.

Helmholtz had a personality that was played up as the unifier of German physics, as an analog to the politics of the day. He was highly involved in German liberal politics in the 1840s-1850s, and this surely influenced him to not only strive to increase communication between German states, but also unify the domain of modern physics under the energy theory.

1.4.6 Rational Mechanics and Energy

These British theorists used energy to describe nature. Forces and even particles were too specific of cases to consider; instead, they considered energy as the prime object to describe since it will always be there, according to the conservation of the new theory.

1.4.7 Thermodynamics

Thermodynamics emerged from this maelstrom of scientific research and ideas surrounding energy, post-Newtonian physics, and heat. It became known as the study of energy's transformations, and was originally used as an adjective (thermodynamic).

1.4.8 Carnot Engine

Though many good engines were invented empirically by the early nineteenth century, physics took on the task of creating the one ideal and perfect engine.

This line of investigation begins with Sadi Carnot's (1796-1832) *Reflections on the Motive Power of Heat*, in which he asked what the perfect engine is and what the closest real-life approximation to achieving this could be. Carnot derived his ideal engine which consisted of two adiabatic and two isothermal processes, and was completely based on caloric heat theory. Yet, his findings and postulations seem to be completely compatible with energy theory.

1.4.9 The Second Law

Formulated by both Thomson and Clausius as a result of increased interest in steam engines in the nineteenth century, the *second law of thermodynamics* attempted to reconcile the energy difference between theory and observation in a meaningful way.

Thomson grew up in early nineteenth century Glasgow and was greatly influenced by his brother, a practical engineer who made him notice the conflict between theory and practice in energy conservation.

Thomson claimed that Joule's perfect equivalence of energy was untrue and that some heat would inevitably be irretrievably lost in practical applications. Thomson realized this limit on the perfect interconvertability was a phenomenon related to, but distinct from, the first law.

Clausius saw a different side of the same angle as Thomson. He detached Carnot's perfect engine from heat conservation. Remember that Carnot thought heat, or "caloric," was a conserved quantity, and so he thought that temperature differences drove the work performed by an engine. Therefore, Clausius formulated the idea that heat always shows a tendency to erase temperature differences.

There are many interpretations of the second law:

1. Directionality: heat flows from hot to cold in a closed system
2. Irreversibility: some processes only run in one direction
3. Entropy: never decreases (coined by Clausius)

For example, heat flows on its own in a room from areas of higher temperature to areas of lower temperature. There is potential work in this temperature difference, but it is not recoverable energy.

A key point is to realize the second law was formulated under influences from Laplacian Physics as a postulate. They didn't care so much as to why the law existed as to what other natural phenomena could be derived from the law.

Thomson's early 1850s paper on the laws of thermodynamics claimed that scientists needed to try to understand how energy could be lost yet not annihilated. As a Calvinist, Thomson saw a moral analog to the second law in that God asserted the human world was tainted and imperfect after the original sin.

Because of his contacts with Joule and Helmholtz, Thomson assumed the conservation of energy even five years after its publication and could then formulate the second law based on the first.

1.5 Electricity and Magnetism

Although seemingly unrelated in ancient times, the phenomena of electricity and magnetism were both interactions without apparent causes and were subject to human manipulation.

In 1734, Charles Dufay observed the first static electricity, which resulted from some of the new technological innovations such as carpets, good insulators, and batteries.

The reason why current electricity would not be observed and explained until almost a century later is that, although there were plenty of wires able to carry current, there were no batteries large enough to supply an observable current.

Laplacian Physicists postulated subtle fluids as the driving forces behind these strange phenomena.

1.5.1 Coulomb

Charles Augustin Coulomb made precise measurements of electrical force as a function of distance with very specialized instruments, and found that the force adhered to the law:

$$F \propto \frac{1}{r^2}$$

There was massive appeal to another inverse square law in physics, namely because

1. The mathematics of inverse square laws could be easily adapted from Newton's formulations with gravity

2. There was speculation as to electrical force being caused by the same forces as gravitational force

Coulomb's results were accepted in mostly Laplacian circles, but rejected elsewhere, mostly because the results were nonreproducible. Coulomb was a master of making appartus, and did not reveal the precise specifications of his instruments in his publication, for reasons unknown. Even modern historians were only able to reproduce his results with the help of a later-developed invention, the Faraday cage. This led the historians to conclude that either:

1. Coulomb concluded the rightness of an inverse square law in advance and purposefully fudged the data, OR
2. Experimental precautions he took were undocumented

1.5.2 Ampéré

The investigations of Ampéré (1775-1836) were focused more on interactions of current-carrying wires, which he explained with an inverse-square law. A true Laplacian Physicist, Ampéré imagined current flowing in a loop as the basic unit of magnetism.

1.5.3 Faraday

The discovery of induction, the phenomena by which current is stimulated in a wire by current in an unconnected nearby wire, in 1831 is credited to Michael Faraday. Wrapping up the previous findings of the electrical physicists in a nice, easily digestable package, Faraday intensified interest in electricity and magnetism.

1.5.4 Oersted

In the 1820s, Oested (1777-1851) made progress on realizing a theory of the interconvertability of electricity and magnetism.

Due to his mental groundings in *naturphilosophie*, Oersted was deeply committed to seeing underlying connections in nature between electricity and magnetism.

Unsatisfied with a description of the new phenomena of induction with previous physical terminology, Oersted postulated that, rather than the wires themselves, the space outside the current-carrying wire is altered by the current.

Always concerned with forces acting between bodies instantaneously *through* space, not *from* space, Laplacian Physicists initially wrote off Oersted's idea as "typical *naturphilosophie* obfuscation." Though these two approaches to physics were for the most part diametrically opposed, there were some situations in which they agreed.

1.5.5 Lines of Force

Drawing on the ideas of Oersted, Faraday postulated a continuous field of forces in space that is created by a permanent magnet or induction.

A field was defined as:

- A way of representing how bodies can influence each other
- A modification of the space itself
- A region in which a force operates
- An equation

Since the concept of a field was distinct from any Laplacian physical formulation, there was no straightforward representation for a field initially. Faraday had a visual intuitive feel for the nature of the field, but his concept was refined by mathematicians, making the notion of a field very powerful. Once the mathematics were worked out, field theory was even applied to some problems of classical mechanics.

1.5.6 James Clerk Maxwell

Maxwell attempted to guide the confused natural philosophers of the mid nineteenth century by introducing *physical analogies* to make understanding the nature of a new concept more intuitive.

His first use of the concept applied what was already known about fluid mechanics to the example of force fields:

Force lines	↔	Fluid mechanics
Density of lines Strength of force	↔	Density of lines Speed of fluid
Origin of lines	↔	Sources or sinks or fluid

Neither rational mechanics nor Laplacian physics used analogies to explain physics before Maxwell. His thinking combined the intuition of the old physics to a new application, thus providing great fuel for ideas:

1. The already worked out, better known mathematics was applied to a new concept, thus borrowing mathematical quantitation of the old analog

2. The physical intuition accompanying the old concept lends hints as to the true nature of its new analog

1.6 Light

1.6.1 Luminiferous Æther

Since Newton's *Opticks*, light was assumed to be a corpuscle, as in refraction, that was acted on by matter through forces.

The nature of light was furter investigated following Newton by Huygens, Young, and Fresnel, who postulated that light is a pulse or wave in an omnipresent medium. Though Huygens believed light to be only a longitudinal wave, the later investigators also observed phenomena of light (polarization) that behaved like a transverse wave. This "two-sidedness" of light was well-developed by the early nineteenth century.

Comparing light to a vibration in a solid medium was the only way to accurately represent light using an analogy. As strange as supposing that light could only exist in a solid medium was, it was a useful analogy that eventually led to the postulate of an invisible, omnipresent, solid luminiferous æther.

1.7 Maxwell's Equations

1.7.1 Thomson's Fluid Æther

An odd phenomena known as "magneto-optical rotation" was observed in connection with the Faraday effect. A strong magnetic field could affect the direction of polarization of light.

Thomson explored the analogy of electromagnetism as a torsional force in the solid luminiferous æther to get ideas about the subject. Thomson pushed the boundary of the ontology of this æther: he tried to theorize what a physical manifestation of it could exist as.

In contrast, Faraday saw fields as the only real phenomena of electromagnetism and didn't think these analogies were useful in understanding the nature of the observations.

In exploring the many options suggested by this theorizing, Thomson developed a model of a fluid luminiferous æther with vortices like liquids. This theory leads to some minor offshoots such as a vortex atom that resembled a toroid, had varying modes of vibration, and was quite stable. Supposedly Thomson was led to this theory by the influence of his smoke-rings, which exhibited all the characteristics of his vortex atom.

As a side note, there is a possible analogy to be drawn between Thomson's vortex model of the atom and current work in string theory. Historical investigation into the extent of Thomson's influence on string theorists has not begun.

1.7.2 The Second Analogy

A physical analogy that supposed elastic cells and cell walls were accurate models of Thomson's vortices. This highly abstract analogy postulated tiny movable bearings as carriers of force between cells.

Maxwell studied how this model system responds when it was set vibrating with a transverse wave. Using his intuition with the known physics and mathematics of his model system, Maxwell drove his theorizing about electromagnetism forward. Surprisingly, he was able to derive an analogy to many observed electromagnetic phenomena.

The most incredible finding, by translating and back-translating physical constants with his model, was that the velocity of propagation of the transverse wave was equal to the speed of light within 1%. Maxwell then deduced that light was actually the physical manifestation of a transverse electromagnetic wave. However, he acknowledged that "the nature of this mechanism is to my mechanical model as the solar system is to an orery" (a mechanical solar system).

It is important not to think of light as a wave in the fluid sense, but rather as an oscillation of the electric and magnetic fields in space. However, Maxwell knew of it only really in the sense that he had derived a relation of the oscillation's velocity to the speed of light.

1.7.3 *Treatise on Electricity and Magnetism*

In this gargantuan work, Maxwell stepped back from his analogy and stated his results in their full mathematical splendor. In fact, much was a statement of the importance of previously known laws, but nevertheless Maxwell's rational mechanical explanations of electromagnetism clearly revolutionized the field.

This publication also marked a unification of electromagnetism with energy physics, thermodynamics, and Newtonian mechanics.

Maxwell's original publication was not in terms of familiar vector calculus, which was then thought of as a "hermaphroditic monster" by some.

Though it seemed like an end-all to physics, it must be understood that Maxwell's understanding of basic universal components was nothing like ours.

1.7.4 Porting the Theory

Maxwell, Thomson, and Faraday did their work in a very close-knit community, full of insider knowledge and even jokes. For example, in a book Thomson published with Tait, he managed to express a physical law with an equation that included Maxwell's initials:

$$\frac{dp}{dt} = JCM$$

Subsequently, Maxwell would sign correspondence to Thomson with $\frac{dp}{dt}$!

With such an insider community, it was difficult to translate British field physics, much less Maxwell's equations, to the Laplacian outside world of Germany.

However, with the help of a translation of the *Treatise* by Helmholtz, physicists outside Britain began to understand even Maxwell's equations. Maxwell's theory reformulated by Helmholtz agreed with experiment, but was only comprehensible to an elite few. Even Heinrich Hertz said of Maxwell: "Maxwell's theory is Maxwell's system of equations." As such, the complexity of the mathematics often shrouded the significance of the physics, causing many scientists and, later, undergraduates, to think twice about entering physics.

1.8 Reform of Maxwell

Thirty-five years after the joining of the electromagnetic theory with optics, there still had been no discovery of "undetected" jumps between observed frequencies.

Hertz did some work which became the basis of "wireless" radio broadcasting. He worked on Maxwell's equations and tried to make an experimental test of the theory.

1.8.1 Maxwellian View

To the followers of Maxwell, fields were the only real phenomena. They were the natural entities which generated charges and currents, which were seen to be secondary effects of discontinuity in the fields. In contrast, what we think of these days is that charge causes a field.

1.8.2 Reform

Hertz had to leave his familiarity with charge and current behind to work with Maxwell's field theory. Hertz reformulates Maxwellian ontology and includes charge and current as principal objects. This creates a "two-leggedness" that makes the field theory conceptually awkward during the early 1900s. For example, in Maxwell's equations, the current is defined as a derivative of the field, which makes no intuitive sense to us, nor did it to Hertz.

1.9 Unification of Physics

The hallmark of classical physics, the unification of thinking of the physical world was marked by:

1. Unity of communities and people
2. Unity of approaches and methods of understanding
3. Unity of subject matter

There should be some way to capture all phenomena under one model system. How can we prove this unity?

What substance is there to the assertion that physical analogies reveal insight into the true nature of the world?

1. Methodology/epistemology assumes truth in all experiences. The question of the model versus reality drives the philosophy of physics.

2. Ontology assumes the world's underlying components are some substance and analyzes results based on these assumptions.

3. Metaphysics in general says something about the universe's character, readability, simplicity, and rationality. It asks questions on the nature of mind and matter, the spirit world and the physical.

4. History had revealed that since there was no more appeal for stories of creation, people turned to explain their experiences with logic and physics. Synthesis of the past to gain insight into the present is useful, but past events of course need not imply future happenings.

1.10 Mechanical Philosophies

Established by Maxwell in the 1860s and 1870s, these questions promted by Maxwell asked if the nature of the universe, or simply our view of the world, was revealed by a physical theory.

Maxwell proved that there can always be more than one mechanical model that accurately serves as an analog for an observed physical system. This gave rise to the question of which mechanical model was most valid.

1.10.1 Britain

For some reasons outlined below, British physics had an inclination to formulate most of the physical analogies — mechanical models — of the late 19th century. There was a uniform distaste for this approach to physics among scientists on the continent, with the exception of Boltzmann.

New philosophers had the belief that science will move culture forward with its proposed new methodologies and epistemologies.

1.10.2 Pierre Duhem

This late 19th century French philosopher (1861-1916) saw the goal of science as to, classically put, "save the phenomenon." The point wasn't so much to explain as to represent it completely, simply, and exactly.

Duhem advanced the philosophy that there was nothing behind the equations. Like fitting the best line to a set of cartesian coordinates, you need to examine the space of all possible theories to arrive at the one most applicable to explain the observations.

Later in his life, he laid out his thoughts in the Duhem-Quine thesis: "Your choice is underdetermined by the evidence. There is an element of convention in which you choose. No crucial experiment can force you either way."

1.10.3 Ernst Mach

An anti-religion sensationalist, Mach's philosophy was that science was the process of finding a way to represent an idea concisely. Physical laws are the easiest, most logical way to condense sensations this way.

Mach agreed that there was nothing more than this; the question in science is not why something happens, but how.

Trained in math and physics, Mach spent much of his life determining the function of the ear and other sensory physiology.

1.10.4 Overall Trends

There were overall trends toward the:

1. Antimetaphysical: science says nothing about the world's fundamental nature
2. Intrumentalist: science is about coming up with tools that let human beings act effectively
3. Convention: These tools aren't dictated by nature but chosen by us

1.10.5 Hertz' Rethinking

In Hertz' *Principles of Mechanics*, he insisted that if mechanics is the center of physics it must be understood and clarified. He critically reviewed some of the more abstract concepted of mechanical physics, such as force, which was invisible and made no intuitive sense in problems such as statics.

Hertz attempted to explain everything in terms of matter in motion rather than force, which resulted in a reformulation of mechanics based on myriad tiny hidden masses.

1.10.6 Wilhelm Ostwald

Treating physics and chemistry with the talk of energy and electromagnetism, Ostwald (1853-1932) believed the only reality was formed of fields and from these everything must be derived.

1.10.7 Hendrik Anton Lorentz

Lorentz (1853-1928) believed that the measurable mass of a particle depended on its velocity, and that any particle's speed has the upper limit c, the speed of light.

Though Einstein is popularly attributed this discovery, Lorentz had indeed formulated it first.

1.11 Statistical Mechanics

1.11.1 Micro v. Macro

This theme had been troubling physicists since Laplacians speculated about the micro universe.

"How can we be sure Newtonian mechanics can be applied in the microscopic world?" many physicists asked.

The attempt to reconcile classical mechanics with thermodynamics was the slipping of the micro under the macro that resulted in statistical mechanics.

1.11.2 Kinetic Theory of Gases

Newton's theory of gases, further studied by Bernoulli, postulated corpuscular particles in the key components of the gas. It "explained the macro properties of gases in terms of motions of micro constituents."

The hypothesis was that the units were elastic spheres which obey the laws of Newtonian mechanics. This supposition led to the prediction of pressure as a function of impacts of these spheres on the walls of the container.

However, the slight complication was that there was no definite way to predict the behavior of the gas since it was a multi-body problem in Newtonian mechanics, which was a complete mess.

1.11.3 Clausius

In 1857, Rudolf Clausius published *The Kind of Motion We Call Heat*, which assumed uniform speed and uniform free path of gases, and found he could derive the three phases of matter.

1.11.4 Maxwell

Maxwell grasped the complexities of the problem and found a middleground between the tough Newtonian mechanics and the simple Clausius analysis by treating the speeds of the molecules statistically.

Maxwell assumed a distribution of speeds was the best way to represent the particles of a gas, and was able to derive a number of actual interesting phenomena from his postulates.

1.11.5 Boltzmann

Boltzmann generalized Maxwell's distribution by showing how it could handle more complex situations involving many kinds of gases.

He was able to derive viscosity as a function of pressure and velocity.

