# The Role of Concrete Models in the Revolution in Superconductivity

by

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# AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

# Abstract

The distinction between the abstract and the concrete is useful in understanding the way in which theories relate to phenomenon, respectively, or vice versa. The connection between theory and the actual workings of scientific experiments can further be situated within scientific revolutions. This distinction has been considered in light of revolutions by Thomas Kuhn and via the concept of model use in science by Nancy Cartwright. Philosophers including Cartwright have argued that scientific models that focus on the phenomenon are important in scientific use. This argument has faced criticisms that argue of the temporariness of these types of models. Ultimately, in this thesis, I will show that the temporariness of concrete models is not a valid criticism due to the models' role in problem solving in times of scientific revolution. To do so, I will first present the abstract-concrete distinction given by Cartwright, and Kuhn, I will then present a case study of the revolution in the development of models within superconductivity theory in order to trace the distinction between theories, the abstract level, and the phenomenon, the concrete level. The London-London model of superconductivity (a model created by Fritz and Heinz London to describe the expulsion of a magnetic field within a superconducting material) has previously been discussed in the abstract-concrete context by Cartwright, but BCS theory (named after the scientists who proposed it, John Bardeen, Leon Cooper, and John Robert Schrieffer to describe the low energy state of superconducting materials) has been largely absent in the same discussion context. I will use both, the London-London model and BCS theory, to argue that during times of scientific revolution, focus that was initially placed on an abstract level (theory) is moved to the concrete level (phenomenon) as a method of solving previously unsolvable problems.  In discussing the London-London model, I will present Cartwright, Towfic Shomar, and Mauricio Suarez' arguments for the London-London model being a phenomenological model.  I will also present criticisms of this view with a particular focus on the notion that concretely developed models are temporary; I will argue that concrete models may be temporary, but they are necessary in resolving scientific crises.  In this manner, I am extending Cartwright et. al.'s argument for the usefulness of non-theory-driven model construction. Finally, I will show the parallels in development of BCS theory with the London-London model, and present the resolution of the revolution in superconductivity with the connection of the concretely developed model and the abstract, quantum theory via BCS theory's discovery of Cooper pairs (electrons that pair up in low temperatures).

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# Table of Contents

# Chapter 1

# Abstract/Concrete Distinctions in the Philosophy of Science Literature

## 1.1 Introduction

Nancy Cartwright, along with Towfic Shomar and Mauricio Suarez, outlined an argument for the use of phenomenological modeling in describing phenomenon using the London-London model[1]. They argued that in the development of the London-London model of superconductivity, the London brothers relied on their observations of the Meissner effect (see footnote 1) rather than the predictions of pre-existing theory. Phenomenological models were developed to show the place of models as problem solving tools when theories cannot account for a certain phenomenon.

A complaint, however, about phenomenological models is that they would only be temporarily useful. These models would only see use when a pre-existing theory failed to account for a phenomenon, and would once again be discarded when a new theory can account for the previously unsolved phenomenon. While a reliance on the phenomenological model may indeed be temporary, this is not necessarily a drawback. In fact, problem solving via models that rely on the phenomenon can be helpful during times of scientific revolution. In this thesis, I will show that scientists have in fact relied on phenomena as the main method of problem solving throughout the history of superconductivity via the London-London

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[1] A model developed in 1935 to describe the observation of the expulsion of magnetic fields from within the superconducting material (the Meissner effect). I will go into further detail regarding this model and the Meissner effect in chapter 2.

model and BCS theory. This involves not only an extension on the application of Cartwright et al.'s argument to a case study not previously examined, but also a more comprehensive version of Cartwright et al.'s argument to include the scope of concrete models that are not necessarily phenomenological.

First, I will discuss the stages of scientific revolutions as posited by Thomas Kuhn. In order to describe a nuanced notion of the relation between theories and observations, I will adapt Cartwright's argument about the concrete and abstract in model construction, where the concrete refers to the phenomenon and the abstract refers to a theory. The usefulness of temporary models that rely on the concrete level is shown in their role in advancing science when theories cannot.

In this chapter, I will outline the distinctions present in literature between the abstract and the concrete along with comparing and contrasting similarities and differences in their definitions. I will focus on the distinctions presented by Thomas Kuhn and Nancy Cartwright. I will show that as Cartwright herself argues, she tends to agree with Kuhn's distinction but adds the distinction between models and theories to the original abstract-concrete discussion. I will then ultimately argue that a combination of Cartwright's and Kuhn's distinctions best explains the methods in which the abstract or the concrete are relied upon during problem solving at times of scientific crises, along with providing supporting examples in following chapters.

## 1.2 Thomas Kuhn

Thomas Kuhn's distinctions between the abstract and the concrete are discussed with the terms of symbolic generalizations and manipulations. Since the approaches to model construction depend on the stages of scientific revolutions, and since Kuhn discusses his distinctions within the framework of revolutions, let us first visit these stages.

### 1.2.1 Stages of a Revolution

Kuhn outlined the notion of scientific revolutions in relation to paradigms and paradigm shifts in *The Structure of Scientific Revolutions,* where working scientific paradigms are "announced" together with their applications in real phenomenon (47). Kuhn first discusses the notion of normal science, and moves on to how normal science may face a crisis that leads to a revolution.

Normal science is the stage where a working paradigm has already been established with the acceptance of some fundamental theory being crucial. The paradigm serves as a guide for scientists within the field to perform experiments and solve minor puzzles that arise. An example of a paradigm is Newtonian physics including his theories of motion and optics (Kuhn 13). Newton's three laws of motion were accepted by the scientific community after due scrutiny, and following this acceptance, the laws were applied to a variety of cases such as calculations of work, or more specific cases of harmonic oscillators. Working within this paradigm meant solving kinematic problems by using and building upon the ideas of Newton.

Kuhn argues, “To be accepted as a paradigm, a theory must seem better than its competitors, but it need not, and in fact never does, explain all the facts with which it can be confronted” (18). The modern focus on quantum mechanics rather than Newtonian mechanics displays an area where quantum theories seem to explain more facts than the competing Newtonian theories. This foundational change in the manner of explaining phenomenon and theory is a paradigm shift. He also argues that these shifts are similar to gestalt shifts, where the world view of the scientists changes drastically. In a sense, the scientists working with Newtonian motion in mind sees the world differently than one working with relativistic motion (Kuhn 121). With the example of Newton’s theories serving as paradigms for kinematics and optics, we can see that paradigms are accepted conditions for working within a scientific field (Kuhn 23). Furthermore, paradigms require articulation through experimentation so as to extend the facts that the paradigm displays as revealing (Kuhn 24). Students learn the accepted methods and conditions of a paradigm through resolving canonical problems usually through textbooks published by scientists already subscribed to and working within the paradigm (Kuhn 20).

A change in paradigms, a paradigm shift, occurs with the encounter of many anomalies that cannot be explained via the theories of the paradigm. Accounting for anomalies requires the upheaval and ultimate rejection of the original paradigm. These anomalies are the main problems that incite paradigm shifts since the new paradigm that accounts for anomalies must be different in a non-trivial manner from the old paradigm. Regarding Newtonian optics, Kuhn argues that, “... the wave theory that replaced Newton’s [theory of light] was announced in the midst of growing concern about anomalies in relation of diffraction and polarization effects to Newton's theory." (68) As such, we see an awareness of the anomalies surrounding Newtonian theories in certain fields of Newtonian optics. These anomalies can be solved by observations over time and retooling the methods of the current paradigm.

Since working within a paradigm also affects the way a scientist sees the world, in a paradigm change, previously anomalous problems may be seen as solved. For instance, the difficulty in reconciling retrograde motion in a geocentric paradigm of astrophysics was no longer an issue in Copernican heliocentrism (Kuhn 93). An anomaly in one paradigm need not be an anomaly in another paradigm, so different paradigms include different particular theories.

Described above are the stages in which a scientific revolution occurs. First, the working paradigm of normal science encounters one or more anomalies that it cannot solve. When the anomalies become more than just another puzzle, they evoke a crisis (Kuhn 82). This causes scientists to search for a new paradigm. When anomalies are solved using methods outside of reliance on the defunct paradigm, a new paradigm may be proposed and adopted (Kuhn 85). Regarding the details of normal science, Kuhn argues that it seldom aims to produce major conceptual or phenomenal novelties (35). Furthermore, results of experiments that cannot be used to articulate the theory from which they were derived remain as mere facts, unrelated to the progress of that paradigmatic theory (Kuhn 35). Rather, normal science aims to solve puzzles using the tools provided by the paradigmatic theory. These puzzles are contrasted with anomalies that the paradigmatic theory is ultimately at odds with.