1.11.6 Statistics

In the sixteenth through the eighteenth century, statistics was primarily a study of games of chances and variation in human populations ("social statistics").

As an analog to the micro world of individuals being described by the macro population parameters, the statistical mechanicians hoped to use the results from probability to explain the macro gas phenomena with a micro world of gas components.

1.11.7 Atoms and Gases

To Maxwell, gas theory was just a physical analogy used to get a better sense of the nature of gases.

Atoms had been hypothesized by Dalton, but his notions about the nature of the atoms were entirely different from ours today.

Thomson (1827-1903) declared in the 1870s that atomism was mostly speculative.

1.11.8 The Second Law

The second law of thermodynamics was revisited in light of the statistical picture.

Maxwell proposed a little demon that operated a door between two samples of hot and cold gas. Each gas has an associated distribution of speeds, and the demon gets to choose which molecule gets to pass. In this way, he can make the hot gas hotter and the cold gas colder.

Is this a contradiction with the second law of thermodynamics? Yes, since we can't control these small molecules. Since it is possible to imagine the demon, it must be possible to image a world without the second law of thermodynamics.

The point is that the demon is a stimulating thought-piece. This proves that there are problems with asserting the second law in microscopic situations. It was a provokative sentiment that drove the field forward. Abandonment of Laplacian determinism fueled growth.

1.11.9 The Arrow of Time

This statement refers to a fomulation of the second law, which states that diffusive processes do not reverse, except for microscopic irreversibililty.

This was the real argument against using Newtonian mechanics on the micro level: Newton is always reversible but micro gases are, as a rule, not.

Boltzmann tried to derive the macro irreversibility from micro reversibility using mechanics but concluded that it was an impossibly flawed approach. He asserted that the macro irreversbility was better explained by a statistical argument that said that even though some phenomena were statistically improbable, they were nevertheless theoretically possible.

Boltzmann also derived a relation between entropy and the micro description by counting the number of microstates:

$$S = k \log W$$

Thus, statistical mechanics abandoned absolute irreversibility.

1.11.10 Import

The second law of thermodynamics being proven wrong in some cases suggested that the classical world pictures most physicists saw the world as should be questioned and thrown out if data contradicts experiment. In this way, statistical mechanics acted as a bridge between classical and modern physics.

1.12 The Infrastructure of Physics

The term “physicist” was termed in Britain in 1840, at a time when the discipline was tending to become more professionalized. The system of credentialing (doctorates, degrees, etc.) to a large extent determined who was a physicist, and often would determine a young scientist’s career path.

Though most science work took place in France, Britain, and Germany, other countries were involved, such as Italy, Holland, Japan, Russia, and U.S.A.

1.12.1 Centralized France

Science in France was science in Paris at the turn of the nineteenth century.

Beginning a long tradition with the Paris Academy of Sciences set up in 1666, the educated in France came to see Paris as the destination for science.

Though there was a separate system of Ecoles, such as the Ecole Polytechnique which trained engineers, most scientists saw the research positions and professorships at the central Paris Academy the most valuable.

In the mid-nineteenth century there was an overall complaint of declining lab facilities, equipment, and staff, that let Britain take the lead in physics research.

1.12.2 Provincial Britain

Much research in Britain was done in provincial industrial cities such as Glasgow and Manchester. For example, Joule, Thomson, and Maxwell researched at these red-brick universities, which were designed to reflect the discipline’s humble origins. These institutions were oriented toward practical training and were centers for educational and intellectual innovation.

In contrast, the major site of research in Britain was at Cambridge, the site of Newton and Maxwell. Only the Anglican elite were allowed to enter the school, which for a long time focused more on raising gentlemen leaders than on science. There were many arguments about science’s place in the curriculum, and in society in general, but science was finally integrated into the coursework with mathematics, which was viewed as a field that promoted mental discipline, akin to the study of Latin or Greek.

Cambridge's Math Tripos was an extraordinarily challenging mathematics exam that was seen as the culmination of years of study of physics. The highest scorers were called wranglers and were publicly ranked, with their rank often determining their careers' future progress. Maxwell was only a second wrangler, and this fact stymied the development of his otherwise excellent career for the rest of his life.

Science labs entered the university starting with the Cavendish Lab in 1871, first directed by Maxwell.

The British Association for the Advancement of Science (BAAS) was established in 1831 to strengthen the connections between the provincial research sites. From the outset, it had ambitious goals, such as planning a trans-Atlantic telegraph cable.

1.12.3 Competitive Germany

The university of Berlin became the archetype for universities worldwide, and especially within the newly-united Germany. The university's main goal was the idealistic pursuit of knowledge in its own right, an ideal only accurately described with the German word *wissenshaft*.

Theoretical physics differentiated from experimental physics and became a field of study in its own right. However, tensions built between the quest for ideals and the desire for useful applications of knowledge.

Academic research in Germany fluorished. The number of papers published skyrocketed. Many new buildings were built and professors were hired to accomodate this expansion.

Germany also saw a massive industrialization of science.

A system of Technical Institutes was established in Berlin and repeated throughout the country.

The Imperial Physical-Technical Institute (PTR) was also established to maintain applications of physics, such as standard measures.

The Kaiser Wilhelm Institute for Physical Chemistry and Electrical Chemistry was established as applications of physics grew more diversified.

Chapter 2

Challenges

2.1 Radiation

2.1.1 Away from Classical Mechanics

Despite the somewhat complacent feeling physicists had for the "perfect" classical mechanics of the nineteenth century, the well-ordered, secure, and harmonious theories of the past were about to be thrown out by the discovery of the new phenomenon of radiation.

More than a strange transition from classical physics than a revolution, the attempt to explain radiation was the first in a series of discoveries that shifted physics toward a new era of exploration.

This era saw a trend away from the emphasis on theoretical exploration characteristic of classical mechanics, and toward innovative experimentation in small labs not necessarily at the center of the physics establishment.

2.1.2 Cathode Ray Tube

In a glass "cathode ray tube" mostly evacuated with air and attached to a battery, a series of luminous colors and glowing lights from the tube was detected.

More evacuated tubes showed a series of strange bands, and tubes filled with no air showed no light. The emphasis on exploring the phenomenon of this non-ideal (i.e. non-evacuated) system contrasted with technological progress, which was ready to supply devices for full evacuation.

In addition, the ray was deflected with the physicist's laboratory staple, a common magnet.

The apparatus for these experiments was very low-tech, and, consequently, any provincial physicist could make one. This resulted in a string of Nobel Prizes at the turn of the twentieth century.

2.1.3 Röntgen

The provincial German physicist Wilhelm Conrad Röntgen (1845-1923, say "Rundgen") noticed some strange new phenomenon outside one such cathode ray tube.

When bent with a magnet, the ray would come in contact with the glass, fluoresce, and emit an invisible but nonetheless detectable stream of rays to the outside of the tube. These rays were detected with photographic paper which happened to be nearby and were dubbed Röntgen rays or X-rays.

He made some observations about X-rays that were consistent and inconsistent with phenomena of light:

1. Propagates in a straight line
2. Unaffected by a magnetic field
3. Absorbed by matter
4. Not reflected or bent by prisms or lenses
5. Not polarized

There were many explanations of this phenomena:

- Uncharged particles
- Sound waves
- Gravity waves
- Æther vortices
- Longitudinal waves in the electromagnetic æther
- Transverse waves in the electromagnetic æther
- Short wavelength light

2.1.4 Applications

Applications of X-rays were known before the nature of the phenomena was revealed.

Using only screens and photographic plates, Röntgen was able to photograph human bones.

The first X-ray crystal structure of a molecule was that of ZnS powder in 1912.

W.L. Bragg and W.H. Bragg received the Nobel Prize in 1915 for their discovery of a generalizable X-ray diffraction method.

2.1.5 Becquerel

The Frenchman Henri Becquerel (1852-1908) was, due to a longstanding family tradition, interested in phosphorescence, the phenomena that causes some materials to glow in the dark.

Consequently, he was interested in the behavior of the phosphorescent spot on the glass tube in a CRT when the ray was bent with a magnet. He knew of the X-rays that were generated by this ray.

Along the same lines, he took another phosphorescent material, uranium, and exposed it to a photoplate. The photoplate darkened even when the uranium had not been exposed to light, which indicated he was observing a phenomenon distinct from phosphorescence, what we now know as radiation.

No one had noticed before, even though uranium had been around for many years. This is a great example of Louis Pasteur's statement that "chance favors only the prepared mind." Becquerel received the Nobel Prize in 1903.

2.1.6 Rays

As a result of the legacy of a classical education, the newly discovered three rays that were emitted from the uranium were given the names α, β, and γ:

α Bent a little

β Bent a lot in the opposite direction

γ Straight trajectory

2.1.7 Curies

The couple Pierre and Marie Curie discovered that uranium in its usual form was just a heterogenous blend of many types of rock and that only a portion of it was radioactive.

Through a series of painstaking chemical treatments, the Curies were able to isolate pure uranium and discovered the elements radium and polonium in the process.

Though they were working in an outdated, minimalist French laboratory, they were awarded the Nobel Prize in 1903.

2.2 Radioactivity and the Electron

2.2.1 Energy of Radioactivity

The phenomena of radiation was begging to be explained in terms of energy, a paradigm established by the thermodynamics of the nineteenth century. What was the source of the conspicuous amount of heat generated in radiation?

Possible explanations considered were:

- Energy somehow not conserved (violation of first law)
- Ambient heat somehow being concentrated (violation of second law)
- Energy picked up from some mysterious, invisible, omnipresent external source
- Inside the radioactive substance

2.2.2 Rutherford

With Soddy, Ernest Rutherford conducted a series of experiments in 1902 that led him to conclude radiation “transmuted” one chemical into another. Invoking the alchemical term was somewhat taboo in science, but it was an adequate description of the phenomenon.

Rutherford was a physicist who described the discipline of chemistry as “stamp collecting” compared to physics. Nevertheless, Rutherford was awarded the Nobel Prize for the chemical techniques he used to explore the properties of radioactive decays.

2.2.3 Radioactivity as a Decay

Radioactivity was seen as a decay in the sense that α particles could be collected and compared with samples of known elements. It was in this manner that α particles were identified as helium atoms. The substance left behind after release of the particle was transmuted into a new chemical.

By characterizing the properties of the chemicals resulting from successive decays, physicists like Rutherford described radioactive elements with a series of decays of radioelements (names such as Radium A and Radium B assigned for convenience). It was only later established that these intermediate decay products were chemically equivalent to other known elements. Conversely, some new elements were discovered through investigation of radioactivity.

The decay was found to follow a negative exponential probability distribution, which accurately described the behavior of a large population of atoms but made only probability statements about single atoms. Using this framework, the rate of decay of a substance was found to be a unique characteristic of that element and was quantified via the “half-life,” or the amount of time it takes for half of a sample to decay.

Without the idea of the nucleus, these initial investigators had no idea about the nature of this decay phenomenon in the context of the atom, and simply used the probabalistic interpretation to get applicable results in the rational mechanical tradition. The physical basis of decay was only known as the throwing off of a small particle and transmutation of the substance. These phenomena would only be fully described with a formulation of quantum mechanics later in the century.

2.2.4 Radioactivity and the CRT

Many physicists asked what was happening in the CRT based on the findings of radioactivity. There were two schools of thought, which were primarily centralized in two respective regions:

Germany In some ways, the CRT behaves just like light. It causes phosphorescence which can be interpreted as a disturbance in the luminiferous æther.

Britain The CRT can be explained in terms of particles. Current flows in a circuit somehow and should be carried by a particle of some sort.

Hertz made the observation that the CRT was unaffected by an electric field, and so deduced that the nature of the CRT was best explained by light.

This polarization of views about the CRT between countries resulted in a slough of counterintuitive differences in interpretations of the same experiments, and many unstable, confused explanations.

2.2.5 Lorentz

H. A. Lorentz (1853-1928) formulated charges as particles of electricity and called them ions. Specifically, he termed “electron” for the negative particle.

His development of this aspect of electromagnetism afforded physicists an integration of forces on matter with electromagnetic field theories. He was awarded the Nobel Prize for his work in 1902.

2.2.6 Lenard

Philipp Lenard was a student of Lorentz who conducted many experiments on CRTs and was awarded the Nobel Prize in 1905.

2.2.7 J. J. Thomson

Unrelated to Lord Kelvin, J. J. Thomson was awarded the Nobel Prize in 1906 for his “theoretical and experimental investigations of the conduction of electricity by gases.”

The third director of the Cavendish, J. J. Thomson was a mathematically inclined second wrangler who was a bookish type who initially was interested in a theoretical formulation of the electrodynamic properties of Thomson’s vortex atom. As director of the lab, however, J. J. Thomson was required to do some lab work, even though he was not well prepared for it.

Logically, he chose to investigate the nature of the theory with which he was familiar. He used an experimental apparatus that consisted of a CRT with a focused beam that passed between two electric plates. An electric field applied across the plates deflected the ray’s trajectory, contradicting Hertz’ previous observation that the ray was unaffected by an electric field.

J. J. Thomson argued that cathode rays are charged material particles based on this observation. He demonstrated the identity of the two by showing that wherever the rays go, the charges go, and vice versa.

In addition, by applying a magnetic field to his ray, he was able to calculate the velocity of the rays and the charge to mass ratio of the rays.

J. J. Thomson's new result showed that matter could exist in a new state that was smaller than chemical atoms. Even more compelling was that these new pieces of matter in the rays were generated by all sorts of cathodes interacting with all sorts of gases. The evidence suggested that these were some sort of fundamental building block of nature.

In publishing his theory, J. J. Thomson deliberately used Maxwellian overtones, calling the new particle a "corpuscle" and made no mention of the (somewhat far removed) concept of the Lorentz electron.

J. J. Thomson's discovery of the electron serves as a great example of why it is misleading to state grand summations of history like "J. J. Thomson discovered the electron." The fact that the discoverer would have made no such statement illustrates the point that the complexity and confusion characteristic of the history and practice of science is masked by making such oversimplifying statements.

2.3 Radiation Problems

2.3.1 Planck

Max Planck (1858-1947) began investigations in classical physics such as radiation, the selective emission or abosorption of light.

When he began his work, crucial in its own right, the EM theory of the Æther fed into the relevance and motivation for his research.

Planck tried to apply thermodynamics, originally developed for the study of gases, to the phenomena of light. He tried to explain the irreversibility of emission and absorption as an analog to the thermodynamic principle of entropy.

Planck also developed standards for light intensities and studied the correlation of intensity of emission with temperature.

2.3.2 Defining Light with Spectra

Light was previously known as an EM wave, characterized by its color, which is defined equally well by either its wavelength λ or its frequency ν.

In any sample of light there is usually many more than just one frequency. This observation led to the technique of analyzing light using spectra, or plots of intensity versus wavelength. Spectra can be generated for bodies' emission and absorption.

As an aside, the light's wavelength was more commonly used on plots, rather than an equivalent measure, frequency, because it was just easier to measure, and the conversion was tiresome for many data points.

There are two types of spectra:

1. Continuous spectra which are defined as a well connected line over an entire range of wavelengths

2. Discrete spectra which are essentially single wavelength peaks for a variety of individual values

2.3.3 Blackbodies

By applying thermodynamics to light, Planck found that emission is proportional to absorption. Furthermore, the constant of proportionality depends only on the wavelength and temperature, not the character of the material. Therefore, Planck deduced that the new constant, h, described a universal law.

The utility of this finding was paramount. It implied that if a simple model system with good results was picked, then the results would be universally applicable.

A simple model system was that of a body which absorbed totally but did not emit light: a "blackbody." An example of this was a ball covered in soot, which absorbs so much light that it is difficult to make out the features of the ball.

An even simpler model system was that of an object with a hole leading to some interior cavity, in which light would bounce around, be absorbed, and not return from.

After shining light in a blackbody, the emissions spectrum of the light was measured from the blackbody. This emission spectrum was universal for light of the absorbed wavelength.

Most of these experiments were done by experimenters at the Berlin PTR, and were funded by states interested in generating standards for use in industry.

2.3.4 Thermodynamic Integration

An attempt to mathematically define a relation between temperature and wavelength was carried out by **Willy Wien**.

He used an analogy of the Stefan-Boltzmann distribution to develop a law that was specifically designed to reproduce known experimental observations. Not really a deductive argument, this law was unaccepted by theoretical physicists.

In contrast, the very theoretical Max Planck was interested in providing some coherent deductive reasoning in the highly empirical field of blackbody radiation. He ended up changing his views on thermodynamics and statistical mechanics in a way that illustrates the later logical transition the entire physics community underwent in the shift from classical to modern physics.

2.4 Light Entropy

Planck had a theoretical interest into thermodynamics, especially the abstract rigor of the second law. He was unhappy with the probability argument which stated that the second law was in fact conditional and possibly broken.

A classical thermodynamicist, Planck's rethinking of his native theories are what led him to new domains.

2.4.1 Second Law and Radiation

Applying the second law to emission and absorption of light, Planck asked if the processes were irreversible and if that was a natural consequence of EM.

Because he was a pure thinker, Planck started his career as only an extraordinary professor at Berlin. In many ways, he is the model of Russell McCormmach's Victor Jakob in *Night Thoughts of a Classical Physicist* [3]. His problem of how to approach the problem of radiation from a purely theoretical standpoint mirrored that of Clausius decades earlier when he succeeded in tackling thermodynamics from an entirely theoretical view.