Now that we have discussed the stages of a scientific revolution, let us consider the distinction between the symbolic generalizations and manipulations as presented by Kuhn.

### 1.2.2 Symbolic Generalizations and Manipulations

Kuhn presents a distinction between symbolic generalizations and manipulations of symbolic generalizations in the puzzle solving activity of science. Symbolic generalizations are aspects of a fundamental theory such as the law of motion, $F = ma$ (Kuhn 187). These symbolic generalizations can be manipulated to suit and problem solve for specific conditions such as the motion of a pendulum or other simple harmonic oscillators (Kuhn 188). The manipulations, as Kuhn describes them, are more concrete than the symbolic generalization itself since they are used in specific situations such as those of pendulums or springs. $F = ma$, on the other hand, is part of the overarching theory through which formulae for pendulums or springs can be attained.

The manipulations can be used in mundane situations such as students of science learning various formulas or learning to problem solve in class. Learning some manipulations along with the generalization, Kuhn argues, allows the student to learn to design other appropriate manipulations that interrelate with the generalization (187-189). The similarity relation gained through understanding the interrelation between a generalization and its manipulations is one way in which normal puzzle solving occurs. Regarding solving problems in paradigms, Kuhn argues, “Scientists solve puzzles by modeling them on previous puzzle-solutions, often with only minimal recourse to symbolic generalizations” (189). This puzzle solving is accomplished through considering previous, related concrete puzzle solutions rather than continuously deferring to the symbolic generalizations of theories since the generalizations of normal science are already commonly accepted.

This puzzle solving directly applies to normal science where scientists simply focus on articulating phenomenon that the theories already supply (Kuhn 24). In this manner, there would be minimal need to rethink the symbolic generalizations since the puzzles that require solving all share the same theories within the paradigm.

### 1.2.3 Generalizations, Manipulations, and Revolutions together

As discussed, Kuhn argues that anomalies that drive paradigm shifts cannot be solved through the paradigmatic theory alone (65). These anomalies must occur and be solved via tools that do not rely on the previous fundamental theory entirely. By combining Kuhn's comments on the use of symbolic generalizations and manipulations with his framework of paradigm shifts, we can begin to see an outline of times for reliance on both abstract symbolic generalizations and concrete manipulations.

During a period of normal science, the symbolic generalizations form part of the framework theory for a paradigm. The framework theory outlines the theoretical explanations and expectations of scientists using that theory to solve puzzles. Furthermore, these generalizations underlie the worldview of the scientists working with them. During a time of crisis, these generalizations, however, cannot create useful derivations to explain and solve the anomaly. As such, specific manipulations for the anomaly are relied upon. These manipulations may be gathered from experimental data on the occurrence of the anomaly. By this, I mean that during a time of crisis, since the general theory fails in explaining away the anomaly, scientists must focus on the particular phenomenon of the anomaly itself. This argument is adapted by Nancy Cartwright to be applied in model creation techniques.

### 1.3 Nancy Cartwright

The distinction between the abstract and the concrete has been developed more thoroughly in Cartwright's works about models. Cartwright stresses her interest in the way models function through her distinction between models and theories. While she ultimately argues that she and Kuhn share many similarities in thinking about the relation between theory and observation, Cartwright more specifically argues that, "Models make the abstract concepts of physics more concrete. They also help to connect theory with the real world" ("How we Relate Theory to Observation" 270). Fundamental laws of physics involve abstract concepts. This is presented in "Fables and Models," where she states that, "We tend to think of the concepts of physics, though theoretical, as very concrete, like *is red*; or *is travelling at 186000 miles per second*. But it is better to take them as abstract descriptions, like *is a success*, or *is work*." (36) The fundamental laws of physics, and arguably the laws of non-physics sciences as well, ought to be considered as abstract.

Similar to Kuhn's argument about manipulations of symbolic generalizations as showing the relationship between concrete variations and the abstract fundamental law, Cartwright argues that abstract concepts need "fitting out" in more concrete ways. For instance, in the abstract notion of "working" lies more concrete descriptions of work activities such as washing the dishes, writing grant proposals, preparing lunch (Cartwright, "Fables and Models" 40). At first glance, it may seem as though concrete descriptions are subsets of the abstract, and that the concrete cannot give you any more information than the abstract. However, as Cartwright argues, there may be information present in the abstract (e.g., theories) that is not in the concrete (e.g., models that describe phenomenon). For instance, if we were to simply say that we were washing the dishes last night without any indication of our enjoyment level of that activity, it could not be known that we classify dish washing as "work" rather than "leisure". As such, for complete information, we can accompany the concrete description with the abstract and say that we were working by washing the dishes (Cartwright, "Fables and Models" 40)

Cartwright further discusses this distinction with terminology of reliance on the abstract as a "theory-driven" approach, and reliance on the more concrete through the instrumental approach. Of these instrumental approaches, the phenomenological approach is discussed in detail in "The Tool Box of Science." "Tool Box" also discusses the London-London model of superconductivity, so it is crucial that we analyze this first.

### 1.3.1 The Tool Box Method and Problem Solving

Since this thesis focuses on the abstract/concrete distinction as a method of problem solving, we must visit Cartwright, Towfic Shomar, and Mauricio Suarez's notion of how phenomenological models along with theories are simply tools in the tool box available to scientists. This differs from views that hold theories as necessary in the creation of models, e.g., the theory-driven view discussed below. In this manner, the Tool Box method looks at the manner in which the various tools are organized, where phenomenological modeling places the reliance on phenomenon as key for model creation.

Specific to the London-London model of superconductivity[2], further presented in chapter 2, Cartwright et al. discuss the notion of abstract concepts requiring fitting out within "Tool Box" by arguing that the initial theory-driven approach could not account for the Meissner Effect[3]. As such, the London-London model acted as the catalyst required to abandon the old fundamental theory for a new, more fitted out formulation.

The theory-driven approach is the notion that models are merely useful approximations to theories[4], and the heuristics of model building dictated by theory-testing (Cartwright et al., "Tool Box" 138). Theory-driven approaches to model construction include the covering law account, where theories have a "belly-full" of already-formed models within them, and the semantic view, where theories are just collections of models (Cartwright et al., "Tool Box" 139). Under either of these formulations, a model is created directly from the theory. This approach emphasizes the reliance on theory more than any other factor in the process of model creation.

Cartwright et al. endorse the instrumentalist[5] view, where abstract theories should be used simply as a tool similar to a worker's tool. Theories are but one tool in the scientific tool box in the same manner that a hammer is but one tool. In "Tool Box", the instrumentalist interpretation is focused on the manner in which physics aims to represent the world.

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[2] Superconductivity is the phenomenon where a super cooled material may exhibit zero resistance. This only occurs in certain materials, and the materials must be cooled beyond a critical temperature.

[3] The Meissner effect is the expulsion of magnetic fields within a superconducting material once it reaches its superconductive state.

[4] It may be important to note that I have not explicitly discussed what theories *are* outside of their relation to models or observations as it is beyond the scope of this thesis.

[5] It must be noted that the word "instrumentalist" is used in a different sense here than what is normally found in Philosophy of Science literature regarding the realism/anti-realism debate. Instrumentalist in this case is merely concerned with using whatever tool they may to solve scientific problems.

Without the theory-driven approach, physics aims to represent the world through models, which describe the concrete, rather than theories (Cartwright et al. 140). Cartwright et al.'s motivations for the instrumentalist, and more specifically, the phenomenological, approach to model construction arises from the thought that theory-driven approaches do not properly account for the manner in which some models have been created. This is supported by the case study of the London-London model of superconductivity.

The theory-driven views are ultimately rejected due to the manner in which theories are underdetermined by any amount of data, so the heavy reliance on theory cannot be justified as the best representations of the world. Under the theory-driven view, theories and auxiliaries imply the data procured from experiments since theories are most dominant. However, due to underdetermination, we cannot know which underlying set of theories or auxiliaries truly imply the data we observe.

$$T + A \rightarrow d \qquad (1)$$

$$T' + A' \rightarrow d \qquad (2)$$

T represents theories, A are auxiliary assumptions, and d is the set of data. Similarly, T' represents a non-T theory, and A' represents non-A auxiliary assumptions. With only the set of data, d, we do not know whether 1 or 2 is the true set of theories and auxiliaries that imply d (Cartwright et al. "Tool Box" 139). We can consider the theory-driven view as a hierarchical one, where models and data must be derived from the theory in some manner. Note that I use the term derive and imply here interchangeably since the ultimate ideal of the theory-driven view is that theories are foundational to scientific representation and interpretation.

We may expand upon the criticism that Cartwright et al. presented to show how models relate to underdetermination of theory. The "formula" of underdetermination above may be augmented with restrictions as follows to include the relationship between models and theories:

$T + A \rightarrow d$, where T is a set of models, M (Semantic View) (3)

$T \rightarrow M + A \rightarrow d$, where M is a set of models (Covering Law) (4)

Within the theory-driven views, model construction would occur as a result of the theory itself rather than any data implied. This illustrates the issue of underdetermination in the theory-driven view since we would ultimately not know whether our models are part of the correct set that imply our data, d. From the augmented equations, we can see the following for covering law accounts:

$$T \rightarrow M + A \rightarrow d \qquad (4.1)$$

$$T' \rightarrow M' + A' \rightarrow d \qquad (4.2)$$

Representation of the world by either models or theories is highly dubious in a theory-driven view since theories and auxiliaries already imply data. We cannot be sure which set of theories and auxiliaries, 4.1 or 4.2, imply our data set given our observations of solely the data set. This issue can be mitigated with the instrumentalist approach, where scientists can configure the tools they use in order to represent the world. In this manner, rather than theories and auxiliaries both implying and representing data, models can represent data without the implication. As such, there is a different relationship between models, theories, and everything else in the instrumentalist approach.

### 1.3.2 The Instrumentalist Approach and Phenomenological Modeling

The distinction between the instrumental method and phenomenological modeling argued for by Cartwright et al. is one of breadth. The instrumental method is where a scientist uses the most appropriate tool available to her in order to solve a problem. In this method, there are multiple tools, or instruments, available. Phenomenological modeling is a way of ordering the use of these tools. Phenomenological modeling is concerned with model construction where models are constructed without sole reliance on theory. In this manner, tools and models are some of the tools available to scientists in problem solving. To reflect the theory-data relationship provided in the last section, we can categorize phenomenological modeling as follows:

$$d \rightarrow M^{6}\text{, where M is a model representative of the world} \qquad (5)$$

In accordance with the last equation above, we can see that data sets act as key in model creation since models reflect the phenomenon observed. Scientists may weigh any of the factors as they see fit in order to create a best representing model. This also shows a level of autonomy that a model may have from theories since there is not necessarily a direct relationship between theory and model with theories being more fundamental; rather, all

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[6] Note that this arrow is not the same as the implication arrows presented in 1 – 4.2. This arrow can be known as “represented by” for 5 to become: d is represented by M.

factors in model creation are weighted individually (Cartwright et al., “Tool Box” 138). Even if the theory, T, alone cannot account for a phenomenon captured by the data, d, there are other factors, such as the measurements of the phenomenon itself, which can aid in model, M, construction.

Here, we can also revisit the notion of representation, where it is argued by Cartwright et al. that theories do not represent the world, rather it is the case that models represent the world (“Tool Box” 140). Indeed, the underdetermination problem arises when considering how theories and auxiliaries seemingly imply data in the theory-driven view rather than representing it. Cartwright et al. further argue, “It is the implication in $T + A \rightarrow d$ that I want to challenge. Theories and auxiliaries do not imply data – or better following Matthias Kaiser’s advice in this volume, ‘phenomena’ – even in principle. Representations of phenomena must be constructed and theory is one of the many tools we use for construction” (“Tool Box 139). Due to underdetermination, we would not know which set of theories and auxiliaries imply data were the theory-driven view to be supported. Constructed models, however, rather than implying data, represent data. This representation may be done without a heavy reliance on theory if the theory does not match what was expected to be seen in data allowing concrete models to have a non-trivial sense of autonomy from theory. In a sense, there are fewer intermediaries between the data set and the model than there are between the data set and the theory.

It is this autonomy from the theory that clashes with the theory-driven view. In cases of phenomenological modeling, the model created is at least autonomous from the prevalent theory of the time. This autonomy serves as a delineation between the phenomenon-based model and the previous theory that could not account for the phenomenon.

### 1.4 Similarities and Differences between Cartwright and Kuhn

To compare the definitions of abstract and concrete offered by Kuhn and Cartwright, it will be helpful to understand what Cartwright has to say about Kuhn's distinctions between symbolic generalizations and the manipulations of symbolic generalizations.

Cartwright argues that the relationship between Kuhn's symbolic generalizations and manipulations is a similar relationship to that between the abstract and the concrete. This comparison between the two schemas allows Cartwright to argue that our understanding of symbolic generalizations consist in our understanding of the concrete versions we use to for individual cases ("How we Relate Theory to Observation" 262).

Ideas I will consider in approaching the discussion of the abstract/concrete distinction include the significance of both in construction of models as a method of problem solving as well as their significance in scientific revolutions. Let us start with the significance of the distinction in general, and move on to their possible significance in revolutions.

Cartwright defends a Duhemian view where "for most of the symbols of mathematical physics, there are no quantities in nature for them to name", so symbolic formulas need more concrete concepts of the laboratory or everyday life to connect them to the physical world ("How we Relate Theory to Observation" 265). This aligns with Kuhn's argument that symbolic generalizations must be manipulated in order for students to learn and ultimately create new manipulations as scientists (Kuhn 188). In this manner, a significance of concrete descriptions is that they are essentially more usable since they pertain directly to the experiments for a physical phenomenon.

I will argue in the next few chapters that the significance of this distinction in scientific revolutions is in the switch between which tools are relied upon. This bolsters Cartwright et al.'s arguments for the usefulness of phenomenological models, though it is not an area they have discussed. In normal science, the abstract level can be seen as being relied upon since theories assist new scientists in realizing the concrete situations that consist in the abstract. The reliance on the abstract in normal science provides the scientist with a foundational framework to construct new concrete manipulations to further articulate the paradigm. This reliance shifts to the concrete, however, in times of revolution. Since the revolution poses a crisis that the current foundational abstract cannot solve, scientists must turn to directly assessing observations. Chapters 2 and 3 will present examples to support this argument.

Let us now consider the way in which Kuhn and Cartwright's distinctions of the abstract and concrete are parallel to the other through both of their discussions on harmonic oscillators.

### 1.4.1 Manipulations in Harmonic Oscillators

Both Cartwright and Kuhn present an example of how symbolic generalizations are manipulated via the exposition of harmonic oscillators as a concrete example of Newton's second law of motion. This example provides a sketch of the relationship between symbolic generalizations and their manipulations, and as argued by Cartwright, the relationship between the abstract and the concrete.

Kuhn begins his argument by presenting the drawbacks of working solely with symbolic generalizations. He brings up the example of Newton's Second Law of Motion, $F = ma$. He argues that in a conversation where Newton's Second Law is uttered, someone outside of the relevant field will not understand the meaning of the expression or how the community of scientists attach the expression to nature (Kuhn 187). One may ultimately ask how these scientists have come to agree on this expression, and how they have learned to pick out relevant forces, masses, and accelerations (Kuhn 187). Kuhn continues to argue about the importance of a concrete phenomenon in the understanding of these generalizations through arguing that when students learn to identify forces, masses, and accelerations in various physical situations, the student has learned to design the appropriate version of $F = ma$, where $m$ represents mass and $a$ represents acceleration, via their exposure to other concrete phenomenon. Some such concrete phenomena include the case of free fall, where $F = ma$ becomes $F = mg$, where $g$ is a constant for the approximation of acceleration due to gravity, or the case of a simple pendulum, where $F = ma$ becomes $F = mg \sin\theta = -ml\frac{d^2\theta}{dt^2}$, where $m$ is the mass of the pendulum, $l$ is the length of the pendulum, and $\theta$ is the angular displacement. With more and more complex situations, the family resemblance between these formulae may become harder to discover, so the as the student learns to identify forces, masses, and accelerations, they must also become adept at interrelating them (Kuhn 188).

Cartwright comments on Kuhn’s distinction between the specific manipulations and the symbolic generalization of $F = ma$ using the distinction between the abstract and concrete (“How we Relate Theory to Observation” 269). She adapts German playwright Gotthold Lessing’s thoughts on fables to an argument regarding models. She argues that the manipulations posited by Kuhn are in fact models that contain exactly the information needed in order to provide a concrete form for the force. Using Lessing’s analogy of fables and models, she argues that for us to clearly understand the abstract law of motion, we require concrete cases where it can be applied (“How we Relate Theory to Observation” 268-269). Her adaptation emphasizes the idea of fitting out abstract concepts of *force, mass,* and *acceleration* using concrete concepts. She argues, “I may give you the abstract advice ‘Be careful,’ but until you know more concretely what being careful consists in for different situations, this will be of little help to you” (“How we Relate Theory to Observation” 270). In this manner, the expression $F = ma$ is unhelpful for the scientist until they know what concrete phenomenon to apply it to. The specific formula for harmonic oscillators assist in the understanding of the Second Law of Motion.