Planck's model supposed a simpler model of radiation than previous, complex, mechanical formulations. It modeled radiation in terms of a collection of charges oscillating on springs. This was a system whose properties can be simply derived and whose components, including simple harmonic oscillators, had been extensively studied.

2.4.2 Planck's Model's Characteristics

Planck has three principal results. Firstly, he applies the results of mechanics and EM to derive what kind of light is radiated from his simple system — light with frequency the same as the frequency of the harmonic oscillator.

Secondly, he asked how the system behaves thermodynamically. He found a quantity that behaves just like entropy, in that it never decreases overall and it is maximal at equilibrium. He then inferred that the second law must hold for his system and called the quantity entropy.

Finally, his formulation of entropy served as a basis for deriving Wien's empirical distribution law for a blackbody.

The result of his analysis was a theory that successfully dictated observation.

Careful attention must be taken to make the distinction between a physical analogy and Planck's theoretical model. The key difference is that Maxwell was using meta-level "intuitive" inferences about his physical phenomena, but Planck was using more direct analysis-level inferences.

2.4.3 Unexpected Deviations from Wien

As measuring apparatus became more accurate, small departures of Planck's model's predictions from experiment was detected at high wavelength values.

Planck had thought his theory was steadfast and correctly derived. However, this little glitch reoriented him, and he quickly made a small modification to his model to accomodate it.

Planck's model equation looked like this before:

$$E(\lambda) = C_1 \frac{1}{\lambda^5 \exp(\frac{C_2}{\lambda T})}$$

He changed it to look like this after:

$$E(\lambda) = C_1 \frac{1}{\lambda^5 \exp(\frac{C_2}{\lambda T}) - 1}$$

A simple subtracting one from the denominator made the model agree with reality!

2.4.4 Planck's Thermodynamics

Despite a heavily inclination not to use probabalistic formulations of the second law, Planck put thermodynamics to work by deriving an entropy expression from this energy density.

This formulation of entropy turned out to look just like Boltzmann's probabalistic definition, which Planck perceived as a mind-warping idea to wrap himself around. It meant that Planck's theory could only make sense in terms of a universe consistent with Boltzmann's statistical mechanics.

Finally in acceptance, he assigned $C_2 = K$, Boltzmann's constant.

The interpretation of probability in Planck's system was to take ontologically seriously the concept of many oscillating charges. The energy density he derived represented the distribution of energy in oscillators.

As any true theoretical physicist would do, Planck applied calculus to his probability density. He divided the system into finite chunks ϵ and looked at how they were distributed over the oscillators. However, when he tried to use the standard method of letting $\epsilon \rightarrow 0$ to find the asymptotic value, the results were inconsistent!

Therefore, Planck came to realize that energy must be fixed in discrete packets (later called "quanta") in light, namely $\epsilon = h\nu$.

2.4.5 Significance

Anachronistically, this was an incredibly significant discovery, since h was a quantity which was an absolute quantity of the universe.

However, the meaning of his results is initially hazy. Planck gave his first lecture on "Wien's Paradox" on 14 Dec 1900, still not realizing the significance of quantization.

2.4.6 Myths

One myth expounded by physics textbooks is that Planck was motivated to postulate quantization based on the alarmingly contradictory evidence suggested by the "ultraviolet catastrophe." This was Raleigh's application of the equipartition theorem to radiation, which resulted in the prediction of infinite energy light in low wavelength areas of the spectrum.

However, as with other statistical mechanical concepts, Planck had no faith in the universality of equipartitioning, and so was in fact not driven by the large deviations at the low wavelength end of the spectrum. Instead, he was driven by the very small deviations from observation at the high end of the spectrum.

2.5 Motivating Relativity

2.5.1 The Photoelectric Effect

A step beyond Plank, who postulated that light exists on its own in discrete packets $h\nu$, Einstein proposed the **Photoelectric Effect**.

Hertz was the first to notice the effect, when in the 1880s he observed that electrons were ejected from a metal when special light was shined up it.

Maxwell's equations predict that more intense light will give a more intense beam of electrons being emitted. However, Lenard's experiments proved this prediction false.

Einstein considered a quantum of light hitting the metal as creating the kinetic energy of the electrons emitted:

$$E = h\nu + P$$

Millikan (1868-1953) measured this in 1916. When he plotted light intensity versus kinetic energy of electrons, a straight line with slope h resulted, indicating that Einstein's prediction was correct.

The theory proposed by Einstein turned out to be fruitful, he said, if not "true" to nature. This opinion was reflected in the title of his 1905 publication, "On a heuristic point of view..." By being far from assertive, Einstein succeeded in increasing the acceptance of his work by not forcing acceptance of the theory's underlying assumptions as fundamental to nature.

Still, many physicists thought there were good reasons to not accept Einstein's photoelectric effect, foremost among them being Maxwell's equations' contrary prediction. Even 10-15 years after publication, people were thinking him wrong, until he was awarded the Nobel Prize for "the law of the photoelectric effect" in 1921. In effect, the Nobel committee was saying, "Accept Einstein!" Additionally, the Nobel served as somewhat of a lifetime achievement award, citing Einstein's "services to theoretical physics."

2.5.2 Einstein in his Prime

Although **Albert Einstein** is often seen as the radical consolidator of modern physics, his theories were solidly anchored in nineteenth century physics. He wasn't so much a radical as a logical thinker.

He published three papers in 1905:

1. The Photoelectric Effect
2. Brownian Motion
3. Special Relativity

2.5.3 Brownian Motion

This odd phenomenon was first characterized by naturalist Robert Brown as the motion of pollen in water.

The motion was hypothesized to arise from the particle's bombardment with moving molecules of the liquid. This phenomena embodied one of the few visible manifestations of the macroscopic ramifications of the universe's supposed microstructure. The theory had a large component in the fields of kinetic theory and statistical mechanics.

Einstein's idea was to treat the motion as a diffusion problem, essentially applying the results of this already solved problem to diffusion. In particular, Einstein modeled the motion with a random walk and quantitated the motion with the root mean square (RMS) velocity, a quantity he found to be proportional to time.

The import of this theory's development was that it implied a definite structure of the microscopic nature of matter.

Jean Perrin (1870-1942) received the Nobel Prize in 1926 for his excruciatingly meticulous experimental confirmation of Brownian motion. This evidence provided persuasive evidence to the physical community of the atom's reality.

This was an interesting early twentieth century ontology shift that served to reconcile statistical mechanics with atomic physics.

2.5.4 Special Relativity

Einstein sought to redefine mechanics with special relativity.

A reference frame was defined as a coordinate system by means of which the elements of a system can be located in terms of place and time. Einstein used the elevator and train as real life examples of reference frames.

Furthermore, an inertial reference frame is a frame in which all laws of Newtonian mechanics hold. Bodies inside the frame move in straight lines with constant speed. No forces exist inside the inertial reference frame. Examples of inertial frames include elevators and trains moving at constant speeds

A non-inertial reference frame is just that: a reference frame in which not all laws of Newtonian mechanics hold. Examples of non-inertial frames include elevators decelerating or accelerating and trains accelerating around a turn.

The central postulate of special relativity is one of invariance. Specifically, if laws hold in one reference frame, then they must be true in all other frames that are moving relative to it at a constant speed.

This provides interesting consequences for moving magnets and wires with respect to one another. Maxwell has two equations to describe electromagnetic behavior: one to characterize electricity in a changing magnetic field and one to characterize magnetism in a changing electric field. However, Einstein's relativity says that these are essentially the same problem, since their motion is the same relative to one another, and thus a uniform solution must be found.

Like Maxwell's demon, Einstein is asking, "Do we really understand everything about electromagnetism's consistency with Newtonian Mechanics?"

2.6 Einstein's Relativity

2.6.1 Relative Electrodynamics

Einstein purposefully designed his paper's outline to mimic that of Newton's classic *Principia*, simply because he was overthrowing it.

There are two primary postulates of special relativity that form the foundation of Einstein's argument:

1. In every inertial reference frame, all of the laws of physics hold. Nothing in these laws singles out a state of absolute rest.

2. The speed of light is always the same in empty space. It makes no difference whether the source emitting it is moving.

Some features of these postulates, especially the second one, had been standard in the physics community for a time. Lorentz was the first to propose uniformity in the speed of light.

Einstein's theory is better called "invariance" than "relativity" since the laws of physics are supposed to be invariant between any inertial reference frames.

2.6.2 Kinematics

Again, kinematics is the study of the motion of physical bodies. Einstein felt that this field needed immediate attention, and that "revisiting notions of kinematics will force us to reconsider everything that has been built upon them."

Taking nothing for granted, Einstein's first task was to define simultaneity, in effect providing a concrete definition of time as something measured by a clock or light signals. Much care was taken to emphasize the importance of realizable, careful measurements to facilitate this definition.

Rather than the Newtonian supposition that time is universal and that clocks are derived from it, Einstein took the clock as given and from it derived the physical concept of time.

Likewise, Einstein sought an objective definition of length, which was based on marks on a measuring rod at rest, and based on the previous definition of observable time.

There were many consequences to interframe relations that Einstein derived that complicated things and resulted in changes to Newtonian mechanics:

1. Moving objects behave strangely
2. Clocks behave strangely
3. Velocities don't add usually

It is worthy to note that no discovery of the twentieth century was essential to this proposition. Relativity could have been proposed much earlier.

The theory was argued primarily with an "end-justifies-the-means" mentality. Since the results of applying his theory were so fruitful, it must be of some value.

2.6.3 Electrodynamics

In a more complex way than his explanation of kinematics, Einstein developed a system of results in electrodynamics that is as rich as Lorentz' electron theory, but even more concise.

2.6.4 Philosophical Motivation

Einstein's development of relativity was philosophically sound in that it was based on operational definitions and observable consequences of those definitions.

He was involved in the study of Hume, Poincaré, and Mach in his younger years, and was especially influenced by Mach's ideas of sensationalism. Poincaré's idea that if the æther exists it must be observable in the optical domain was also highly influential to the young Einstein.

This question of the detection æther was a troubling one for many scientists of the early twentieth century, and was finally measured by **Michelson (1852-1931)**. The interferometer that he developed had the purpose of detecting the movement of the earth relative to the æther. The negative results of his experiments were instrumental evidence against the æther and against absolute space, but he nevertheless received a Nobel Prize in 1907 for the invention of the interferometer.

Einstein was also aware of Lorentz' electron theory, which already postulated the concept of space dilation.

Though he was aware of all these developments, Einstein was seemingly not driven by any one of them in particular.

More likely is his pre-academic predisposition to electrical technology while working a job in a patent office. He formulated many problems early in life about time synchronization for practical purposes, such as facilitating accuracy in train scheduling, that would only be solved later with his theory of relativity.

2.6.5 Acceptance

Experiments seemingly disproved his reasoning, but Einstein was unphased in his support of relativity. Only a small number of physicists accepted the theory from the outset, and those who did had to based on sheer mechanical unity and elegance. Some pointed out flaws in the theory's formulation of electrodynamics.

Einstein argued that the theoretical structure of relativity is what made it so plausible. Emphasizing his opinion that matching experiments with prediction is just one criterion to gauge a theory in addition to its simplicity and elegance, Einstein argued that relativity's operational definitions and structure revealed an underlying unity to the universe.

Einstein also distrusted past accelerated electron theory and observations, confident that more precise measurements would be made in support of his theory.

Planck accepted the transition easily, whereas others such as HA Lawrence and Michelson did not, which seems curious in retrospect since Einstein's theory was based off of Michelson's work.

2.6.6 Strange Consequences

Einstein's new kinematics had some curious results not seen before in the physical world:

1. The mass of an object varies with the speed at which it is moving. Mass is resistance to acceleration just like with Newton, but as an object's speed approaches the speed of light c, it gets harder and harder to apply a force that accelerates the mass.

2. The mass and energy of an object are interrelated in the body's inertial reference frame. No longer could there be independent laws of conservation of mass or energy, but rather now they must be thought of together as a conserved quantity.

3. Time and space are interrelated. Measures of time in a system depend on the velocity of the system. Space and time must be thought of as a single object, a four-dimensional manifold of space-time. This concept captured a cultural fixation with Einstein that focused public interest away from the previous popular concept of radiation. For example, Dali's 1931 painting "The Persistence of Metaphor" embodied this sentiment with its distorted clocks and landscape.

4. Temporal order of events was decided in a more complex fashion. An observer sees two events happening, of which the simultaneity depends

on the relevant reference frames. It is then possible to reverse the order of events that happen based on changing the reference frame of observation. This doesn't result in time travel, as one might think, but rather, it results in a "space-like separation" that assures causation across space and time.

5. Velocities add strangely. No longer can two velocities be summed with a simple formula. This is still a good approximation for speeds much lower than that of the speed of light c, but for higher speeds relativity must be considered to get consistent results.
6. Time dilation. Moving clocks are observed to run slower. Moving objects are measured to be shorter. This results in the twin paradox (hilarious 70s cartoon), which states that a pair of twins will age differently if one is blasted into space at a high speed to return at some future time and the other remains on earth. The twin on earth will age much more rapidly than the twin traveling quickly through space.

Can we just ignore these odd effects? In our everyday experiences, yes.

But Einstein's proposition of them had the effect of sending physicists out to look for observable consequences of these effects.

This also led to a major paradigm shift, which replaced Newtonian mechanics with relative mechanics, which included Newtonian mechanics as a special case. This fundamental change in the basic notions of physics resulted in reworking of conservation laws and concepts assumed to be universal.

It is natural to think of these effects as goody and amazing, but the more you work with them, the more comfortable you get with them. Einstein's strange concepts were certainly domesticated by experience, and many grew to accept relativity with time.

The public view of Einstein is for the most part the old sage, which misrepresents the sharpness of the man's thoughts during his youth. He stood on his own as a strange entity aside his theory.

2.7 General Relativity and Beyond

2.7.1 Relativity After 1905

Einstein's major theoretical preoccupation after 1905, the year of his great publications, was the extension of the theory of relativity beyond just inertial reference frames. A relevant example he wished to explain was the mechanics of an accelerating or decelerating elevator.

Einstein wanted to find an easy tranformation to explain the relation of all non-inertial reference frames as an analog to his finding one for all inertial reference frames.

The key point that Einstein noticed is that there exists a similarity between objects in non-inertial reference frames and objects in gravitational fields.

Einstein combined this idea with the sensationalist argument from Mach that there was no way inside the reference frame to tell the difference between gravity and acceleration.

The result of his theoretical searchings is what he later referred to as "the happiest thought of my life..." — his realization that gravity and acceleration were inseparable.

The two concepts of mass were unified as a result of the new relativity. Previously, there were two somewhat distinct definitons for mass:

Inertial $F = ma$

Gravitational $F \propto mM/r^2$

Einstein's new theory, called **General Relativity**, claimed that these two concepts of mass were the same.

It is worth noting that the mathematics involved in general relativity in exceedingly difficult.

2.7.2 Experimental

The Hungarian geophysicist **Loránd Eötvös (1848-1919)** worked in the public sector as an oil prospector. His precision measurements of local specific gravity somehow served as a confirmation of general relativity.

Einstein cited deviations in Mercury's perihelion that could be explained no other way as evidence for general relativity at the time of publication.

The British astronomer Arthur Eddington predicted that a star's light will appear to be bent around a star that it passes near to, thus causing us to detect it in a place it isn't. He experimentally confirmed this prediction during a complete lunar eclipse, which served as compelling evidence for general relativity.

2.7.3 Geometry

Sometimes it is useful to think of the four-dimensional manifold of space-time as a plane of rubber being deformed by a ball being set upon it.

This analog led physicists to generate a new concept of what defined a straight line, and warped space-time itself, based on alternative geometries.

	Euclidean	Riemann
Parallel lines converge	Parallel lines never meet	Parallel lines diverge
Trianges have $> 180^\circ$	Triangles have 180°	Triangles have $< 180^\circ$
Spherical geometry	Planar geometry	Hyperbolic geometry

These concepts are hard to visualize, but somehow Riemann geometry turned out to be physically valid for general relativity.

Chapter 3

The Quantum Mechanical Era

3.1 Atomic Physics

There are two reasons why atomic physics was developed in the early twentieth century, despite the fact that it was not the “natural next step” that so many textbooks portray it to be:

1. Physics provided a demonstration of the existance of atoms with kinetic theory and Brownian motion
2. Physics unintentionally investigated many phenomena related to atoms: light, x-rays, radioactivity, and electrons

3.1.1 Falsity of Inward Bound

Many textbooks teach the discovery of atomic physics as a physical journey that was always inward bound in the study of the atom. This *post facto* argument usally features:

- Palpable directionality of research front
- Main direction of research with side branches
- Distinct cutting edge of discovery

This representation of atomic physics would no doubt be peculiar to atomic physicists of the early twentieth century, so this anachronistic view doesn’t help in understanding the physics at all.

3.1.2 Atomic Ontology

These two main problems were what was being investigated about atoms by the beginning of the twentieth century:

1. Constituents: electrons and consequently counterbalancing positive charges
2. Mechanics: how the atom was held together in bigger structures, both statically and dynamically (which seemed like a paradox since theory predicted that all the energy of the atom would radiate away)

In considering each model that is proposed, it is important to remember that each investigator was only trying to account for the phenomena he had observed in his model.

Also important to realize is that France and Germany for the most part were unconcerned with atomic physics, and saw the whole field as on the periphery of physical interest. The initial atomic models were all developed in a close circle around Cambridge in Britain.