### 1.4.2 Definition of “Abstract” and “Concrete”

Thus far, I have used the terms “abstract”, “concrete”, “symbolic generalizations”, “theory-driven”, and “phenomenological” to represent a variety of ideas. Before moving on, let us discuss and differentiate these terms in relation to each other.

#### 1.4.2.1 The Abstract, Theory-Driven, and Symbolic Generalizations

Kuhn describes symbolic generalizations as mathematical formulations of fundamental theories. These symbolic generalizations are the most general, mathematical manner[7] in which a theory can be described. For instance, $F = ma$ is the symbolic generalization Kuhn used to describe Newtonian motion. This is similar to Cartwright's consideration of the abstract, as presented in "Fables and Models," where she argues that the abstract concepts of physics ought to be viewed as general descriptions similar to the general notion of *success* or *work*. Cartwright also presents the notion of the scientific abstract in "Tool Box", where she discusses the prevalence of fundamental theories in model creation.

Cartwright et al. use the term theory-driven to denote a method of model creation that relies solely or extremely heavily on the use of a fundamental theory. This theory may be in mathematical terms (as mentioned previously about Newtonian motion). In "How we Relate Theory to Observation", Cartwright further argues that her notion of the abstract and Kuhn's notion of symbolic generalizations have similar meanings (262). The abstract level and symbolic generalizations are the general ways of describing fundamental scientific theories. Theory-driven, on the other hand, is a manner in which the abstract theories can be used in model creation. As such, theory-driven views are ones that rely greatly on the abstract when problem solving through model creation and use.

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[7] Note that Kuhn does not discuss many non-physics examples, so mathematical formulations may not exhaust what he described to be symbolic generalizations.

### 1.4.2.2 The Concrete and the Phenomenological

While Kuhn uses the phrase “manipulations,” Cartwright argues that these manipulations are analogous to her notion of the concrete in the sense that these manipulations “fill out” general theories. Kuhn’s outline of the manipulations involve specific instances of his category of symbolic generalizations. In this manner, the concrete involves specific applications of $F = ma$ such as those of free fall and simple pendulums presented in section 1.4.1. Indeed, he discusses the concrete applications in harmonic oscillators distinct from simply the abstract of Newtonian motion. In this manner, the concrete refers to the specific phenomenon in occurrence.

The descriptor “phenomenological” is used by Cartwright et al. to describe a method of modeling that is not reliant entirely on theory. Instead, phenomenological modeling relies on the concrete phenomenon to construct models for problem solving. In a similar manner that symbolic generalizations and the abstract are general ways of describing theories, the concrete is a general manner of describing a specific case of phenomenon. Whereas, phenomenological modeling is the manner in which scientists may use the concrete in model creation.

## 1.5 Other Considerations of the Abstract/Concrete Distinction

Other philosophers have approached the relationship between theory and observation through commenting on experimentation and the way in which scientific controversies may be resolved. Due to their focus on a discussion of models within the abstract/concrete discussion, the views discussed here include those of Rinat Nugaev and Samuel Schindler.

### 1.5.1 Nugaev on Mathematical Formalizations

Nugaev presents the distinction between the empirical and theoretical as an issue to be addressed in the theoretical reconstruction of paradigm shifts in his work, “Basic Paradigm Change: The Conception of Communicative Rationality” (23). Nugaev presents a notion that scientists utilize mathemathical formalizations of old theories to “guess” future theories. He comments about the decline of the use of mechanical models in physics giving way to the rise of mathematical formalizations. He argues, “In [Maxwell’s] dynamical analogy, applied to the theory of the electromagnetic field, [he] broke away from the use of concrete mechanisms of interaction and rose to a higher level of theoretical abstraction.” (25) This exposits what Nugaev dubs as the mathematical hypothesis, where the future theories that “guessed” only reach empirical interpretation after a long path of trial and error (25).

This is a similar manner of classifying the abstract as Kuhn’s symbolic generalizations. Symbolic generalizations are the mathematical formalizations of a foundational theory. Nugaev’s argument of the decline of mechanical models shows a larger rift between experimentalists and theorists of science. While this rift will be briefly discussed in Chapter 3, it is important to note that Nugaev’s argument of empirical interpretations coming to fruition via trial and error is similar to the way in which problem solving occurs during periods of normal science. Nugaev agrees with Kuhn on paradigm shifts occurring with a transition between the different theories such as the transition from classical dynamics to relativity and quantum theory (24).

### 1.5.2 Schindler on Theory-Laden Experiments

The abstract/concrete distinction can also be seen in Samuel Schindler's "Theory-laden Experimentation". Schindler outlines three difficulties of the manner in which theory is inescapable in the conversation of experiments and observations. The three difficulties are:

> 1. Theories impact on perceptual processes so that 'what we see' is partially determined by our theoretical presuppositions. 2. Observations cannot be described in a theory-neutral way and the meaning of observational terms is determined by theoretical presuppositions. 3. Theories make certain observations more salient than others because some observations are just more interesting from a certain theoretical perspective than others. (Schindler 1)

Using the three difficulties in teasing theory apart from experiments, Schindler argues that theories are valuable when data conflicts in experiments occur.

These difficulties and Schindler's ultimate conclusion can resonate well with both Kuhn and Cartwright's arguments regarding the abstract/concrete distinction. Difficulty 1 is similar to the gestalt theory posed by Kuhn, where scientists working within a paradigm see the world differently than those working with a different paradigm. Difficulty 1 is a case brought up both in normal science and paradigm shifts. Difficulties 2 and 3 show the connectivity between the abstract and the concrete. While Kuhn and Cartwright argue (using their own terminologies) that the concrete fills out the abstract by making discussions of the abstract meaningful (discussion of an abstract level must be accompanied by the discussion of the concrete), Schindler argues that the abstract is required to make discussions of the concrete useful. Indeed, this does not conflict with Kuhn or Cartwright's views when looking at normal science. However, when understanding this distinction during times of revolution, a more nuanced view need be adopted. As I will present through the examples in the following chapters, concrete models may be created with little reference to theory when the paradigmatic theory cannot account for a phenomenon. It is also the case that these concrete models may ultimately aid in the development and acceptance of a future theory. As such, while the abstract may be required to make discussions of the concrete useful in times of normal science, this requirement is minimalized during times of crisis. Difficulty 3 and Schindler's ultimate argument are relevant to the Tool Box method described by Cartwright et al. It may indeed be the case that theories make certain data more salient. Following the tool box method, it may even be appropriate to sometimes use theories in order to adjudicate between conflicting data sets. However, as presented in Cartwright's case study, the issue of a conflict between expected data and occurring phenomenon in superconductivity was not settled via theory. In this manner, while theory does indeed have the ability to play a role in model creation, it is not necessary to rely mostly on theories during times of crises.

While these views are important in situating the debate around the role of the abstract/concrete distinction, I will focus on Cartwright and Kuhn's distinctions due to Cartwright's pre-existing discussion about the case study of superconductivity as well as her pre-existing comparison between herself and Kuhn.

## 1.6 Summary

I have now outlined the abstract/concrete distinction as presented by Kuhn and Cartwright. I have also shown that Cartwright generally agrees with theory/observation distinction presented by Kuhn through comparing their presentations of harmonic oscillators.  I have also presented other views that discuss this abstract/concrete distinction in times of transition between paradigms.

# Chapter 2

# The London-London Model

## 2.1 Introduction

Scientists may move from a heavy reliance on the abstract to a heavy reliance on the concrete in model construction during times of scientific crisis. This reliance shift occurs when abstract components of a paradigm cannot account for a new anomaly. To illustrate how this reliance can change during times of crisis, let us consider the development of the London-London model of superconductivity alongside the development of BCS theory of superconductivity.

I will begin with the development of the London-London model in light of the Meissner effect, and a timeline of this development can be found in *Appendix A*. I will endorse Cartwright et al.’s view that reliance on the abstract was abandoned by the London brothers in the development of the London-London model. By this, I mean that since the previously established theory that was based on Maxwell’s equations could not account for the Meissner effect, the London brothers had to turn their attention to the concrete phenomena of a lack of “frozen-in” magnetic field as a basis for model construction. This section will first present the history of the development of this model, then discuss the application of the abstract/concrete distinction.

I will argue that, while Cartwright et al.’s emphasis on actual use of phenomenological models in problem solving was correct, it must be fit within a Kuhnian framework to fully understand its role in the transition between paradigms. I will also argue that in its problem solving role during a time of crisis, this concretely developed model may be temporary, which was a critique of Cartwright et al.'s account of phenomenological models, but this temporariness does not conflict with its necessity.

In the next chapter, I will show that a reliance on the concrete level arose once again in the development and acceptance of the BCS theory, which serves as an explanation of the low energy state of superconducting materials, through Bardeen's focus on the phenomenon of the energy difference between a material's superconducting and non-superconducting states.

## 2.2 History

### 2.2.1 Pre-London Brothers

In the early 1900s, successes in the quantum theory of metals, such as the development of Bloch's theory of a wave function of an electron in metal, led theoretical physicists to be optimistic about the tools for explaining superconductivity (Hoddeson 141). Bloch's early quantum theory of metals began to be applied in new areas of solid state physics, superconductivity included. However, theories such as relativistic electrons, spontaneous current theories, and "trapped" electrons did not explain the characteristic loss of resistivity of superconductors (Hoddeson 141).

The Meissner effect was discovered in 1933 by experimentalists Walther Meissner and Robert Oschenfeld. When a solid cylinder of tin or lead was cooled below its superconducting transition point in a constant magnetic field, the magnetic field within the material was suddenly expelled from the metal (Kragh 376). This effect and the diamagnetic[8] character of superconductors were not predicted by previous theoretical models. This experimental discovery showed how future experimentalists can focus on the issues of superconductivity not readily answered by theory.

### 2.2.2 London Brothers

Fritz and Heinz London went against the grain of theoretical frameworks of the time by utilizing quantum phenomena at the macroscopic level to explain superconductivity (Matricon and Waysand 67). Prior to work with his brother, Fritz London collaborated with Walter Heitler to calculate the binding between two hydrogen atoms in a hydrogen molecule as the first quantum mechanical approach to the chemical bond (Matricon and Waysand 67). Marking this time as a turning point in London's intellectual pre-occupations, he and his brother began work on a macroscopic theory of superconductivity. The London-London model arose with the need to explain the Meissner effect, which was unexplained through previous electromagnetism theories and was not yet handled by new quantum theories such as Bloch's. Superconductors, materials that exhibit unique conductive behaviour under certain circumstances have two observable findings: resistance-less conductivity and the Meissner effect (Cartwright et al., "Tool Box" 143). The Meissner effect is the expulsion of magnetic flux in a superconducting material. An observational effect of this is a seeming act of levitation when a magnet is placed above a superconductor. The Meissner effect

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[8] Diamagnetism is a quantum mechanical effect that occurs in all materials. Diamagnetic materials create an induced magnetic field in a direction opposite to an externally applied magnetic field, and they are repelled by the applied magnetic field. A perfect diamagnet expels all magnetic fields due to the Meissner effect.

suggested that the fundamental character of superconductivity is one of perfect diamagnetism rather than a vanishing resistivity (Hoddeson 142).

An initial theory explaining the findings of superconductive material prior to the discovery of the Meissner effect was an acceleration equation based upon Maxwell's equations to account for a stationary current flowing at a constant rate in the absence of electric fields (Cartwright et al., "Tool Box" 145). This equation, however, was shown by the London brothers to be unable to account for the Meissner effect, where the magnetic field within the conducting material is expelled and the material appears to exhibit diamagnetism (Bueno et al., "Returning to the London Account" 99).

Not only could the previous equation based on electromagnetism not account for the Meissner effect, but it directly contradicted the existence of the Meissner effect. The previous theories of electromagnetism drew analogies from ferromagnetism to hypothesize that an outside magnetic field would be "frozen-in" when a material reaches superconducting state. The material, however, expels magnetic flux rather than having its initial flux "frozen-in" after it reaches superconducting state (Bueno et al., "Models and Structures" 45). Since the previous equation did not predict the occurrence of the Meissner effect, its experimental discovery marks the start of the shift in reliance from the abstract level to the concrete level within the topic of superconductivity.

### 2.3 The Development of the London-London Model

A new model had to be created to account for the Meissner effect. This new model abandoned the acceleration equation of electromagnetism and proposed a new "fundamental law" of superconductivity (Cartwright et al., "Tool Box" 147). Since this model was constructed with the phenomenon of the Meissner effect as a motivation, this model has been dubbed a phenomenological model in "Tool Box". This new model directly utilized information resulting from the observed phenomenon rather than solely relying on the defunct theory.

The previous model of superconductivity referred to by Cartwright was built upon an acceleration equation, $\Lambda\frac{d\vec{J}}{dt} = \vec{E}$, where Λ is a constant that depends on the mass, charge, and number density of electrons, $\vec{E}$ is the electric field, and $\vec{J}$ is the current density , that could account for a stationary current flowing at a constant rate in the absence of electric fields by setting $\vec{E} = 0$, which modifies the equation to $\frac{d\vec{J}}{dt} = 0$ (Cartwright et al., "Tool Box" 145). London and London realized that this equation contradicted the Meissner effect. Using a constraint on the magnetic field inside the superconductor and integrating with respect to time, the equation for the constraint on the magnetic field becomes $\Lambda c^2\nabla^2\left(\vec{H} - \overrightarrow{H_0}\right) = \vec{H} - \overrightarrow{H_0}$., where $\vec{H}$ is the magnetic field, $\overrightarrow{H_0}$ is the magnetic field at time = 0 (possibly before the transition phase has occurred). All possible solutions to this equation involve an initial magnetic field within the superconductor. This is was, however, simply not the case since all magnetic fields within the superconductor are expelled due to the Meissner effect.

> The general solution means, therefore, that practically the original field persists for ever in the supraconductor. The field $\overrightarrow{H_0}$ is to be regarded as 'frozen in' and represents a permanent memory of the field which existed when the metal was last

> cooled below the transition temperature. (Cartwright et al.,
> “Tool Box” 146)

Given the initial acceleration equation, with no initial field or flux in the superconducting material, after the transition to the superconducting domain, we expect there to be no change to the lack of initial field or flux in the superconductor. In the case of an initial field, however, the initial acceleration equation predicts that there will be a non-zero amount of magnetic flux within the superconductor. The Meissner effect, however, shows that there is the flux within the superconductor is expelled, and directly contradicts the theory’s predictions (Cartwright et al., “Tool Box” 147).

In order to account for the lack of a frozen-in magnetic flux in the superconductor, the London brothers gave precedence to their observations rather than the predictions of the defunct theory. The London brothers developed two London equations, $\frac{dj_s}{dt} = \frac{n_s e^2}{m} E$ and $\nabla j_s = -\frac{n_s e^2}{mc} B$, where $j_s$ is the superconducting current density, $e$ is the charge of an electron and proton, $m$ is electron mass, $n_s$ is a constant associated with a number density of superconducting carries, $B$ is the magnetic field within the superconductor, and $E$ is the electric field within the superconductor. In accounting for the expulsion magnetic fields in superconducting materials, both $B$ and $E$ were set to 0 since there are no magnetic and electric fields within the superconductor as a result of the Meissner effect (Matricon and Waysand 71). These equations can be written as a London equation in terms of a vector potential, so they will be hereby referred to as the London equation. As argued by

Cartwright, this development occurred through relying on the phenomenon itself rather than previous theories in order to account for the Meissner effect.

This example shows not only a method of creation for phenomenological models, but also how theory-driven models may react to unexpected results. Since theory-driven models must keep theory in a dominant position, when encountering unexpected phenomenon, old models may add in correction terms to comply with both the original theory and the new phenomenon or place a restriction on an auxiliary assumption (Cartwright et al., “Tool Box” 148). The London account, however, took neither of these options, and instead created a new equation not derived from the original acceleration equation. We see here the emphasis on the actual method of model creation by scientists in “Tool Box”. This argument for the existence of phenomenological models may be construed as descriptive in nature. The following sections will deal with arguments against the phenomenological modeling method along with my argument that this form of modeling fits well within a Kuhnian framework of paradigm shifts.

The difference in importance of theory and phenomenon arose in the development of this model of superconductivity.

## 2.4 The Case Study of Superconductivity in the Philosophy of Science Literature

It is important to note that the revolution in superconductivity[9] involving the London-London model has been presented and analyzed by Cartwright and other philosophers. I will briefly discuss their analysis to show that, while I do not disagree with their analysis, further study must be done to fully fit this case study within the context of the revolution. I will also show that, while their emphasis on the actual use of phenomenological methods by scientists was correct, it does not fully account for this method of problem solving during a revolution.

### 2.4.1 An Assessment of Cartwright and the London-London Model

To assess how Cartwright's phenomenological modeling may fit into a process of paradigm shifts, we can view the shift from pre-Meissner effect superconductivity to the London account as an anomaly recognition that led to the start of a paradigm shift from macroscopic theories to quantum theories. Indeed, this macro-micro move is something amenable to critics of Cartwright: Steven French, James Ladyman, Otavio Bueno, and Newton Da Costa (hereby: FLBD) (Bueno et al., "Returning to the London Account" 99).