3.1.3 Saturnian Model

The Japanese Cambridge student **Hantaro Nagaoka (1865-1950)** proposed the **Saturnian Model** in response to a problem he confronted on the tripos.

The model suggested electrons exist in orbits that formed concentric rings around a large, positively charged ball. Drawings of the model looked somewhat like photographs of the planet Saturn and its rings, hence the name of the model.

3.1.5 Rutherford Model

The **Rutherford Model** which of the atom was, in some ways, a middle-ground between the Saturnian model and the J. J. Thomson model.

In Rutherford's experiments, he sent a beam of α particles against a thin metal sheet, and observed that a few α particles were scattered in random directions, while most just passed through. Consequently, he postulated a positively charged, small sized nucleus that would repel the α particle beam and produce the observed result. Though he was uninterested in electrons, his model accounted for electrons outside the nucleus for completeness.

Another stipulation of Rutherford's initial model was that it was only really accepted for scattering problems, and remained ungeneralized for some time.

3.1.6 Bohr Model

The **Bohr Model** of the atom, developed in the 1910s by **Niels Bohr**, was the result of a chance meeting.

Always drawn to places where something is going wrong with theory, Bohr initially wanted to start work at Cambridge by investigating the electron with J. J. Thomson. However, by the time Bohr arrived at Cambridge, J. J. Thomson had already abandoned work on the electron, so he suggested Bohr work with Rutherford instead.

During his spare time in lab, Bohr read Rutherford's papers on his atomic model, and began to think about how to reconcile the instabilities of Rutherford's model.

This led to Bohr's extension of Rutherford's model, which postulated that all electrons move in circular orbits around a central nucleus, and that, for some reason, some specific orbits are stable.

When trying to formulate the specifics of his theory, Bohr turned to Planck's constant. Almost humorously, when Bohr was trying to calculate the energy of his atom, he threw in a factor of h simply because he was dealing with the realm of "modern physics." This arbitrary stabilization term turned out to be a good guess and became an essential component of his atomic theory.

3.2 Bohr Model

The Bohr model, as previously discussed, postulated certain electron orbits as being stable.

3.2.1 Spectral Connections

An unintential theoretical consequence of the Bohr model was the slight modifications that made it compatible with atomic spectra experiments.

The discrete spectra characteristic of the gas observed when running a CRT experiment produced a finite set of bands that was explained quite well by the Bohr model.

The majority of experiments were carried out by **Robert Bunsen (1811-1899)** and **Gustav Kirchoff (1884-1887)**, who developed a unique apparatus that burned a sample, and sent the light generated through telescopes and prisms to separate light into component wavelengths.

This technique was improved by the diffraction gratings perfected by **Henry Rowland (1848-1901)**. The many gratings he made were used to identify the specific set of spectral lines that was characteristic of each atom, effectively granting each atom an optical signature. By using these gratings, the element rubidium was discovered, and α particles were shown to be identical to helium.

Fraunhofer, a Bavarian glassmaker, detected dark lines in the solar spectrum that he initially suspected were products of defects in his craftsmanship. Later, investigators matched these dark bands to the light lines observed in atomic spectra and deduced that, since atoms absorb light at the same frequencies at which they emit light, the solar atmosphere must contain certain elements, such as sodium.

3.2.2 Modifying The Model

As an analog to the oscillating charge model that Planck used to explain the origin of light emission, Bohr postulated that electrons rotating around his atom would be able to emit light.

However, there were problems that Bohr needed to resolve. Even the simples atoms have many spectral lines. How could this be explained? By picking out only certain frequencies of oscillation?

It is worth noting that Bohr initially knew nothing of spectra, but when he began studying them, he realized that he could explain the spectral observations with his model by modifying it slightly.

Bohr postulated the quantum rule that said an orbit is stable if an electron in it moves with energy proportional to the frequency of oscillation. A consequence of this supposition was that light emission will not occur when electrons remain in one orbit, and that light emission will occur when an electron makes a jump from a high energy level to a lower level.

The led to Bohr's statement of his first two principles:

First Quantization Frequency of of radiation in transition between orbits is given by $\Delta E = h\nu$

Second Quantization Energy levels of orbits are fixed by quantizing the electron's orbital motion, given by $J = n\frac{h}{2\pi} = n\hbar$, where $\hbar = \frac{h}{2\pi}$, a quantity that would appear often later on in physics

However, these principles still left some questions unanswered. Bohr still needed to determine how many electrons were possible per orbit.

The fact that the X-ray spectra of many elements were similar was used to confirm chemical predictions of atomic relatedness that had been supposed and used to construct the periodic table.

Henry Mosely was a Cavendish physicist who investigated atomic spectra alongside Bohr. He eventually became one of the many casualties the physics community sustained as a result of the World War I.

Bohr's third principle was the correspondence principle that somewhat vaguely stated that there needed to be a smooth transition from the quantum to the classical description of the atom. This principle was prompted by the observation that not every electron transition is permissible and that at high quantum numbers, the discrete quanta were so close to each other that they were approximately continuous, like the classical atomic description. The correspondence principle was somewhat of an art in that only Bohr and the scientists around him had a good idea of how to apply it. It stood firmly behind the statement that the physics community needed to not abandon classical physics but instead build upon it.

The complete Bohr model served as a foundation of the formulation of modern quantum mechanics later in the twentieth century.

3.3 Quantum Mechanics

3.3.1 Problems with Bohr

The first problem with Bohr's initial formulation of quantum atomics is the realistic complication that electrons probably travel in a wide variety of ellipses rather than circles. The many possible shapes of orbits implied a vastly greater variety of atomic shapes and many more quantum numbers.

The second problem with Bohr was his application of perturbation theory to the atom. The mathematics came directly from celestial mechanics.

The third problem was the effect of electromagnetic theory. Applying perturbation theory to electrical and magnetic fields caused spectral complications that were manifest in the Zeeman and Stark effects.

The fourth problem was with dispersion theory, and dealt with light scattering.

The fifth problem was the relativistic implications that needed to be considered since electrons were probably traveling at speeds close to the speed of light c.

3.3.2 Locality Shift

During this period, there was a locality shift in quantum mechanics from England to central Europe:

Copenhagen Bohr

Munich Arnold Sommerfeld and students

Göttingen Max Born

Bohr's school of old quantum theory was a good training program that didn't so much deal with Einsteinian problems, but instead lots of small observations that needed to be synthesized.

3.3.3 After Bohr

The program's goal was to refine Bohr's model, and it was taken up by a number of youthful and intelligent young physicists. There were many data and details from experiment that needed to be reconciled with theory.

However, with each refinement, the researchers uncovered more problems, which were small at first, but then became larger.

Additionally, no one attempted to clarify the unclarities with the Bohr model, such as the correspondence principle, which was getting no closer to rigorous articulation.

There were some major failures that saw the Bohr model fall flat for no apparent reason.

To accomodate, Bohr even made the suggestion of abandoning the principle of conservation of energy.

Others suggested the abandonment of assumed orbital trajectories, since they were invisible and hypothetical in a problematic sense. This resulted in a detachment from the phenomena and reliance on indirect observation that was contrary to the very sensationalist underpinnings of the thinkers of the time, such as Einstein and, previously, Mach.

Wolfgang Pauli (1900-1958) (say "Pow-Lee") was a student of Sommerfeld, Born, and Bohr, who was a child prodigy raised in the antimetaphysical tradition as the godson of Mach. At the young age of 19, Pauli wrote the definitive review of general relativity. He had a sardonic personality, and refused to get up for morning lectures.

3.3.4 Heisenberg's Analysis

Werner Heisenberg (1901-1976) was a pragmatist who, in the classical spirit of rational mechanics, preferred generalizable solutions to the existing special theories of the Bohr model. His strategy of attacking the problems of the Bohr model was to abandon considerations of Plank's simple harmonic oscillating charge. He looked at the idealized system proposed before and gave up all talk of space-time in the atom, along with discussion of orbits and position of electrons. Heisenberg only considered the observable properties of the atom: the frequency and intensity of emitted light and how these waves interacted with other light.

Heisenberg's analysis just relied upon the macroscopic variables, which had already been described thoroughly in the physical community. In this way, Heisenberg's work can be seen as building quite nicely upon the previous research on the atom. Yet, he later would often claim that the inspiration for the final formulation of his quantum mechanics came to him on a solo retreat to Helgoland.

The idea with his new analysis was to mathematically characterize Bohr's complex correspondence principle by using classical quantities and a new supposed **Commutation Relation** which stated

$$pq - qp = -i\hbar$$

where p is an atom's momentum and q is its position. The leap in logic was that, before Heisenberg, the difference of the quantities was assumed to be zero. Heisenberg postulated that this difference was actually non-commutative in the usual sense and equal to an imaginary multiple of Planck's constant. Although Heisenberg himself did not talk in terms of the equation above, his work was reformulated in these terms for usefulness by one of his students, Max Born.

Paul Dirac (1902-1984), a Cambridge physicist, realized that the non-commutation of Heisenberg's relation was equivalently represented in matrix notation, a concept from the field of linear algebra, which had very strongly developed mathematics. His extension of Heisenberg relied upon the intensely abstract concepts of linear algebra, and were used to non-intuitively generalize quantum mechanics.

Heisenberg can be seen as a twentieth century rational mechanist in that his theory was:

1. Abstract
2. Focused on the macro properties of the atom
3. Uninterested in postulating a micro mechanism
4. A general solution to a wide class of problems

Pauli worked to confirm Heisenberg's theory for the Hydrogen atom, but it was a lot of tough mathematics.

Heisenberg's quantum mechanics was a complete reconstruction of mechanics so far removed from ordinary experience that it is a good place to start rewriting all of mechanics.

3.4 Reconciling The Wave/Particle Duality

3.4.1 Exploring Duality

Even with Dirac's matrix formulation of Heisenberg's quantum mechanics, there was no attempt at an explanation of why electrons jump between quantum levels and how to predict when this will happen.

There was a need to reconcile this new description of light with the classical Maxwellian concept of light. Surprisingly, there is not really a sense of crisis in this integration.

With the photoelectric effect, Einstein said that light must be counted in discrete quanta in 1905. The question was: how far was it possible to take the wave/particle duality of light?

In the 1910s, Einstein proved that light quanta and light waves were simultaneously necessary for a complete description of light, solidifying the wave/particle duality in the nature of physics. However, the descriptions were largely separate and begged for integration.

Also, this strengthened the analogy of light as a quantum, a particle that could experience collsions and emissions in a Newtonian system.

The physicist **de Broglie (1892-1987)** (say "day Broy") inferred that matter might be treated as a wave since light was as well. Particularly, this integrated well with the Bohr model, which already treated electrons as particles that exist in energy levels in standing waves. De Broglie said that there was a wave that accompanied a particle such as the electron, but did not refer to it as a "matter wave," as it was later to be called. The theory was confirmed by electron scattering experiments.

It is interesting to note that electrons were first formulated as particles then as waves, and, inversely, light was first formulated as waves and then as particles.

3.4.2 Schrödinger's Alternative

Erwin Schrödinger (1887-1961) was an atomic physicist raised in a different tradition than the Bohr school. He disliked Heisenberg's abandonment of the spacetime description of the atom and tried to get the quantum out of the description of the atom, assuming an underlying continuity in nature.

Schrödinger built up a description of the atom from an entirely new framework in which electrons were represented by continuous waves in the atom.

Along with de Broglie, his work was a big push toward a matter wave description of the electron. Schrödinger's description included a mathematical characterization of matter waves in a medium that was partially borrowed from classical physics.

The central idea in his theory was representing general particles with a **Wavefunction**, or wave equation, such as $\Phi(x,t)$, that gives the wave's value as a function of position and time. The mathematics of wave equations was already fully developed, and easy to apply; Schrödinger had learned all of the concepts in graduate school. An interesting feature of his solution was that there were superposable and complex, which meant that the only real interpretation of the equation was by taking the square and interpreting it as a probability density of the particle.

Most historical accounts of Schrödinger's discovery claim he developed the theory at a winter ski hotel in Arosa with a possibly underage mistress.

Proof of his theory was verified by applying it to the simple system of the Hydrogen atom, and, unlike Heisenberg's solution, the results were easily generalizable to more complex systems.

3.4.3 Two Theories

Using two different approaches and two entirely different fields of mathematics, Heisenberg and Schrödinger delivered precisely the same results for the quantum mechanics of the atom. Schrödinger was quick to prove the mathematics equivalency of his wave equations with Heisenberg's principles which were discovered only months before.

It is interesting that current physics students are taught these two independent formulations of quantum mechanics in the same historical order in which they were proposed.

3.4.4 Max Born

Max Born was the quantum mechanist who realized, from experiments with particle collisions, that Schrödinger's wave equations were not really waves of matter but actually waves of probability.

One would expect a particle to be localized in a single point, but from experiment, it was determined that an electron could never be pinned down to an exact spot. Therefore, Born deduced, the wave equations must refer to the probability of observing the particle at any given point in spacetime.

This statistical description of electron location fit in well with radioactivity and electronic transition which were also explained by quantum mechanics in a way that did not claim the cerainty of the event but rather expressed it probabalistically.

3.5 Making Sense of QM

3.5.1 Heisenberg's Uncertainty

With classical concepts operationally defined by Heisenberg, his theory was poised to make a direct statement about where to draw the line between classical and quantum descriptions of the atom.

This is precisely what Heisenberg's **Uncertainty Principle**, perhaps more accurately described as a indeterminacy principle, quantifies. It was a restatement of his commutation relation that had a more interesting application.

Heisenberg's gamma ray microscope was a thought experiment he used to explain the uncertainty principle:

1. Imagine observing an electron and wanting to identify its position to within Δq
2. To do this, you need to use ligh with wavelength $\lambda \approx \Delta q$
3. Gamma ray light has small enough wavelength λ, so it has a large frequency h and therefore momentum p
4. When the light quantum collides with the electron, the electron's momentum changes by a small amount Δp
5. The uncertainty relation states $\Delta p \approx h/\lambda \approx h/\Delta q$

The consequences of the uncertainty principle are:

1. There is a new limitation on the amount of information extractable from the microscopic world
2. The law of causality does not apply to the microscopic world
    - Position and momentum are never precisely known

- Heisenberg states this deliberately philosophically, like Kant
- Cause and effect still holds, but the uncertainty principle states that sufficient information, exact measurements, needed to predict the effect is impossible to obtain

Bohr was Heisenberg's advisor and much more careful than he was in proposing new radical theories. Bohr said that a much more rigorous treatment of the gamma ray microscope example was needed. However, Heisenberg managed to get a publication about the gamma ray microscope our when Bohr was on vaction, effectively circumventing his advisor's usual inhibitory role.

3.5.2 The Copenhagen Interpretation

Quantum mechanics became familiar to most physics through the synthesis known as the **Copenhagen Interpretation**, which was articulated by Bohr and Heisenberg.

It had the following features:

1. Quantum mechanics is a generalization of classical mechanics
2. A statistical interpretation of Schrödinger's wavefunction
3. Heisenberg's uncertainty principle set a limit on the amount of information obtainable from the microscopic world
4. Operational redefinition of classical concepts
5. Consideration of the effect of the act of observation on the object of observation
6. Focus on complementarity, or the emphasis on a need to reconcile the known classical concepts with the addition information granted by quantum mechanics

The development or the Copenhagen interpretation proceeded around Bohr, who acted as a general mentor for the quantum mechanicians. He connected with the physicists on both a professional and personal level that allowed ideas to flourish. The common social bonds established through

Bohr are evident in, for example, a production of *Faust* that the physics department at Copenhagen put on one year.

At Copenhagen, the theory is generally accepted as truth, but in other locations of physics, there are many critics who do not agree with the specific interpretation.

Einstein made the claim that “God does not play dice,” assuming that all physical phenomena could be reduced to deterministic physical laws. One of the reasons quantum mechanics was so unsettling to many was that it refuted this basic idealization of the physical world.

Quantum mechanics marked a radical change in the epistemology of physics:

Quantum Mechanics	Classical Mechanics
Statistical laws	Causal laws
Complementarity	Unified description
Role for the observer	Objectivity

Because of the radicality of this new domain of physics, the Nobel committee awarded no prizes in 1931 and 1932. Eventually, in 1933, Heisenberg was awarded the 1932 Nobel for physics, and other quantum mechanics Nobels followed in subsequent years.

Later, in the 1960s, Heisenberg remarked that to make a revolution in physics, the best way was to change as little as possible. Though the statement definitely has a political interpretation, it is an enlightened view into the history of the discovery, and how much of it really was dependent on the established findings of the physical community.

3.5.3 Wacky Consequences

Like Einstein’s relativity, quantum mechanics forced many logical oddities onto those who accepted the theory.

For example, quantum tunneling is the phenomenon of particles seemingly disappearing in one place and appearing in another, that was only discovered after quantum mechanics.

Probably the best known example is that of Schrödinger’s cat, an elaborate thought experiment to demonstrate how quantum mechanics might affect everyday objects. Imagine a system where Schrödinger’s cat is set up inside a sealed glass chamber. There is a sealed can of cyanide inside the chamber that can kill the cat, but it is only opened if a detector observes the radioactive decay of an atom. Schrödinger said that, in advance, the system could only be represented by a system of superposed wavefunctions. In effect, the cat was both alive and dead at the same time!