The initial acceleration equation not being able to account for the Meissner effect alludes to an anomaly in the original paradigm present in superconductivity. With magnetic fields

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[9] It may be contentious as to whether or not there truly was a revolution in superconductivity. However, given my discussion of Kuhn's definition of a revolution, I have assumed that the multiple issues in explaining superconductivity (first, through the Meissner effect, and later, the difference in energy between a material's superconducting and non-superconducting states) amounts to enough anomalies that render the original paradigm of electromagnetic equations defunct. The ultimate shift to explaining superconductivity through quantum means is distinct enough from the original electromagnetic explanations to warrant the title of a revolution.

being expelled rather than frozen-in, the superconducting material not only did not cohere with the acceleration equation, but in fact could not cohere with it. This strict contradiction between the phenomenon and expectations of the theory at the time show how this may be seen as a critical anomaly in the field.

The acceleration equation was able to account for what FLBD may dub as "macro-structures", but the current theories of electron pairing required the shift to utilizing "micro-structures" (Bueno et al., "Returning" 99). Moving from the acceleration equation to the London equation provides a shift from the explanatory macroscopic interpretation to a microscopic one that sets out a program for generating quantum models (Bueno et al., "Returning" 100). With the London equation still in use within electromagnetism, the Meissner effect compelled us to understand the behavior of electrons that were not explained by Bloch's theory of metals. Fritz London's solo paper explicitly considering the diamagnetic atom shows how the London-London model may be considered microscopic (Bueno et al. "Returning" 100).

The London account's creation was likely not motivated by the deterrence of ad hoc additions or restrictions in the theory-driven view. Rather, this model was generated simply due to the need to account for a phenomenon that was not being accounted for in the previous model. The previous model's tools relied heavily on theories, but the new model shifts this reliance on to the phenomenon itself.

This shift in focus of research shows the manner in which the world views of scientists in the field may change. What was once explained via the Lorentz force and eddy currents would need to be re-evaluated to fit the discovered processes of superconducting material. The shift in world view is not necessarily as dramatic as a gestalt shift, but Kuhn himself distances the paradigm shift from a gestalt shift in later work (See Kuhn, “Possible Worlds” 49 qtd. in Hacking 276). Distancing himself from a severe gestalt shift, Kuhn further discussed smaller scale revolutions such as the discovery of minor planets in 1801 not being a full scale change in astronomical paradigm (Kuhn 116).

### 2.4.2 Criticisms of Cartwright

Major critics of the phenomenological modeling regarding the London-London model presented in “Tool Box” include FLBD. FLBD’s arguments against this type of phenomenological modeling consisted of their emphasis on a partial structures account, the issue of temporality in phenomenological models, and the issue that Fritz London himself was wanting to divest from a phenomenological framework (qtd. in Bueno et al., “Theories versus Models” 69). While I will briefly address their argument about partial structures, my focus will be on their concern regarding Fritz London and the autonomy and temporariness of models from the abstract theory.

#### 2.4.2.1 The Definition of “Phenomenological”

One of the criticisms of Cartwright’s work is that Fritz London situated the London account outside of the phenomenological framework. London explicitly denied that his model was phenomenological. London’s denial of the phenomenological framework of the London-London model would undermine the phenomenological method of model building and

Cartwright et al.'s emphasis on the notion that phenomenological model building is actually used in science. However, as Cartwright and Suarez rebut in "Theories – Tools vs. Models", there may be multiple uses of the phrase phenomenological[10] (70). London primarily uses it to denote relying solely on measurements gathered on the phenomenon; whereas Cartwright et al. use it to denote models that are not constructed in a theory-driven manner. Cartwright and Suarez argue that relying solely on measurements does not necessitate the construction of models outside of a theory-driven view, so that definition of phenomenological does not cohere with their own. While this is true, it is also not necessary that all models constructed of measurements must belong to a theory-driven view, so there may be some room for compatibility with the instrumental account in "Tool Box". Measurements and predictions derived from a general theory may not be amenable to testing; however, measurements gathered from observation of phenomena are not entirely theory-driven, and also do not have same restrictions in testing since the data was presumably gathered from practical tests. In this manner, the measurements London speaks of as phenomenological may not be phenomenological in Cartwright's terms at all.

Without relying solely on measurements as Fritz London argues, but still focusing on the phenomenon that is observed for the construction of their model, the London-London model is still phenomenological in the way that Cartwright et al. define the term. Since this paper is concerned with the focus on the concrete rather than solely measurements, a feature of the

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[10] They also briefly dwell on their own minimal usage of the phrase phenomenological that arises only twice in *Tool Box*.

phenomenon in question, London's avoidance of what he defined to be phenomenological does not show an avoidance of the concrete.

#### 2.4.2.2 The Partial Structures Argument

FLBD's criticisms also stem from their endorsement of a partial structures argument for the relation between theories and models. Under their argument for partial structures, mathematical structures and physical structures may be partially isomorphic (Bueno et al., "Models and Structures" 45). The partial structures account holds that there are some relevant features shared between theories and models that may be represented in a set-theoretic manner (Bueno et al., "Models and Structures" 45). This implies that models are not entirely autonomous from theories since relevant features may account for any isomorphism. This aspect of the criticism, however, is not entirely contradictory to the instrumentalist emphasis placed by Cartwright, Suarez and Shomar. In using theories as a tool, there may be a partial structure overlap between theories and models, but this does not necessitate that theories always be relied upon as a tool. Similar to the manner in which a hammer is the perfect tool for a nail, but not the perfect tool for a screw, a theory may be the perfect tool for model creation for some phenomenon, but not the perfect tool in other situations. In this manner, both parties have agreed that the instrumentalist approach and the partial structures account are not necessarily mutually exclusive (Cartwright et al., "Tools versus Models" 63, "Models and Structures" 45). However, Cartwright and Suarez also argue that this partial structures method does not figure into the London account since the new and old models have no partial isomorphism. While this ongoing debate may see an opportunity to fit within the Kuhnian framework, I will set this issue aside and focus my attention in this thesis on the issue of the temporariness of phenomenological modeling.

#### 2.4.2.3 Temporariness

A criticism of the phenomenological approach to model construction also noted that phenomenological models are at best temporary. It is less contested that the London-London model may be autonomous from the theory of the previous acceleration equation, but it may not be the case that it remains autonomous from future theories in that it may be applied to further explain a different, new theory (Bueno et al., “Representing the Relationship” 515-516). Phenomenological models seem temporary since their autonomy from theory rests on the prevalence of a certain theory at the time of its creation.

Indeed, it may be the case that the London-London model’s autonomy from theory was temporary as it was ultimately considered alongside other high-level theoretical and mathematical considerations (Bueno et al., “Representing the Relationship” 516). A model’s autonomy, however, short lived, can still be of use when considering its place in the start of a paradigm shift. In fact, without autonomy, phenomenological models of the London sort cannot account for the anomalies of a paradigm.

The temporariness of phenomenological models also shows the case-by-case nature of this account. It is not necessary that all modeling methods switch to being phenomenological. Rather, that domains may adopt this method of modeling when the current method of modeling does not assist in problem solving. In this manner, the London-London model can assist in problem solving to account for the Meissner effect when the previous model of the acceleration equation cannot.

An issue that will be later expanded upon is the difference in level of autonomy and temporariness between the London-London model and the later BCS theory of superconductivity. It is the case that the London-London model did not connect to future theories in the same way that BCS theory did. The London-London model presented the quantum, but macroscopic equation of the Meissner effect. However, with budding prevalent quantum theories of the time, including Bloch's theory of metals, unable to account for superconducting metals, this model remained a mostly autonomous solution to the Meissner effect.

## 2.5 Reliance on the Abstract

Let us recall that prior to the London account, theories of superconductivity were largely based on variations of Maxwell's equations as well as theories used for semi-conductors from the quantum theory of metals. In attempts to explain his experimental observations, Heinz London developed a phenomenological theory of superconductivity. This theory contained the important idea that super-currents flow in a small but finite penetration depth. Coupled with theories of De Haas-Lorentz, Becker, Heller and Sauter, the London brothers set out trying to account for the infinite direct current conductivity by assuming that metals were perfect conductors. However, this led to a dependence on magnetic field theory, a result now unsuitable due to Meissner's results (Hoddeson 502 – 503). Given the budding quantum theory of metals by Bloch, the abstract components of the London account can be seen through both the influence of electromagnetism and early quantum mechanics.