3.6 The Pauli Exclusion Principle

Historically, the Pauli exclusion principle can be seen as an example of the larger trend in physics toward a desire to solve the many-body problem. The precise relationship of the analogy of the many-body problem to electrons in the atom will be revealed in the following discussion.

3.6.1 Origins

The Pauli exclusion principle had its origins in the old quantum theory of atomic structure.

There were many explanations suggested by physicists such as Bohr and Heisenberg to the problem of explaining the **Anomalous Zeeman Effect**. The problem was manifest when examining the atomic spectrum of an atom in a large magnetic field. The spectrum showed dual lines where the Bohr model predicted only one. This observation effectively meant that the number of energy levels in the ordinary atom should be doubled. The explanations that Bohr and Heisenberg didn't catch on in the physics community.

3.6.2 Enter Pauli

In contrast, the exclusion principle suggested by Pauli was attractive and explanatory, if not intuitive. This was Pauli's attempt to reconcile the "two-valuedness not describable classically" with what was already known about atomic quantum numbers.

Pauli postulated an intrinsic angular momentum for the electron, an angular momentum distinct from the quantum numbers used in the Bohr model. Furthermore, he said that this new atomic number could take on values of only $\pm\frac{\hbar}{2}$.

Though the theory was somewhat unprecedented in its suggestion of quantization by non-integer multiples of h, it gained much support because of the extensive applications it facilitated. In the true Laplacian tradition of classical physics, by making these micro suppositions, it was possible to derive many useful real-world results.

3.6.5 New Statistics

Taking quantum statistics to the next level, Dirac and Fermi formulated a precise mathematical way of describing and counting electrons that came to be known as **Fermi-Dirac Statistics**. This method of counting electrons also very profoundly stated an indistinguishability of any electron from any other while at the same time being built from the Pauli exclusion principle.

By 1927, it was possible to use the new tools to investigate many interesting real-world applications such as solid-state physics and nuclear physics. It allowed physicists to make definite atomic predictions about bond length, valence, reactivity, and other atomic properties.

3.6.6 The Hydrogen Molecule

In 1927, graduate students were able to apply the results of Pauli and Dirac to a simple system: the two-atom hydrogen molecule. They examined how the wavefunctions of the electrons of each atom changed when the atoms were brought nearer to one another.

Based on a classical intuition, the electrons should want to exist between the two positively charged nuclei. From there, it was easy to deduce the simple bonding that was readily observable in the hydrogen molecule.

This was one of the first examples that physics was used to successfully predict interesting properties, such as bond length, of a real molecular system.

3.6.7 Physicists' Arrogance

After the physics community realized they had formulated laws they could use to predict chemical behavior, physicists like Dirac would pompously propose that a hierarchy in science was now establishable. In particular, many physicists liked to call chemistry a clear, and more trivial subset of physics.

However, this wasn't entirely the case. Although many zealous physics graduate students with no professional knowledge of chemistry were quick to apply the new physical laws to solve chemical problems, the solutions they obtained were to a great extent applicable in theory and not in practice.

3.6.8 Many-body Problem

When the electrons are viewed as bodies in the classical sense, the problem of the additional force that appears for more than two electrons turns into an analog of the many-body problem.

Like the example with planets, when more than two bodies are introduced in the problem, an unexpected mathematical or practical complexity is introduced that causes previous theoretical assumptions to break down.

In this way, these radical new quantum physical theories, and even observations, can be seen as extensions of a theme long explored by physics.

3.7 The Solid State

3.7.1 Sociology of Physics and Chemistry

Pauli referred to solid state physics as “dirt physics” in contempt. This was just one manifestation of the entire physics community’s view of chemists with disdain.

Pauli’s exclusion principle drove the development of solid state physics. Yet, many problems in chemistry had to be modeled as many-body problems with over 10^{23} bodies. The theory did not scale up as well as one might have hoped.

Indeed, physicists witnessed qualitatively new behavior with many bodies, such that scaling up the theoretical predictions of physics to chemistry didn’t work very well.

In addition, there were real world complications to the chemists problems:

- Impurities
- Fractures
- Scratches

3.7.2 Idealizations

Yet, the **Idealizations** predicted by physics are applied. The goal was to pull out one characteristic feature that was easy to treat mathematically buried within the complications.

By this point in the development of physics, there was no assumption of capturing the mechanism of the phenomena in the overall theoretical formulation of a theory. Physics had come a long way since the analogies of Maxwell.

If there was an idealization that did not agree with observation, it was thrown out and a new idealization was to be applied.

Thus, solid state theory was dependent on idealizations.

3.7.3 Applications

But it was equally the case that idealizations were dependent on solid state physics. Particularly, many solid state physicists had contact with people concerned with industrial applications of theory.

For example, the electrical behavior of solids was theoretically interesting because of quantum mechanics. Because of developments in Fermi-Dirac statistics, electrons were then thought to obey these laws in a ideal "electron gas." The idealizations of the theory were that no interactions happened between electrons and that no electron is tied to any atom. Both were pretty big idealizations, but the latter was justified by the earlier theoretical demonstration of the indistinguishabilty of the electron.

The result of the idealization was, of course, the simplest possible quantum picture of the phenomenon. There were fruitful results, though. Conductivity was shown to appear only in the electrons in the highest energy levels. They were predicted to leave behind "holes" when promoted to higher energy levels.

Another application was the idealization of the crystal lattice in the late 1920s. In 1931 Alan Wilson predicted a broad outline of conductivity and arrived at the odd result that there is a gap in the energy levels permitted. If the most energetic electron is next to the gap, then for some reason there was no conductance, and the material was found to be insulating.

3.7.4 Rectification

Crystal radio receivers were examples of this phenomenon. Semiconductors were used initially in electronics, but then went out of style in the 1920s due to their tough mathematics. CRT's were comparatively more well described and had applications in industry already, so they surged ahead in popularity for about a decade.

3.8.2 Classical Mechanics with a Twist

Heisenberg and Pauli constructed **Quantum Field Theory** such that it was classical mechanics but just with an added quantization as a rational generalization.

With this quantization came the creation of **Operators** that could create and destroy particles in the world. The creation operator a^* creates a single particle, whereas the annihilation operator a destroys a single particle. Operators act on physical states and can be used to build wavefunctions and wave equations. Operators obey quantization and can be combined to form new operators, such as a^*a, the number operator that counts the number of particles in a system.

Some at first objected to quantum field theory because it seemingly violates the conservation of energy in its creation and destruction of particles. However, the results of the theory were so useful that many quickly adopted using the theory. One thing that didn't happen was the adoption of considering the physical model of quantum field theory as indicative of the underlying mechanism of the particles involved. It was more of a descriptive theory that produced good results than a theory that illustrated some mechanism.

3.8.3 Antimatter

There were two immediate results of the postulation of quantum field theory:

1. The energy-mass relation of Einstein's relativity could be invoked to finally integrate relativity with quantum physics

2. Existence of antiparticles and, generally, **Antimatter**, was predicted by quantum theory

Antimatter was of particular interest to quantum field theorists. When an ordinary matter particle was destroyed, these physicists saw that it was completely equivalent to think of an antiparticle being created, and vice versa. One example of an antiparticle is the positron, the antielectron. These antiparticles thus have negative mass-energy and have the odd result that a force applied to them in one direction will result in their acceleration in the opposite direction.

By 1929, the theory of antimatter was well in place and in 1930s the reality of antiparticles was seriously being considered. There are three non-intuitive ways of thinking about an antielectron:

1. A new, positively charged operator
2. Empty space (a hole) in a sea of regular electrons
3. An electron moving backwards in time

The same mathematics describes each of these three interpretations, so the investigator gets to pick which one his results best explains.

One sudden change as a result of the theory of antimatter is the evaporation of reluctance to let mathematics dictate what is reality. Unlike in Maxwell's time, physicists were now willing to accept the physical reality of the mathematical model.

The diagrams used to represent particle destruction and creation consisted of lines for particles and squigglies for photons.

Even more abstract that antiparticles were the so-called **Virtual Particles** that could wink in and out of existence seemingly randomly and without the presence of other matter. These virtual particle pairs would consist of a spontaneously created particle and antiparticle, which would exist for a moment, then annhilate one another. This was legal in physics so long as the particles could not be measured, that is, $\Delta E \Delta t \leq \hbar/2$. This theory had the power to explain the effects of charge in a vacuum, effective charge, and vacuum polarization.

3.9 Quantum Particles

3.9.1 New Behavior

There were other systems of quantum particles than electrons. For example, these other systems could have the following characteristics:

- Particles collect in lower energy levels
- No exclusion principle
- What some view as an attractive force

A description of particles of this sort, which include photons, motivates the new class of mathematics called **Bose-Einstein Statistics**.

In general, particles that had a spin of $\pm 1/2, \pm 3/2, \ldots$ were referred to as **Fermions**, whereas particles that had a spin of $0, \pm 1, \pm 2, \ldots$ were referred to as **Bosons**.

3.9.2 Spin Statistics Theorem

In 1940, Pauli formulated the generalization of quantum field theory that applied to all particles that come out of quantum fields called the spin statistics theorem.

3.9.3 Quantum Electrodynamics

The new quantum field theory sought to be reconciled with Maxwell's formulation of electromagnetism. **Quantum Electrodynamics** represented this as the interaction of two quantum fields, the electromagnetic field and the electron field.

These efforts were largely carried on by Heisenberg and Pauli, who relentlessly derived the equations of the proofs, and Fermi, who made the equations look sensible. They derived an equivalency of the two theories in the 1920s. Retranslating results into classical terms gave a new way of thinking about physical forces as virtual photons exchanged between electrons. These twentieth century physicists had achieved Hertz' nineteenth century desire to rid forces from physics and replace them with particles.

Quantum electrodynamics allowed a general way to postulate a new particle as a force carrier for every known force. It was found that every force carrying particle would be a boson. One example of this is the meson Yakawa discovered in 1934.

3.9.4 Problems with QED

A generalization of field theory was accomplished by building off QED, but not everything was consistent in the theory. For example, in many instances of measuring charge, values of infinity were calculated which made no physical sense. Other things in the theory work out very well, so the theory isn't thrown out. Instead, a way to make sense of the infinities by subtracting them away is worked out.

However, this is more of a problem because, since quantum field theory is a generalization of quantum mechanics, which is a generalization of classical mechanics, there seems to be something entirely wrong with the quantization that the theories propose.

Einstein did not trust QM, so of course he did not trust its extensions, QFT and QED, either.

3.9.5 The Fine Structure Constant

Some of the fundamental constants of the universe are Planck's constant h, the speed of light c, and the basic unit of electron charge e. These numbers all have arbitrarily chosen units, but they are combined in a dimensionless unit called the **Fine Structure Constant**:

$$\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

This constant is, put simply, the strength of attraction between electrons. It should be interpreted as the factor of mass-energy above that of an electron where QED breaks down due to uncertainty.

Why is it the reciprocal of a well-defined integer? Nobody knows, and no theory predicts why.

As a result, this number has become somewhat of an enigmatic joke in the physics community. For example, Pauli's death bed hospital room number was 137. Also, Physics 137 at UC Berkeley is quantum mechanics.

3.9.6 Adding Particles

The crisis in quantum electrodynamics in the 1930s led the old physicists to believe that alternatives to QED may be necessary. These studies were localized in Germany, Denmark, the United States, and Japan.

Enabled by new technologies, physicists began detecting new kinds of fermions and bosons to add to the list of known particles. These updates resulted in radical changes in the physics community's sense of the population of the physical world. For example, the **Cloud Chamber** used superdense water between two lead plates to detect the paths of particles. Also, emulsions and thick photographic plates were used to capture the images of many particles. Other projects involved taking measurements of particles from balloons and setting up research stations on mountaintops to obtain more accurate numbers.

The Positron, theoretically predicted by Dirac, was experimentally discovered in 1932.

The Neutron, an uncharged particle that was previously difficult to detect, was discovered by James Chadwick (1901-1954) in 1932.

The Muon was discovered in 1937. It was previously predicted to be a meson in 1934 by Yukawa.

3.10 Modern Physics at Cal

3.10.1 Early UC Physics

From the University of California's foundation in 1868 until about 1920, its physical science instruction was somewhat handicapped.

It was originally founded as a land grant university under the Morill Land Grant Act, to educate members of the broader population. It drew on the resources of the previous College of California in Oakland, and had three principal educational goals:

1. Agricultural extension
2. Mechanical arts
3. Physical sciences

The ambitions of the university's founders were to make it a national center of education.

The campus was almost empty in 1874 except for the two halls: North and South Hall.

Professors with German training in science (with an emphasis on labwork) were hired from other schools. In the 1890s, the mechanical and thermodynamics labs were the most prevalent, principally because they were the most practically useful. In those days, the departments of physics and engineering were almost identical, and a professor would regularly be required to teach courses in both disciplines.

Under the administration of chancellor Benjamin Ide Wheeler, the physics department experienced a large burst of growth. He built the first dedicated physics building, called LeConte Hall, after the prominent Berkeley physicists John and Joseph LeConte.

Raymond Thayer Birge (1887-1980) took physics at Berkeley beyond the classical era and introduced classes that focused on experimental and theoretical quantum mechanics. He was a technically inventive professor who was constantly refining his apparatus in order to generate increasingly accurate measures of the fundamental constants. He wrote the first article in the *Physical Review* about the definition of physical constants.

Birge was also a critical player in chairing the physics department. It was hard to get talented physics students to study at Berkeley before the 1920s, which was when Birge hired a pair of professors that would forever change the reputation of the University of California. The changes that Birge brought about were more qualitative than quantitative. Ernest Orlando Lawrence and J. Robert Oppenheimer were cutting edge physicists, and that was precisely the kind of physics Birge wanted for UC.

3.10.2 Oppenheimer

J. Robert Oppenheimer (1904-1967) started out as a very talented young physicist who studied in Europe with the greats. With Max Born, he developed what is now known as the Born-Oppenheimer Approximation, and with Wolfgang Pauli, he developed some key concepts of the initial formulation of quantum electrodynamics.

In the 1920s, Oppenheimer returned to the U.S. to accept a dual professorship at Cal Tech and UC. He was heard to say "Berkeley was a desert," which meant that there were no quantum theorists in Berkeley with which he could discuss current developments. Oppenheimer was of the last generation of physicists who went to Europe to train. He effectively brought the first theoretical school of physics to America.

Oppenheimer attacked the many problems in QED that he thought were solvable, althought he was largely unsuccessful at solving them. He was working on QED with the expectation that the theory would fail in order to pinpoint where the breakdown occured. Students and fellow faculty were immediately in awe of his ability to readily cite facts and synthesize theory, but he remaining fixed on trying to solve the big problems of QED, which he was never able to do.

Despite his initial misgivings, Oppenheimer began teaching at UC and attracting many fine physics students to Cal. Oppenheimer made Berkeley the most desirable place for theoretical physics in the U.S.

Oppenheimer had sympathies with the international left, and although he was never found to be a member of the communist party, he made his political idealogies very clear to friends and students.

3.10.3 Lawrence

Ernest Orlando Lawrence (1901-1958) was a "hands-on" practical American physicist. Trained in the U.S. and infused with the country's pragmatic spirit, Lawrence's work when he came to Berkeley revolved around construction and refinement of the **Cyclotron**, the particle accelerator for which he received a Nobel Prize in 1939.

The cyclotron was able to cause particles to collide at high speeds and energies that caused reactions to go more readily. These particle accelerators allowed physicists to deduce characteristics of atoms and fundamental particles. The first cyclotron constructed was about the size of your palm, but

3.11 Nuclear Physics

The most exciting discoveries since radioactivity came in the 1930s with nuclear physics.

3.11.1 Theory

Before 1930, it was widely held that electrons are present in the nucleus. Also, the neutron had not been discovered.

In the early thirties, nuclear theory was pretty much a mess, and was mostly qualitative, but did get the theoretical physicist some important results.

Two questions unanswered by quantum mechanics were:

1. What makes them stick together?
2. What makes them fall apart?

Eventually, physicists found two key problems with nuclear electron theory:

1. Imagine trapping an electron in the nucleus, a very small distance Δx. Then, by uncertainty, this would imply that the electron's momentum Δp would be high enough to escape the nucleus!
2. The electron energy spectrum was observed to be continuous, not discrete. But quantum mechanics predicts that the electron spectrum should be discrete!

Some of the prominent atomic physcists proposed solutions to these problems. Notably, Bohr suggested a violation of the conservation of energy.

Correctly, Pauli suggested a mysterious other particle (the neutrino, ν) that carries away the other energy. Though eventually this postulate was accepted, this strange idea should be taken in historical context to indicate a crisis in the field of atomic physics.

3.11.2 The Neutron

James Chadwick (1901-1954, NP 1935) was the key player behind the rethinking of the nucleus that incorporated the particle he discovered in 1932, the **Neutron**.

The neutron was initially said to be a proton and an electron combined in the same particle. The nomenclature of the word "neutron" originated with Rutherford's coinage of the term. Pauli and Fermi played off of this to coin the term "neutrino." Chadwick finally solidified the modern meaning of the word "neutron," also playing off of Rutherford's usage.

Upon hearing of Chadwick's discovery, Heisenberg immediately applied the results in a series of 4 papers. The key concept he put forward was **β-decay**, a process in which a neutron turns into an electron, a proton, and an antineutrino.

3.11.3 Fermi Field Theory

Heisenberg's ideas about β-decay were made more rigorous and expanded upon by Fermi in 1934, with his introduction of what became known as **Fermi Field Theory**. Fermi postulated particle transitions between neutrons, electrons, protons, and antineutrinos as the source of the neutron-proton nuclear force interaction.

Fermi Field Theory turned out not to be strong enough to adequately describe the nucleus because of mathematical difficulties brought about by infinities. But the effect of the theory was to convince the physicists of the world of the reality of particle transitions.

A consequence of this acceptance of transitions is the questioning of the concept of a fundamental particle.

Fermi Field Theory was a very influential precursor to later field theories, in that it was the first to establish the doctrine of constructing a field theory in which what you know (i.e. proton-neutron attraction) happens.

3.11.4 Experiments

Daughter of the other Curies, **Irene Joliot-Curie (1897-1957, NP 1935)** and **Frederic Joliot (1900-1958)** did critical experiments with chemically controlled radioactivity. It should be noted that this was one of the only fields with women in it at this time. Coincidentally, it was also a low-tech field of physics, so was interpreted by many as just chemistry. Because of this blurring of the roles of physicist and chemists in theis period, there was a lot of physicochemical teamwork in the discovery of new elements and nuclear characteristics.

Fermi used neutrons to systematically bombard pretty much all the known atoms. When he got to Uranium, he realized he was inducing radioactivity. In 1934, he bombarded Uranium with neutrons and created an unstable uranium isotope. He concluded that neutrons come in to the uranium nucleus and add to it to create a transuranic element.

As a result of the experiments, the models of the atom evolved:

1. Shell model based on the Pauli exclusion principle
2. Liquid drop model
3. Bohr's compound nucleus model

3.12 Nuclear Fission

3.12.1 Initial Investigations

The compound nucleus model gave physicists of the 1930s a grasp of nuclear reactions.

After Fermi's publishing of his bombardment experiments in 1934-5, **Otto Hahn (1879-1968)** and **Lise Meitner (1878-1968)** got to work in 1938 on the investigation of the transuranics. However, the group was broken up by increasing Nazi power in Germany. Since Meitner was a Jew, she left the country, but managed to maintain contact and the ability to do experiments.

That left Hahn in Germany with **Fritz Strassman (1902-1979)**, where they were still working on the transuranics. Their key discovery was when they found one weird decay product which theory predicted to be radium, but they dug a little deeper. The detection method they used to identify the element relied on the reactivity of radium, which is actually very similar to that of the element barium.

They made the logical leap that they were in fact detecting barium rather than radium. In all previous experience, uranium should decay to radium since it is much closer to it in atomic weight and would be able to be produced by a few simple (and already well-characterized) α decays. However, the overwhelming chemical evidence forced them to conclude that it was barium, and that it must have been produced in an entirely new kind of nuclear reaction.

Hahn and Strassman wrote to Meitner, who was then in Sweden, and she said that their discovery marked the breakdown of the compound nucleus model of the atom.

3.12.2 Rethinking the Nucleus

Together with Meitner, **Otto Robert Frisch (1904-1979)** reworked the theory of the nucleus in light of the new evidence of Hahn's neutron bombardments. Their theory envisioned the nucleus as a mass which, on impact of a neutron, would be set in oscillations which may render the nucleus unstable. This instability would sometimes result in the production of smaller nuclei, **Fission Fragments**, and excess neutrons.

Meitner and Frisch made the key deduction that if there were many nuclei involved in such a reaction, there was a possibility of a self-sustaining **Chain Reaction**.

It was understood from the start that such a reaction would liberate a substantial amount of energy. This theoretical prediction came from calculations of binding energies. The quantity which Uranium possesses is much greater than the sum of that of the two fission fragments. As an aside, it is interesting to note that an iron isotope is the most stable (in terms of this binding energy per particle) of all known substances.

3.12.3 Soviet Physics

From the mid to late 1920s, there were high hopes for science in the Soviet Union. Party talk was filled with expression of support and favor from high officials.

There was a rise of a generation of physicists who signed on to the political goals of the state which initially coincided with the goals of physicists.

However, in the early 1930s, there was a change for the worse. With the creation of **Red Universities**, the Marxists began teaching skepticism toward general relativity, calling it an idealization. Their theory was embodied in their belief that sensationalism and operational definitions, concepts widely accepted by the physics community, were nothing more than capitalist propaganda.

They enforced policies that were interpreted as dialectical materialism by Bohr and Heisenberg.

The Party cut off Soviet scientists from the rest of the world when Stalin came to power. In addition to this loss of international connections, many physicists died in the great purges of 1936.

One prominent physicist who was imprisoned by the state was **Lev Davidovich Landau (1908-1968, NP 1962)**, who was sentenced to Lubyanka prison in 1938, because he was committed to socialist ideals which conflicted with Stalin's dictatorship. He was eventually released because his physics research was very good and he had some political connections.

3.12.4 Facist Italian Physics

Benito Mussolini (1883-1945) came to power in Italy in 1922. Despite this fact, the twenties and thirties were good years for Italian physics, because of Fermi's neutron bombardment experiments.

There weren't many political ramifications for physics until 1938, when the facist race laws began to be imposed. Since Fermi's wife was Jewish, they planned to leave Italy. When he went to Stockholm to receive his Nobel Prize, he departed for the United States rather than facist Italy.

3.12.5 Facist German Physics

The interim Weimar Republic never showed much support for physics in the 1920s.

In the late 1920s, dissatisfaction with democracy and polarization in politics in Germany led to Communists and Nazis battling politically and overtly for power. Dissatisfied with the current state of politics, the chancellor dissolved the positions of most elected officials in 1930, and new elections were held that replaced them all with Nazis and some Communists.

The NSDAP (Nazi party) ended up on top, however, as Hitler (1889-1945) was elected chancellor in 1933. Amid escalating conflicts for power, a dictatorship was established in Germany that ultimately had the ramifications of stifling German physics.

Chapter 4

World War II and Beyond

4.1 Nazi Physics

The effect of Nazi rhetoric on physics was a dire one. The years following the Nazi rise to power saw the expulsion of many prominent physicists, particularly in the theoretical domain, and so there was a consequent decline in the quality of German physics.

4.1.1 Nazi Laws

The **Civil Service Restoration Law** of 1933 drove Jews and politically suspect professors from office. Einstein was one of the few who left voluntarily. Most professors initially stayed, despite the unfair treatment of their colleagues. Outside of the university environment, there still were Jews with jobs, for example, at the Kaiser Wilhelm Institute.

The **Nuremberg Laws** were imposed in 1935. These laws served to severely restrict the civil liberties of Jews in society. This also forced many physicists out of Germany.

The lucky ones were able to foresee what was going on and emigrate early. Those who emigrated were able to as a result of international physicist networks, such as Bohr's, that had developed in previous years. Niels Bohr was at the center of a vast many social networks.

There was a spectacular loss of practicing physicists in Germany as a result of the Nazi restructuring of academia, particularly in the field of theoretical physics. Many scientists resigned from their posts in Germany, and many others refused to publish their findings in German journals. One example of this is Hans Bethe, a great loss for German physics and a great gain for American physics. Likewise, Fermi went to Chicago, and Pauli went to Princeton. Planck stayed and tried to compensate for the extreme losses, but failed to, since there really just weren't enough physicists left.

The U.S. wasn't particularly desirable of a destination for physics, but since it was so huge and politically neutral, it offered a great refuge for many physicists. There was only minimal anti-semitism to deal with in the States.

4.1.2 Aryan Physics

Aryan Physics was the attempt to take the Nazi idealogy and apply it to physics. They thought of theoretical physics as synonymous with Jewish physics, hence the exile of so many theoretical physicists and decline of that discipline.

Leaders of the movement were **Philipp Lenard (1862-1947, NP 1905)** and **Johannes Stark (1874-1957, NP 1919)**, who doggedly fought Jewish physics. They labeled Heisenberg, who also stayed in Germany, as a "white jew," since he didn't buy into the Nazi rhetoric and its application to physics. Stark and Lenard thought that their own Nobel Prize winning results had been hijacked by other physicists such as Bohr, and didn't like the changes he and others were making to the nature of physics.

One of the reasons why Stark and Lenard didn't embrace quantum mechanics was that they simply were not trained in the mathematics to handle it. This cursory analysis glosses over an important point: the nature of physics really does change with the introduction of relativity and quantum mechanics. They were some of the only ones who questioned whether that change was a step in the right direction.

In fact, many non-scientist politicians didn't really care about these physicists were emphasizing that they were doing Aryan Physics. These political leaders were more concerned with the lack of physical results that Aryan Physics seemed to be producing.

4.1.3 Heisenberg's Controversy

Sommerfeld's position was emptied in the late 1930s, so Heisenberg was nominated to fill his prestigious position. However, his taking of the position seemed dangerous to some, since he was labeled as a “white jew” by the Aryan Physicists.

To overcome this problem and in effort to secure the professorship, Heisenberg called on a personal connection he had to the Nazi regime. His mother knew the mother of Heinrich Himmler, so he tried to levy that connection to get the position. Heisenberg cunningly enlisted the help of scientists in the Nazi party, forcing many of them to acknowledge that they had to make a choice which amounted to Aryan Physics, or good physics. He even learned Nazi terminology in order to convince party members that his modern physics was the right way to proceed.

When still faced with adversity from the Aryan Physicists, he was forced to advance his quantum mechanical agenda covertly. He taught a class called the “electrodynamics of moving media” which emphasized Einsteinian relativity.

The ultimate result of Sommerfeld’s professorship was an Aryan Physics victory, but a consequent loss for German physics. However, Aryan Physics was discouraged by Nazi Party officials due to their nonsensical disregard for theory.

Heisenberg’s work on the Nazi fission project, an attempt to develop nuclear weapons, is among the most hotly debated topics in the history of physics. Heisenberg was working on it to prove the usefulness of modern theoretical physics. Midway through the war Heisenberg gained the directorship of the Kaiser Wilhelm Institute, so he used this to direct the bomb project. Although ultimately unsuccessful, many scholars debate the reason why.

One speculative account of Heisenberg’s work on the Nazi bomb project is contained in Michael Frayn’s play *Copenhagen* [1]. Frayn is very divided and presents many different outcomes of what may have happened in Heisenberg’s meeting with Bohr. In this way, he also leaves the specifics of what had been the stifling step in bomb development up to speculation.

A new publication, Ranier Karlsch’s *Hitlers Bombe*, promises an analysis of new documents that show evidence of a dirty bomb explosion in late WW2 Germany [2].

4.2 Big Physics

4.2.1 Introduction

Big Science is the term historians use to characterize the massively political, economic, and military science research projects that emerged in the twentieth century. Therefore, the term "big physics" can be used to describe the atomic bomb project, one example of big science in the domain of physics.

Physicists were being mobilized to develop new technologies for war in countries such as Germany, Japan, and the U.S.S.R. In the United States, radar had been developed and was proving to be a useful technology. In contrast, nuclear fission was a cusp theory with no clear technological feasibility. Constructing a "the Gadget," or nuclear bomb, based on the concept of nuclear fission was seen as a gamble by prewar politicians because physicists did not know it was possible.

4.2.2 Physics of Nuclear Weapons

Understanding the concepts behind nuclear fission is simple, but the application of making the bomb is rather difficult.

One question that needed to be asked was precisely how do neutrons interact with nuclei? Another question was how to make nuclear reaction not only self-sustaining, but also explosive and uncontrolled. In contrast, the first nuclear reactor for generating electric power was created by Fermi based on the principle of a self-sustaining, non-explosive reaction.

Of critical importance to the construction of the bomb was the size and shape of the lump of uranium that was to be used in the fission. To generate an explosive reaction, it was found that a critical size, or mass, was required. This **Critical Mass** was found to be only a few pounds.

4.2.3 Isotope Separation

Uranium comes in two varieties: U-238 and U-235. The isotope that is found very infrequently in nature, U-235, is also the kind that is necessary for the fission reaction. Not only is U-238 much more prevalent, it is also very difficult to separate away from the desirable U-235.

There was a theoretical possibility of a fission reaction with the transuranic element plutonium, which would be generated by decays from U-238. However, the problem with using this technique was actually making the plutonium by stimulating these decays. The plutonium could be made in a nuclear reactor, and then separated out, but the problem was the riskiness of the industrial-sized venture. This was the same problem that deterred the Germans from working out a bomb.

The critical mass of plutonium is in fact a sphere about the size of a softball. It is not really a chemically volatile element in subcritical masses, so it is stable and pretty harmless. However, it is cancerous if it is breathed into the lungs.

4.2.4 Bomb Design

With uranium weapons, the design was a relatively simple gun design, but with plutonium weapons, the design involved a complex implosion design. So, to make a bomb, you need to either separate out U-235 from naturally occuring uranium ore, or make plutonium in a nuclear reactor then separate it out.

To accomplish this, large industrial scale production ventures were needed. This was a risky venture that only the Americans pursued until after the first bomb denotation. The first exploded nuclear weapon was a proof-of-concept that allowed other countries to devote money to nuclear power research, seeing that it was indeed technologically feasible.

To this end, the Soviets immediately got to work on a bomb after the Hiroshima detonation.

Also, before the detonation, a small group of $\approx$ 100 Germans in 1943 was working on a bomb design, but they never completed it. Some speculate as to why, but the reasons include:

- Heisenberg's possible sabotage
- Lack of urgency in development
- Dwindling war resources
- Overestimation of critical mass
- Lack of development of isotope separation

4.2.5 American Mobilization

The physicists of the U.S. were really mobilized in development of nuclear weapons after Einstein's letter to FDR was acted upon. Inspired by Leo Szilard, the letter argued that the Germans had the capability to produce nuclear weapons and that the Americans needed to pre-empt them in development.

The first action was to mobilize the physicists of the Berkeley Rad Lab. Lawrence's magnet yoke, developed in 1942, was quickly reapplied to the war effort for separation isotopes.

Additionally, there was Army oversight. Under the command of general **Leslie Groves**, the nuclear weapons development program went forward under the name "The Manhattan Project."

The plan was to move ahead in production and research into all feasible implementations for "the gadget," as the bomb was initially called. These efforts continued at four principal locations:

University of Chicago Enrico Fermi's Metallurgical Laboratory created the first self-sustaining nuclear reactor, or **Pile**.

Hanford, WA Nuclear reactors and water treatment plants were constructed for plutonium extraction

Oak Ridge, TN Gaseous diffusion plants were constructed for U-235 separation

Los Alamos, NM The principal reseach team, led by Oppenheimer, set out to design the two bombs. The leadership came from the University of California, and was set up also partially by Lawrence and then-chancellor Ida Sproul.

Note that all these efforts have a distinctly industrial component to their operation. Companies such as General Motors and DuPont played a key role in uniting to accomplish the industrial-scale production that was required for the nuclear weapons' development.

In July, 1945, the first nuclear weapon was detonated in the New Mexico desert in what was called **Trinity**.

4.3 Political Physics After the Bomb

4.3.1 Initial Reactions

Bohr foresaw a nuclear arms race as early as 1945. From the Chicago Met Lab, Fermi asserted that it would not be posible to maintain the moral stance of using the bomb.

James Franck (182-1964, NP 1925) constructed a recommendation to Washington, later called the Franck Report, that discouraged the use of nuclear weapons from the start.

The other idea was to make a demonstration of the American nuclear arsenal and employ it from the start on a hostile city.

During the period immediately after the initial bombings of Hiroshima and Nagasaki, physicists are frequently called upon to give advice to the politicians. They can speak of the destruction of nuclear weapons in a way that no one else can. This is the first time that physicists have been invited to the decision-making process, and it marks an irreversible change in the role of physicists.

4.3.2 Scientist's Movement

Many physicists took to the streets and spoke to the public about nuclear weapons in a grassroots advocacy movement. It is from these groups of physicists that the **Federation of Atomic Scientists** and its publication, the *Bulletin of the Atomic Scientists*.

The political ambitions of these groups proved too ideal and unrealizable, and peaked in 1946.

4.3.3 Cold War Distrust

In August 1945, Soviets exploded their own nuclear weapon, informally called "Joe1" — Joseph Stalin's first nuclear weapon — in American circles. Many U.S. politicians thought it could only have been developed as a result of Soviet espionage. However, when consulted, the scientists told the politicians that it wasn't a particularly difficult engineering feat, especially after the American proof-of-concept.

Taking advantage of **Fusion Power**, American physicists led by **Edward Teller (1908-2003)** developed a new type of nuclear weapon that was orders of magnitude more destructive than previous fission-powered bombs. The first **Hydrogen Bomb** was ready in 1952 in the U.S. and in 1953 in the U.S.S.R. Prominent American physicists spoke out against its development, advising that although the weapon was technically possible, it would certainly be a weapon of nothing more than genocide that would also encourage the Soviets to develop their own. Fermi codified this belief in his statement that the hydrogen bomb is an “evil thing an any light.”

At home, J. Edgar Hoover put many suspicious scientists under investigation as communist traitors. Notably, the investigations targeted, among others, Oppenheimer and his friends, relatives, and students. This paranoid search for traitors destroyed the careers of many physicists, and was just as intense in the U.S.S.R.

4.3.4 Funding

Post-WW2 physics experienced a massive boom in the funding it received from federal agencies. This mirrored a trend that saw expanded funding to all the sciences, but physics received special treatment due to the potential for military applications for developments.

Unlike before the war, the federal government became the principal supplier of funds to physics research. Before the war, it was seen as a bad thing to accept funding from the government because ot the potential political strings attached, but after the war, these fears get ignored.