Areas of reliance on the abstract are seen through the previous dependence on microscopic principles as well as the later development of a quantum theory in the postulation of electron coupling. The development of electron coupling will be discussed in the next chapter regarding BCS theory. Prior to the development of quantum mechanics, theories of superconductivity were limited to microscopic principles of single electron theories. Armed with the successes of the quantum theory of metals in ferromagnetism, "[many theoretical physicists] were optimistic that the new tool would also help them to explain superconductivity" (Hoddeson 141). The initial quantum theory of metals led physicists to search for experimental information on superconductors by establishing cryogenic laboratories in Toronto and Leiden (Hoddeson 141). Here, Meissner discovered that the purest single crystals of some normal metal conductors, like gold, do not necessarily become superconducting when cooled down (Hoddeson 141). This, coupled with the discovery of the Meissner effect, alluded to the breakdown of the initial microscopic quantum theory of metals posited by Bloch as a plausible theory of superconductivity.

Indeed, London comments on the reliance of Bloch's theory of metals in superconductivity:

> It seems that the principal obstacle which stands in the way of understanding this phenomenon is to be sought in its customary macroscopical interpretation as a kind of limiting case of ordinary conductivity. The present theoretical situation may be characterized in such a way that it is rigorously demonstrable

> that, on the basis of the recognized conceptions of the electron theory of metals, a theory of supraconductivity is impossible—provided that the phenomenon is interpreted in the usual way (London, 1935, p. 24 qtd. In Bueno et al., “Empirical Factors and Structural Transference”, pg 97)

The “electron theory of metals” London refers to is the theory of metals developed by Bloch. This theory gained traction and saw use in the modeling of semiconductors as well as ferromagnetism (Hoddeson 141). However, this theory, in addition to the use of electromagnetism in metals, could not explain the observable phenomenon tackled by the London brothers. This realization led to the move to place reliance on the concrete during a time of crisis.

### 2.6 Reliance on the Concrete

According to both Kuhn and Cartwright, concrete models are easier for scientists to use than the abstract levels. By this, we mean that concrete models can have more uses in teaching as well as in gathering new information. By this, we can now begin to see the move to the importance of the concrete in the London-London account. The model assisted in gathering new information about the Meissner effect that could not have been previously accounted for. The London-London model lent itself to explaining the Meissner effect by focusing on observations in a way that the previous theory-driven view could not.

#### 2.6.1 Concrete and Phenomenological

The London-London model is phenomenological since the London brothers constructed their model of superconductivity with close attention to observations of expelled magnetic fields –

and because they rejected theory as it was not a useful tool. This model is also a concrete model since it directly relates to problem solving for one class of phenomenon – superconductivity - in light of the Meissner effect. In this section, I will show how the London-London model fits both Kuhn and Cartwright's characterizations of the concrete in addition to being considered a phenomenological model by Cartwright.

Kuhn's account of the abstract, using his terms, showed the utility of the symbolic generalizations to many specific situations; in particular, his definition of the concrete included the application of the model to a specific situation as well as utility in teaching via that model. As such, the London-London model is concrete due to its application to the specific situation of superconductivity, which may be further specified into the specific purpose of solving the issue of the Meissner effect that the previous theory based on Maxwell's equations could not. The London-London model could have also been utilized in teaching physics students with the London equation.

## 2.7 The Shift from Abstract to Concrete

The London brothers themselves rejected the foundational theory preceding their own experiments. This rejection marked the beginning of the revolution in superconductivity, where the previous abstract generalization could not be utilized to solve a crucial problem. By creating a phenomenological model, the London brothers relied on the concrete, specific observations with greater importance. This section will discuss this move in further detail by arguing that the London-London model plays an important role in time of crisis because it is both concrete and phenomenological.

In their 1935 paper, the London brothers begin with the acceleration equation for the older model of superconductivity (qtd. in Bueno et al., "Empirical Factors and Structure Transference 98). This equation used part of Maxwell's theory to obtain its result and was associated with models of ferromagnetism. This acceleration equation represents a magnetic field that must be "frozen-in" the superconductor. The Meissner experiment, however, falsified this by showing that there is no freezing in of magnetic fields as this magnetic field is instead expelled. The London brothers created the "homogenous equation" that represented their abandonment of the old acceleration model in order to account for the lack of a frozen-in magnetic field.

The rejection of the old theory shows the move away from placing importance on the previous abstract component of the old paradigm. The new fundamental law seen through the new equation shows the move to a new abstract level of a paradigm. The time between these different abstract levels, however, was captured by the actual use of the concrete level in model construction.

### 2.7.1 Problem Solving

Similar to the instrumentalist notion that theories are but one tool in the tool box of science, I argue that placing a changing reliance on the abstract and the concrete during times of crises can be regarded as another tool in the tool box. My extended version of instrumental problem solving is similar to but more comprehensive than Cartwright et al.'s account of phenomenological modeling. While in "Tool Box", Cartwright et al. mention the use of the phenomenon without the necessary reliance on the abstract, they do not address how moving between the concrete and the abstract levels can show a long term approach to problem solving.

In a time of crisis, the normal, abstract components of a paradigm cannot account for the unsolved puzzles. As such, importance in model building, or other methods of problem solving, move from the defunct abstract level of a paradigm to a focus on the concrete model that describes a phenomenon. Once the phenomenon can be accounted for, newer theories may be constructed to enter work within a new scientific paradigm. In this manner, as the old paradigm breaks down into a crisis state, it is more useful to utilize concrete phenomenon for problem solving; when the original anomaly has been accounted for, scientists may once again construct and utilize theories to form the abstract levels of a new paradigm under which to conduct normal science.

The London-London model accounted for the Meissner effect without requiring the use of the defunct abstract level of the previous paradigm that applied to superconductivity. While this temporary model was ultimately overshadowed by its successors including modern day BCS theory in 1957, its role in problem solving when previous theories failed was crucial to the development of superconductivity.

## 2.8 Conclusion

I have agreed with Cartwright et al. on the matter that the London-London model of superconductivity was developed via reliance on the concrete level. To further the instrumentalist method, I have argued that the shift in reliance on the abstract level to the reliance on the concrete level was used as a method of accounting for the Meissner effect. I have also presented preceding theories of superconductivity that were based on Maxwell's equations, and I have argued that the London-London model differs from those theories by being a concretely developed model.  I have exposited previous philosophical discussions by Cartwright et al. and FLBD regarding the London-London model's phenomenological and temporary development, and I have defended Cartwright et al.'s instrumentalist method by arguing that, while the model is indeed temporary, it has a crucial role in problem solving during a time of crisis.  With an emphasis on the move from the abstract level to the concrete level as a method of problem solving during crises, I have applied the Kuhnian framework to show that the London-London model assisted in accounting for an anomaly that could not be accounted for using the abstract level of electromagnetism or early quantum theory paradigms.  My arguments show that concretely developed models are useful in not just representing a phenomenon unaccountable for via theory, but also in continuing the problem solving nature of science.

# Chapter 3

# BCS Theory

## 3.1 Introduction

After the London-London model, scientists working within superconductivity developed the Ginzburg-Landau model in 1950 and the later BCS theory in 1957 for a microphysical theory of superconductivity. The development of BCS theory is similar to that of the London-London model in that both rely on a concrete level for problem solving. The problem needing to be solved in this case is the fact that materials exhibit a surprisingly low energy level when in superconducting state. In this chapter, I will show that Bardeen, Cooper, and Schrieffer resolve this issue by relying on the phenomenon to posit Cooper pairs.

First I will discuss the role of experimentalists in superconductivity after the success of the London-London model. I will show that, while I and the creators of BCS theory classify it as an ultimately concrete focused theory, its reliance on the experimental phenomenon is called into question since its discovery of Cooper pairs can be applicable to superfluidity, an area outside of superconductivity.

After drawing the developmental parallel between BCS theory and the London-London model, I will then show that, while BCS theory is more “theory-like” than the London-London model, it still relied on the concrete level to develop a solution for the energy difference in states problem. Finally, I will show that BCS theory is concrete but not phenomenological to show that Cartwright et al.’s instrumental method applies to a greater class of models than the ones proposed in “Tool Box”.  It is important to note that while the London-London model has been discussed in the philosophy of science literature extensively, the abstract/concrete distinction in the development of BCS theory has not been comprehensively explored.  Cartwright has discussed BCS theory briefly in her 1999 book, *Dappled World*; however, that focuses on the domain of quantum theory, whereas, this thesis focuses on its presence in the abstract-concrete distinction.