Some **Secret Science** — funded by the CIA and done in covert circles — started appearing after WW2.

Again, the principal reason for the increases in funding was the federal government’s expectation that basic research would result in a military technology payoff at some time in the future.

A physicist during this period was somewhat of a jack-of-all-trades, in that he was expected to be politically active and academically productive.

There are two principal areas that received major expansions as a result of increased funding:

1. In high energy physics, funds were set aside for the construction of ever-bigger particle accelerators that could detect ever-smaller particles. This trend led to the retelling of this period as the journey inward bound to the center of the atom and the physical world.

2. In solid state research, funding was used to create the high-tech industry of the Silicon Valley in California

The NSF began to fund nonmilitary projects by 1960. This resulted in an unprecedented deluge of experimental research that became possible due to the increased funding, and a very big payoff in scientific terms, as all fields of science rapidly expanded. Scientists overseas would go to the U.S. rather than vice versa (as previously) to obtain their doctorates. LBNL was established during this time to accelerate research. CERN in Switzerland mimicked the American system and was also set up during this period. It should be noted that the demographics of these expansions consisted primarily of white men.

4.4 Rethinking Quantum Field Theory

4.4.1 The Problem

Remember that in QED we were left with a theory before WW2 that was infused with problems with infinities. For example, the electric charge of a lone particle in a vacuum was calculated to be infinity. These unlimited calculations also led to the nonsensical result that some particles had infinite mass.

The results they were getting were:

$$\int_0^\infty E^2 dE = \infty$$

$$\int_0^\infty r^{-2} dr = \infty$$

These problems were ameliorated (at least a little) by a previous method of subtracting away infinities, but to make the field really progress, physicists realized the need for reform.

4.4.2 Initial Solution

The problems seemed to be caused by QED's treatment of high energy and short distances, so the initial solution that physicists proposed before the war was revising their mathematics to include a formal upper limit E_{Max}.

$$S = \begin{bmatrix} P(1,1) & P(1,2) & P(1,3) \\ P(2,1) & P(2,2) & P(2,3) \\ P(3,1) & P(3,2) & P(3,3) \end{bmatrix}$$

Figure 4.1: Heisenberg's S matrix, which was used to consider the probability of particle scattering in QFT systems. Consider three particles and arbitrarily call them 1, 2, and 3. Let $P(i,j)$ denote the probability of observing i go into a system and j go out.

Essentially, this was just a trick to rewrite their integrals in a different way:

$$\int_0^{E_{\text{Max}}} E^2 dE = \int_0^{\infty} E^2 dE - \int_{E_{\text{Max}}}^{\infty} E^2 dE$$

It was shown that these results are mathematically consistent and, more importantly, consistent with reality.

Heisenberg and Pauli claimed the need for an entirely new theoretical approach to QED in 1939, but these desires were largely set aside during World War II as physicists mobilized for the war effort. One notable exception was Heisenberg in 1940-44, who proposed the S matrix.

4.4.3 The S Matrix

Heisenberg's key leap of logic was to consider **Scattering** as the principal concept to model QED.

Like with his uncertainty principle, Heisenberg proposed to abandon all statements about small distances which they couldn't possibly observe. Instead, he proposed to only talk of scattering, or the input and output of particles to the system.

The **S Matrix** is a matrix of probability values that represents the probability of observing certain events.

An example S matrix is represented in Figure 4.1.

Though the S matrix was not a solution to the problems of QED in its own right, it became a useful tool for QFT later.

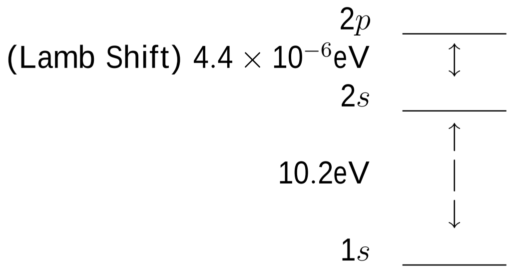

Figure 4.2: The Lamb shift, which was detected with radar-like microwave technology and provided an experimental testing ground for renormalized QED.

4.4.4 Renormalized QED

Between 1947 and 1949, the problems with QED were solved by redefining fundamental physical quantities such that the previously incapacitating infinities were considered from the start.

In this **Renormalization**, physicists made the familiar leap of only considering what is actually observed. The doctrine of renormalization was highly operational, and focused not on the absolute charge of electrons but rather the effective charge.

In essence, renormalization was similar to the integral subtractions. Some physicists asked why they even had the mathematical freedom to rescale infinite quantities to finite quantities. These concerns were alleviated by another recurring theme: the ends justify the means. Renormalization provided such good results that it could not be ignored.

Another reason why renormalized QED was so successful was that it was shown to be relativistically consistent.

4.4.5 Experimental Provocations

Work on the detailed structure of the $n = 2$ hydrogen orbitals revealed an anomalous phenomenon called the **Lamb Shift** which was essentially a slight difference between the energy levels of the $2s$ and $2p$ orbitals. Radar technology made microwave devices practical in the lab, and these devices allowed detection of the very small difference (Figure 4.2).

Previous incarnations of QED made it impossible to distinguish between the two energy levels observed in the Lamb shift, but renormalized QED predicted this quite well.

4.4.6 The Architects

The designers of this version of renormalized QED were **Sin-Itiro Tomonaga (1906-1976, NP 1965)** and **Julian Schwinger (1918-1994, NP 1965)**.

Their approach, previously described, involved clumping infinities together into long, confusing equations that would contrast the approach put forward by Feynman later.

4.5 Renormalization

4.5.1 Feynman's Graphs

The second, more palatable approach to renormalized QED came from a young physicist named **Richard Feynman**. He relativistically consider QED and represented what he mathematically deduced with intuitive visual diagrams, which later became known as **Feynman Graphs**. These graphs consisted of three primary components:

1. Photon $\rightsquigarrow$
2. Electron $\longrightarrow$
3. Vertex $\bullet$

Each component of the diagram corresponds to a term in the equation, so these graphs were essentially recipes for QED equations.

The mathematical term for a vertex includes the fine structure constant, so this has the effect of multiplying successive terms by a factor of $\alpha \approx 1/137$. That is, the more vertices there are, the less likely it is to see a theorized particle. It is here that the classic result of perturbation theory is applied by Feynman. Simple zeroth order diagrams are the most probable, but then the likelihood of first and second order diagrams (with an increasing number of vertices) is calculated by applying a factor of α. This resonates with the theme of sucessive approximations to a complex system that arises from simple theoretical beginnings.

These graphs are little more than doodles on Feynman's notebook paper at first, but with his increasing use of them, they get formalized and popularly accepted in the physics community as the concept gets mapped onto the content of QED.

Another reason why Feynman graphs became so popular was that he described them by using analogies with which everyone was familiar. For example, he described the path of an electron which turns into an antielectron and then back into an electron as a road that is viewed from the sky by a bombardier, something that everyone was familiar with because of WW2. This example system can be thought of in two ways:

1. One trajectory in which the electron changes into a positron, moves back in time, then changes back into an electron

2. Three simultaneous trajectories in which two electrons exist along with a positron

4.5.2 Feynman at Los Alamos

Feynman was recruited to work on nuclear weapons development in at Los Alamos in 1942.

People there were in awe of his ability to do physics. Oppenheimer noticed and recruited him to teach at UC Berkeley after the war.

His job at Los Alamos was to calculate neutron diffusion, a complicated problem that involved considering the uranium samples with non-homogenous isotope composition. What he did to solve the problem was consider microscopic diffusion rather than macroscopic diffusion. He knew the start and finish coordinates of the neutron (i.e. inside the nucleus then outside), so he developed line drawings which represented the path that one neutron could take to get from start to finish. Then he summed over all possible paths to find the solution for neutron diffusion.

In retrospect, it seems that his more famous diagrams were probably derived from these initial scrawlings for neutron diffusion at Los Alamos. Indeed, when the documents that detailed his neutron diffusion results became declassified in the 1990s, it became clear where his inspiration for his more popular diagrams came from.

This is another example of the history of science theme of distinction between phenomena and how we describe them.

4.5.3 Dyson's Fusion

Freeman Dyson (1923-) wrote his honors thesis on QED and showed the equivalency of Schwinger-Tomonaga renormalization with Feynman renormalization.

Dyson accomplished this much-needed synthesis by using Heisenberg's S matrix.

This final fusion of the two forms of QED is what is usually referred to by historians as the Renormalization of QED.

Again, it had amazing agreement with experiments such as the prediction of the Lamb shift. These great results prompted immediate acceptance of the theory among most physicists.

There was some dissent, however. Most of the designers of renormalized QED thought it was just a temporary solution to the problems, to be used only until a better formulation was accomplished. Older physicists such as Pauli, Heisenberg, and Bohr thought a complete overhaul of QFT was still necessary. However, the younger generation was taught renormalized QED in college, so from the outset accepted it as a useful tool.

This reluctance of the older generation to accept modern developments and the next generation's unquestioning acceptance of the same development is a deeply paradoxical theme in the history of science. Other examples of this are Bohr's correspondence principle and commutation relation which was accepted by Heisenberg and Pauli's generation.

4.5.4 Generalization and Problems

QED was generalized to be able to describe various other physical phenomena. This generalization was accomplished by using the Feynman diagrams to represent other particles:

1. Squigglons $\leadsto$ (i.e. photons and bosons)
2. Straightons $\longrightarrow$ (i.e. electrons and fermions)
3. Vertex $\bullet$

However, one problem that renormalized QED faced was the phenomenon of Fermi field theory called the **Four Fermion Interaction**. This occured when a neutron disappears and creates a proton, electron, and antineutrino.

The point was that physicists were thinking of the theory as dictatorial of reality. Because there was no predicted result for the four fermion interaction, physicists actually limited themselves to not even considering it a physical reality. Their view was that if it couldn't be described in terms of renormalized QED than it wasn't worth describing.

4.6 The Standard Model

4.6.1 Themes

Themes of the development of the **Standard Model** of particle physics include:

1. Interplay of theory and experiment
2. Interplay between different kinds of theorizing

   Particles Content

   Mathematics Form

Examining form (i.e. the overarching framework of QFT) as the historical driving force behind the standard model seems to be the more interesting way of describing its development.

4.6.2 New Particles

The postwar decades saw the discovery of a vast number of new particles that no theory had predicted before. They were being discovered at such an alarming rate that theorists couldn't keep up with the experimentalists. These new particles included mesons and heavier particles (Table 4.1).

Most new particles were detected in particle accelerators and had very short lifetimes. Such strange phenomena motivated physicists to question their entire concept of a particle.

Some physicists referred to all the particles that were being discovered as a "**Particle Zoo**," and some even attempted to classify them in a method analogous to that of natural history.

The multiplicity of particles was explained using three principal concepts:

Date	Particles Known
1925	Photon ν, electron e, proton p
1930s	Neutrino γ, Muon μ, neutron n
1940s	Intermediate mass π mesons
1950s	More mesons, more heavy particles

Table 4.1: Particles discovered in the twentieth century that contributed to the development of the standard model.

1. Distinguish them by using the different forces that act on the particles (i.e. weak and strong forces affect particles differently, gravity is ignored on this small scale)
2. New symmetries are proposed and new quantum numbers in the spirit of the Pauli exclusion principle
3. These newly discovered particles were supposed to be a new set of elementary particles

4.6.3 Revising QED Again?

By the 1950s it had become apparent that QFT needed yet another revision. Physicists needed a convergent mathematical description of the particles they were studying. However, in many circumstances, the old version of QFT would not converge and again the theory would not be able to produce viable results. So, for a period, QFT is abandoned.

In its stead, the Berkeley physicist **Geoff Chew (1924-)** proposed the theory of **Nuclear Democracy**, a de-emphasis on fundamental particles that was partially inspired by the American political atmosphere in the 1960s. This theory used the S matrix in a looser, more open framework that was conducive to describing the new menagerie of particles.

For about a decade, QFT was marginalized by nuclear democracy and other theories in particle physics.

4.6.4 Comeback of QFT

A conservative return to the existing framework of previous decades, QFT was reformulated, questioned, then incorporated back into particle physics in 1965.

The theory wasn't really an attempt to get at the content of particle physics; rather, it was an attempt at exploring the **Gauge Invariance**, a subtle phenomenon predicted by QED. The core of the theory involved changing equations that do not have observable consequences, but make for easier mathematics. For example, this new form of QFT proposed a different version of Ψ, the Schrödinger wave equation, which did not alter Ψ^2, which was the observable quantity.

This new quantum field theory was thought of by some as a **Magic Wand** because it made possible a derivation of the light quantum from the assumption of an electron by thinking through the consequences of gauge invariance. This "creation" of a particle for free was seen as the "magic."

Applying these new concepts to the **Weak Force** yielded a coupling constant of $\approx$ 10. Unlike with EM, which uses the coupling constant $\alpha \approx 1/137$, this coupling constant of greater than unity meant that neither perturbation theory nor renormalization could be applied.

Another interesting and critical consequence of the standard model's QFT was that bosons fall out for free, assuming gauge invariance. Bosons, represented by the symbols W^+, W^- and Z, were predicted to be as heavy as a silver nucleus. These force-carrying particles solved the problem of the four fermion interaction by reducing the number of lines at a vertex to 3, which made the problem manageable in terms of QFT.

Physicists in the early days of the standard model became adept at creating stimulating and palatable ways to communicate their research to the laypublic. For example, seeing the **Golden Boson** was visual proof for many nonscientists of the validity of the physicists' work. This boson was visualized in a false color image that was designed to appeal to funding agencies, even though most concepts the physicists actually do research on would be imcomprehensible to the bureaucrats of those agencies.

The parity violation was discovered in the 1950s and consisted of the observation of a particle's spin mirror asymmetry. This was seeming evidence of a charge-parity violation.

4.7 Astrophysics and Cosmology

4.7.1 The Standard Model

Some saw the standard model as the end-all of physics, but others supposed that:

1. Physics was open-ended beyond the standard model
2. Particle physics was not the end of physics

Cosmology is an example of interdisciplinary physics that draws on the standard model but takes it in another direction.

4.7.2 Early General Relativist

In the 1920s and 1930s, physicists began to wield a significant influence on cosmology. This is a trend that had been increasing since the 1850s. Physicists observed solar spectra and these observations needed to be reconciled with other observations from cosmology.

However, the real interplay between physics and cosmology came about with the formulation of general relativity. Solutions to Einstein's field equations were suggested but this line of inquiry was seen as more of a mathematical field of study, and not so much as astronomy. These solutions suggested structural properties of the universe.

Many astronomers were actually doubtful of the universality of general relativity, citing that they saw no evidence that the law holds in all regions of the universe.

However, this view changed after the detection of **Redshift** by **Edwin Hubble (1889-1953)** from Mt. Wilson (near Cal Tech) in the late 1920s. He deduced the shift of light from faraway stars into the red of the visual spectrum to mean that the galaxies were flying away from the Earth. In other words, he took the redshift to mean that the fabric of spacetime was stretching out to carry galaxies away from each other. This led to the expanding universe theory.

However, in the 1930s, an expanding universe didn't necessarily imply the now-ubiquitous **Big Bang** theory. Other explanations of universal formation did exist and were in contention.

Fermi-Dirac statistics were used to suggest and explain the presence of white dwarfs and neutron stars.

4.7.3 Nuclear Physics

Results from nuclear physics were assimilated by cosmologists when they realized that fusion burning in stars could explain the formation of higher order elements.

To concretely formulate a theory of higher order element formation, much experimental data was needed on nuclear reactions. This data was provided by Bethe, who received a Nobel Prize for it in 1967. As an aside, Bethe contributed so much to nuclear physics in the 30s and 40s that many thought he should have received the prize before. Indeed, this is an early example of a Nobel Prize as a lifetime achievement award.

George Gamov (1904-1968) was an eccentric astrophysicist who had a cat he named “Spin.” Another example of his eccentricity is an infamous paper that in total had the authors Alpher, Bethe, and Gamov (Bethe was added for the simple reason of creating the homonym, and Alpher was Gamov’s student). Gamov’s main theoretical idea was a physical big bang that proposed **Nucleosynthesis**, a theory of heavy element creation. Since he never put his theory in contact with astronomical data, his results were for the most part ignored until much later.

4.7.4 Postwar

The astronomers reformulated the big bang in the 1960s as a **Steady State Universe**, which the data really didn’t support any more than Gamov’s nucleosynthesis theory.

Other advances in cosmological theory came about by observing x-rays that were observed only once astronomers had intrsuments that could detect rays above the atmophere. To this end, radar technology was applied to radio telescopy in Britain.

An interesting observation that resulted from these instruments was the **Cosmic Microwave Spectrum**. Many interpret this spectrum as evidence of the big bang theory of universe formation and the slight fluctuations in the spectrum as signs of the quantum fluctuations in the first few seconds of the universe.

4.7.5 Relativity and QFT

The general relativity renaissance and unification with quantum field theory, with widespread applications to cosmology, began in the 1960s.

Physicists put the standard model to work in explaining many problems in astrophysics. For example, the relative abundance of matter rather than antimatter was explained in this way.

There was a big theoretical interplay between particle physics and cosmology, with particle physics often having to play catch up to the astronomers who would suggest new particles.

4.8 Simplicity and Complexity

4.8.1 Themes

Should quantum field theory be considered a coherent world picture, now that it has encompassed condensed matter physics, particle physics, and astrophyics?

Its complexity comes from explaining patters, structural emergent properties, and organized macroscopic behavior. One example is Feynman's crossing over of QED to explain superfluidity.

A recurring theme is the many-body problem, in which complexity emerges because of interations with simple components. The overall rule is "more is different."

4.8.2 Quasiparticles

A **Quasiparticle** is a particle plus a cloud that accompanies it due to interactions with the surrounding media.

For example, an electron being shot into a sea of other electrons can be modeled using quasiparticles. Repulsion dictates that a slightly positively charged field will stabilize around the negative charge of the electron that enters the sea. This surrounding positive charge will change the observed charge and mass of the electron. This example is very reminiscent of renormalized QED, and, indeed, solutions from that discipline have been applied to this problem.

4.8.3 Collective Excitation

Collective Excitation is a wavelike characterization of the excitation of a system as a whole. In this theory, quanta are called **Plasmons** and reverberations in crystals of the solid state are called **Phonons**.

Partially inspired by his socialist political ideals, Landau develops collective excitation to contrast the theory of quasiparticles.

4.8.4 Particles in Problem Solving

Superconductivity was discovered in mercury in 1911. A correlation was established between this macroscopic phenomenon and the movement of electrons in conduction.

John Bardeen (NP 1972), Cooper, and Schrieffer received a Nobel Prize in 1972 for their work in considering "Cooper pairs" of electrons as the basic unit for conductivity in QFT. Their work encompassed reimporting and retranslating ideas between various fields of physical study.

4.8.5 Lessons for QFT

Condensed matter physics brought about some changes in QFT:

1. About fundamental particles, which were different in different theories
2. About scale, which was a function of renormalization
3. About universality, which emphasized applicability to micro and macro systems
4. About unification, which united methodologies of various fields

So, was the twentieth century a journey of inward bound? Not necessarily, but it is a story easy to tell by quantum field theorists and condensed matter physicists.

4.9 Meta-Historical Meditations

4.9.1 Who should tell the story?

Many times in the history of science, there are key players from many different disciplines who all have their own subjective sense of the truth about the past.

For example, consider the history of Berkeley's bevatron. Who should tell its story? The...

- Experimenter?
- Theorist?
- Health Physicist?
- Visitor?
- Funding Agency?

These are all difference perspectives that come from different life experiences of the same history. How can we, as historians, get a firm grasp on, and create a coherent version of, the truth?

4.9.2 Univocally?

One standard narrative device that attempts to reconcile this in the most straightforward and intuitive way possible is the method of **Univocal Instruction**. It essentially outlines an anachronistic unidirectional arrow from classical to modern physics.

The stories told by univocal instruction give a good argument for the acceptance of physical theory for the undergrad who reads it from his textbook, but what does this route say of the inevitability, or lack thereof, of that history?

4.9.3 Alternatives?

The hallmark achievement of modern physics that really signalled the end of the classical age was the Copenhagen interpretation, which many historians portray as an irreversible and inevitable watershed event in the history of physics.

However, as historians, we need to call into question such generalizations and ask what the history really reveals. One historian who has done this is Bell.

Physics itself teaches the **Many-Worlds** interpretation of probability, first argued by one of Oppenheimer's students, **Bohm**. How shallow we historians must be if we are to accept only one interpretation, one voice, and one possible history of the past, when the content we analyze even suggests otherwise!

Bohm provided this interpretation as a viable alternative to the orthodoxy of the Copenhagen interpretation, and thus the moment of supposed decision in 1927 is shown to not be an irreversible one. For Bohm, it was “the problem of choice” that was the center of his investigations. As one of Oppenheimer’s students, he was a political communist, so his work was largely marginalized and he was eventually forced into an unhappy, unproductive exile from the U.S.

4.9.4 Necessity?

It boils down to this: do we have to tell the history of physics with the distinct break between classical and modern that is all-too-often marked by the Copenhagen interpretation in 1927?

One way to say “no” is by examining the problems of classical physics that persisted even after 1927.

There are many examples of this:

1. Turbulence
2. Heisenberg and God
3. Relativity

The point is that classical problems still exist, even today.

A holistic view of history doesn’t necessarily draw distinct lines, or synthesize artificial trajectories of progress, but rather creates a gestalt portrait of of the time in effort to gain a real understanding of the past.

Bibliography

[1] Michael Frayn. *Copenhagen*. Anchor Books, New York, 1998.

[2] Ranier Karlsch. *Hitlers Bombe: Die geheime Geschichte der deutschen Kernwaffenversuche.* Deutsche Verlags-Anstalt, Munich, 2005.

[3] Russell McCormmach. *Night Thoughts of a Classical Physicist*. Harvard University Press, Cambridge, MA, USA, 1982.

Appendix A

Glossary

S Matrix	Mathematical construction that consists of probabilities of scattering events and models macroscopic phenomena of QED systems, 94
β-decay	Heisenberg's nuclear reaction in which a neutron turns into an electron, a proton, and an antineutrino, 80
Albert Einstein	NP Physics 1921, early twentieth century theoretical physicist that proposed models of the photoelectric effect, Brownian motion, and relativity, 45
Alfred Loomis (1887-1975)	Investment banker who gave large financial and social donations to Lawrence and did some amateur physics, 78
Anomalous Zeeman Effect	Problem of the old quantum theory of atomic structure which caused two bands to appear where Bohr only predicted one; Pauli suggested the exclusion principle as a solution, 66
Antimatter	Matter with negative mass-energy predicted by quantum field theory and created whenever ordinary matter is destroyed, 72
Aryan Physics	Scientific assimilation of conservative Nazi idealogy which de-emphasized theory and questioned modern physical developments such as quantum mechanics and relativity, 86
Big Bang	Theory of universal formation involving an initial singularity and rapid universal expansion, 102

Big Science Political, economic, and military integration with science that is typical of the large scale projects of the twentieth century, 88

Bohm Author of the many-worlds interpretation of probability, thinker of a viable alternative to the orthodoxy of the Copenhagen interpretation, and unhappy communist exile from America, 106

Bohr Model Bohr's postulation that all electrons move in circular, stable orbits, 55

Bose-Einstein Statistics Mathematical formulation of the behavior of bosons, which include photons, 73

Boson Force-carrying particles with spin $0, \pm 1, \pm 2, ...$, described by Bose-Einstein statistics, and predicted for free by standard model QFT, 73

Chain Reaction First envisioned by Meitner and Frisch, the self-sustaining nuclear fission reactions that would form the basis of nuclear bombs and reactors, 82

Civil Service Restoration Law Nazi Law of 1933 that drove Jews and political radicals from professorships, 85

Cloud Chamber Device involving superdense water that allowed visualization of quantum particles, 75

Collective Excitation Wavelike characterization of entire quantum systems, which included plasmons and phonons, and was developed by Landau, 105

Commutation Relation Supposed unusual relation of multiplying an atom's momentum and position that Heisenberg set equal to an imaginary multiple of Planck's constant: $pq - qp = -i\hbar$, 60

Copenhagen Interpretation , 64

Cosmic Microwave Spectrum Consistent signal of microwave radiation from all directions in the sky, which many interpret as evidence of the big bang, 103

Critical Mass Amount of fissionable substance required for self-sustaining explosive chain reaction in nuclear weapons, 88

Cyclotron Particle accelerator invented by Lawrence, first constructed in Berkeley, 77

Edward Teller (1908-2003) The "Father of the Hydrogen bomb" who alienated physicist friends with his pro-nuclear proliferation politics, 91

Edwin Hubble (1889-1953) Astronomer who interpreted redshift as evidence for an expanding universe, 102

Ernest Orlando Lawrence (1901-1958) Berkeley physicist that invented the cyclotron, 77

Erwin Schrödinger (1887-1961) Formulated wave equations that gave a quantum description of the atom, 61

Federation of Atomic Scientists Post-WW2 grassroots advocacy group for nuclear disarmament, composed of physicists, 91

Fermi Field Theory Postulation of a nuclear force in the interaction of neutrons and protons which convinces physicists of the reality of particle transitions, 80

Fermi-Dirac Statistics Quantum statistics of counting electrons that established indistinguishability of electrons on a secondary level, 68

Fermion Particles with spin $\pm 1/2, \pm 3/2, \ldots$, described by Fermi-Dirac statistics, 73

Feynman Graphs Pictures adapted from Feynman's work on neutron diffusion at Los Alamos that were eventually generalized to be able to represent any particle of QFT, 96

Fine Structure Constant Dimensionless constant of the universe, given in terms of Planck's constant h, the speed of light c, and the basic unit of electron charge e: $\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}$, 75

Fission Fragments

Fraunhofer Bavarian glassmaker who detected dark lines in the solar spectrum, which were later used to deduce the atomic composition of the sun's atmosphere, 56

Frederic Joliot (1900-1958) Radiochemist who, with Irene Joliot-Curie, discovered many heavy elements, 80

Freeman Dyson (1923-) Synthesized Schwinger-Tomonaga renormalization with Feynman renormalization using the S matrix, 98

Fritz Strassman (1902-1979) Chemist who discovered nuclear fission with Otto Hahn after deducing the presence of barium rather than the theoretically predicted radium from neutron bombardment of uranium, 81

Fusion Power Nuclear theory used by Teller to create the Hydrogen bomb, 91

Gauge Invariance Subtle phenomenon of QED that inspires the necessary changes in QFT for it to be once again accepted by the particle physics community in 1965, 101

General Relativity Unification of gravity theory with special relativity, 51

Geoff Chew (1924-) Formulated the concept of nuclear democracy, 100

George Gamov (1904-1968) Eccentric astrophysicist who first proposed heavy element creation in a big bang, 103

Golden Boson Symbol of the complex work of the standard model particle physicist, who used false color images and other æsthetically pleasing devices to communicate their complex physical concepts and get funding, 101

Gustav Kirchoff (1884-1887) Developed apparatus with Bunsen that allowed detection of atomic spectra, 56

Hantaro Nagaoka (1865-1950) Cambridge student who developed Saturnian model of the atom in the tripos, 54

Henry Mosely Cavendish physicist at the begininng of the twentieth century who investigated atomic spectra and died in the Great War, 57

Henry Rowland (1848-1901) Inventor of many diffraction gratings used to identify characteristic spectra of atoms, 56

Hydrogen Bomb Orders of magnitude more destructive than previous fission weapons, developed by Teller on the principle of fusion power, 92

Idealization In solid state physics, ignoring the real world complications in order to make a concrete mathematical prediction that somewhat agrees with experiment, 69

Irene Joliot-Curie (1897-1957, NP 1935) Radiochemist who, with Joliot, discovered many heavy elements, 80

J. Robert Oppenheimer (1904-1967) Cal Tech and Berkeley physicist who reinvigorated UC physics in the 1920s, invented the nuclear bomb in the 1940s, and was dispelled from science due to accusations of communist affiliations in the 1950s, 77

James Chadwick (1901-1954, NP 1935) Discoverer of the neutron in 1932, 79

James Franck (182-1964, NP 1925) Author of the Franck Report, the initial publication for nuclear disarmament, 91

Jean Perrin (1870-1942) NP 1926, meticulous microscopic confirmation of Brownian Motion, 45

Jelly Model J. J. Thomson's model of the atom which postulated a diffuse positive charge in a central jelly and thousands of tiny negatively charged corpucles flying around and through it, 54

Johannes Stark (1874-1957, NP 1919) Aryan Physicist, 86

John Bardeen (NP 1972) One of three dual Nobelists, he got two in physics, 105

Julian Schwinger (1918-1994, NP 1965) Renormalized QED with long equations, 96

Lamb Shift Discrepancy between $2s$ and $2p$ orbital energy levels that was measured early on but not theoretically predicted until renormalized QED, 95

Leslie Groves Army general who headed administration of the Manhattan project, 90

Lev Davidovich Landau (1908-1968, NP 1962) Soviet physicist imprisoned in the great purges, whose socialist ideals inspired him to develop the theory of collective excitation, 83

Lise Meitner (1878-1968) Friend of Hahn who advised him in his investigations leading to the discovery of nuclear fission, 81

Loránd Eötvös (1848-1919) Hungarian geophysicist who made precision measurements of specific gravity that seemed to confirm general relativity, 51

Magic Wand Symbol for the QFT used by the standard model because of its ability to derive the light quantum from the assumption of an electron by thinking through the consequences of gauge invariance, 101

Many-Worlds Interpretation of probability that postulates the formation of a new world at each indeterminate instance in time, forever branching with an infinite array of new worlds, 106

Michelson (1852-1931) NP Physics 1907, Inventor of the interferometer who tried to detect the motion of the earth relative to Thomson's luminiferous æther, 48

Millikan (1868-1953) Confirmed Einstein's photoelectric effect theory by doing measurements in 1916, 44

Neutron Nuclear particle discovered in 1932 by James Chadwick, 79

Niels Bohr Father of modern atomic theory, center of every physicist's social network pre-WW2, developer of correspondence principle, theoretician of the Manhattan project, 55

Nuclear Democracy Particle physics theory that de-emphasized fundamentality and was partially inspired by 1960s politics, 100

Nucleosynthesis Gamov's theory of heavy element creation from a big bang, 103

Nuremberg Laws Severe restrictions on Jewish civil liberties in Nazi Germany, 85

Operator Mathematical tools that theoretically created and destroyed particles, 72

Otto Hahn (1879-1968) Discoverer of nuclear fission after deducing the presence of barium rather than the theoretically predicted radium from neutron bombardment of uranium, 81

Otto Robert Frisch (1904-1979) With Meitner, reformulated nuclear theory to include the production of fission fragments and the possibility of chain reactions, 82

Particle Zoo Description of the confused state of organization of particles as the standard model was being assembled, 99

Paul Dirac (1902-1984) Applied matrix theory to Heisenberg's commutation relation, 60

Pauli Exclusion Principle Solution to the problem of the anomalous Zeeman effect which supposed an additional angular momentum quantum number and postulated that every electron has a distinct set of quantum numbers, 67

Philipp Lenard (1862-1947, NP 1905) Aryan Physicist, 86

Phonon Landau's formulation of solid state oscillations in collective excitation theory, 105

Photoelectric Effect Phenomenon marked by ejection of electrons after light is shined on a metal, 44

Pile Original term for the nuclear reactor, a controlled generation of nuclear energy that was first developed by Enrico Fermi at U. Chicago's Metallurgical Lab, 90

Plasmon Landau's formulation of quanta in collective excitation theory, 105

Quantum Electrodynamics Program of reconciling quantum field theory with Maxwell's electromagnetism, 74

Quantum Field Theory Rational generalization of quantum mechanics with an added quantization that postuled operators and unique statistics for each type of particle, 72

Quasiparticle Theoretical particle that exists in a sea of others, and whose parameters can be predicted by renormalized QED, 104

Raymond Thayer Birge (1887-1980) UC physics professor, measurer of physical constants, and architect of the reinvigoration of UC physics by the addition of Lawrence and Oppenheimer in the 1920s, 76

Red Universities Soviet universities estblished in the early 30s which taught skepticism toward relativity and quantum mechanics, 82

Redshift Observation of faraway stars as more red than they should be, first observed by Hubble, and taken to imply an expanding universe, 102

Renormalization Operationalist revision of QED that considered only effectively measurable quantities rather than absolute theoretical values, 95

Richard Feynman Renormalized QED and invented cool particle interaction diagrams, 96

Robert Bunsen (1811-1899) Developed the famous burner with Kirchoff that allowed detection of atomic spectra, 56

Rutherford Model Atomic model proposed in response to scattering observations that postulated a positively charged nucleus, 55

Saturnian Model Atomic model proposed by Nagaoka which modeled electrons in concentric rings resembling the rings of Saturn, 54

Scattering Operationalist doctrine pursued by Heisenberg in his proposition of the S matrix solution for QED, which considered only the input and output of particles of a system, 94

Secret Science Covert research done in and funded by government (i.e. CIA) labs, 92

Sin-Itiro Tomonaga (1906-1976, NP 1965) Renormalized QED with long equations, 96

Standard Model Post-renormalization description of particle physics which included more particles, more forces, and a new version of QFT, 99

Steady State Universe Alternative to big bang theory that prevailed in the 1960s, 103

Superconductivity Discovered in mercury in 1911 and correlated with electron movement, 105

Trinity The code name for the first successful test of nuclear weapons in the world, which occured in the New Mexico desert in 1945, 90

Uncertainty Principle $\Delta p \Delta q \geq h$: as a particle's position is observed with greater accuracy, its observed momentum is less certain, and vice versa, 63

Univocal Instruction The telling of one possible history with no interpretation necessary, 106

Virtual Particles Particle-antiparticle pairs that can wink in and out of existence spontaneously, even in vacuum, 73

Wavefunction Equation that gives a wave's value as a function of time and position; in quantum mechanics, used to deduce the probability of a particle occupying a certain point in space, 62

Weak Force Weaker than strong force but stronger than EM, 101

Werner Heisenberg (1901-1976) Modern rational mechanist who described the atom in terms of observable macroscopic properties, 59

Willy Wien (1896) Developed an empirical distribution law for blackbody radiation, 41

Wolfgang Pauli (1900-1958) Child prodigy who helped advance and formulate quantum mechanics, 59

de Broglie (1892-1987) NP 1929, Formulated theory of the wave properties of matter, 61

Bulletin of the Atomic Scientists Post-WW2 political physics publication focused on nuclear disarmament, increased international cooperation, etc., 91

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