### 3.2 Experimentalists in Superconductivity

Prior to the paper on BCS theory’s publication, beginning in 1951, an anti-theoretical tone began to gain ground amongst experimentalists within the field of superconductivity due to the advances made by earlier models, including the London-London model, which accounted for the phenomena without pandering to a failed theory.  Bernd Matthias, a German-American physicist and chemist credited with discovering numerous types of ferro-electrics, set out to search for superconducting materials with higher critical temperatures (Bromberg 3).  High temperature superconductors can see more practical applications than low temperature superconductors due to fewer resources being expended in keeping a super cooled temperature.  Matthias, by the time of his death, helped establish a record for the highest recorded critical temperature of 23K.  This result was cited by Bardeen when he received his Nobel Prize for superconductivity research in 1972.  Matthias’ focus on experimental data shows the lasting effect, from the 1950s to the 1980s, that the temporary switch in focus from the abstract level to the concrete level has had in the field of physics.

After its development, BCS theory's allegiance to the concrete was called into question by Matthias.

> With the BCS theory, Matthias now saw the results he had achieved within the field of superconductivity demoted in importance and more generally, he saw the role of the experimentalist being overshadowed by that of the theorist. (Bromberg 4)

Matthias' concern that the experimentalist was once again being overshadowed by the theorist as a result of BCS theory shows that despite the concrete approach in development of the theory, BCS theory ultimately joining up with quantum theory after solving the anomaly was seen as unfavourable to experimentalists since it seemed like BCS theory subscribed to the theory-driven view all along, rather than relying on experimental results. This concern is important for the distinction between the abstract and concrete since it shows that on the spectrum of reliance the abstract and the concrete, the end point of BCS theory is much closer to relying on and accounting for both equally, in stark contrast with the London-London model. This shows the thought that BCS theory was in a sense more "theory-like" or closer to the abstract than the London-London model. This "theory-likeness" can be seen through BCS' categorization as a "theory" when named as so by the scientific community as well as through the fact that its results could later be applicable to the wider field of quantum theory. While this will be described in more detail in the following section, it is important to note this as a major difference between the two cases to show the spectrum of reliance on the concrete level.

### 3.3 Beginnings of BCS Theory

Similar to the creation of the London-London model, BCS theory arose through the need to solve a critical problem that previous superconductivity theories such as the London-London model and the later Ginzburg-Landau theory could not explain due to the lack of a microscopic mechanism in their theory.  Furthermore, theories that correctly captured the isotope effect still had difficulties in calculating the proper level of energies between normal and superconducting states (Bardeen, Cooper, and Schrieffer 162).  In this section, I will show how the development of BCS theory is parallel to the development of the London-London model in the manner in which they distance themselves from the abstract for the concrete as a method of problem solving when faced with an anomaly.  I will also show how the difference between the concrete and the phenomenological arises here since the development of the London-London model can be considered more phenomenological than the development of BCS, which shows how the reliance on directly observable phenomenon can classify a model as more theory like.

While the London-London model could account for the Meissner effect better than the previous models through focusing on the concrete rather than a defunct theory, the issue with the London-London model was that it was ultimately phenomenological, and did not explain the phenomena on a microphysical basis (Kragh 376).  Herbert Frohlich, a German physicist positing the interaction between electrons and quantized lattice vibrations, discovered the isotope effect despite the lack of theoretical reasons for its existence.  The isotope effect posits that the critical temperature of a superconductor's transition would decrease with the atomic mass of the superconductor (Kragh 377). Indeed, with experiments confirming that the critical temperature varies as the inverse square root of the atomic mass, Frohlich's suspicions were supported. However, in only accounting for the electron-phonon interaction, Frohlich's theory could not account for the difference in energy between a material's superconducting state and its normal state. The energy difference arose from the fact that a superconductor exhibited much lower energy than anticipated after the phase transition.

To solve the issue of Frohlich's theory not being able to account for the energy difference between normal and superconducting states, Bardeen set out a four pronged attack. Within the four prongs, we can see the influence of both the importance of the abstract and the concrete as methods for problem solving. This four pronged attack along with the work of Leon Cooper and John Scrieffer resulted in the discovery of "Cooper pairs", where electrons with opposite spin may form bound boson pairs as a result of a previously undiscovered possibility of attractive interaction (Kragh 377). Electrons pairing up to form a boson state means that more than one electron can be in the same spin state. Forming a boson precludes the two electrons in the pair from being subject to the Pauli Exclusion Principle thus allowing for lower energy states.

BCS theory, advanced in 1957, combined electron-phonon interaction posited by Frohlich with the notion of electron pairing. This accounted for direct Coulomb repulsion and showed that at lower energies, there may be an attractive force between electrons. BCS theory explained all experimentally known facts, and it made novel quantitative predictions which were confirmed. While theorists found it worthwhile to investigate connections between superconductors and the more general area of quantum theory, experimentalists began searching for superconducting materials with higher critical temperatures (Kragh 378-9).

### 3.4 The Abstract in BCS Theory

Reliance on the abstract in the development of BCS theory can be seen through previous quantum theoretical applications as well as in contrast to the model developed by the London brothers. Frohlich's theory was an important catalyst for Bardeen's reliance on the concrete level in searching for a solution to the issue of difference in energy levels between a material's superconducting and non-superconducting states.

A difference between the London-London model and BCS includes the end result of the concrete models. The London-London model distances itself from both Bloch's quantum theory of metals as well as the acceleration equation based on Maxwell's equations, but also does not offer a connection to a future microphysical theory. Whereas, BCS theory, being more theory-like itself as it goes beyond experimental data to posit quantum interactions, offers an end connection to abstract theories.

The difference between the London-London model's development and BCS theory's is made explicit through BCS' categorization as a theory, and the London brother's discovery as a model. This distinction can be seen after the development of BCS through the Nobel Prize description and through secondary sources citing BCS as a theory (The Nobel Prize in Physics 1972). This difference in nomenclature shows that BCS is at least closer to a theory in the mind of the non-philosopher. This closeness of theory is seen in the manner of BCS joining up with quantum theory once the concrete model has been utilized for solving the energy differential issue.

> We thus find within solid state physics in the 1950s through the 1980s at least two experimental traditions. One interacts with theory and works with materials amenable to theory. The other, represented by Matthias, is either anterior to theory or parallel to and distinct from it, as he later saw it. (Bromberg 8)

This view from the experimentalist scientists further shows that BCS was ultimately amenable to theory rather than opposed to it. Where the London-London model failed to connect their macroscopic model to a budding quantum theory of the time, BCS allows for this connection on the other side of the crisis.

Working with theory without placing sole importance on that theory shows how the development of BCS theory aligns with Cartwright's view of the theories and models as tools of the scientist. Indeed, it is not the case that Cartwright et al. encourage the whole abandonment of theory in all situations (Cartwright and Suarez "Theories: Tools vs. Models" 11). While theory does not often produce representations on its own, it may be used as a tool to construct models that do represent a phenomenon (Cartwright and Suarez "Theories: Tools vs. Models" 5). By ultimately connecting BCS theory to quantum theory, we see that it is amenable to theory.

### 3.5 The Concrete in BCS Theory

Reliance on the concrete level in BCS theory arose through Bardeen's ultimate consideration of the phenomenon of energy differentials as well as his experimental work to understand the shielding effect of Coulomb repulsion.

We see a return to the need of focusing on the phenomenon rather than the underlying theory which led us astray. Matricon and Waysand argue in *Cold Wars* that, “An invitation to write the article on the theory of superconductivity for *Handbuch der Physik* of 1955 allowed Bardeen to develop a phenomenological description of the main experimental facts.” (149) Phenomenological means that Bardeen is concerned with a focus on the occurrence of the phenomenon as a whole. In developing a phenomenological description of experimental facts, Bardeen referred to the actual, specific instance of electron coupling and the shielding effect of Coulomb repulsion. Handling the main experimental facts without a heavy reliance on previous quantum theories shows the importance of focusing on the concrete during a time of crisis.

Furthermore, collaborators of Bardeen commented on his focus on the concrete during the time that normal quantum science could not problem solve for the energy differential issue:

> David Pines stands out among his collaborators; the two worked side by side for thirty-two years. His impression of Bardeen’s working habits thus has special meaning:
>
> [1] Focus first on the experimental results, by careful reading of the literature and personal contact with members of leading experimental groups.
>
> [2] Develop a phenomenological description that ties the key experimental facts together.
>
> [3] Avoid bringing along prior theoretical baggage, and do not insist that a phenomenological description map onto a particular model. Explore alternative physical pictures and mathematical descriptions without becoming wedded to a specific theoretical approach…. (Matricon and Waysand 148 – 149)

We can see some differences in problem solving approaches between Bardeen and the London brothers through [1], but those minor differences can be forgotten with the great similarities of approaches through [2] and [3]. Where the London brothers did not want to focus solely on measurements (Bueno et al., "Empirical Factors and Structural Transferrence 97), Bardeen focused on experimental results. While I have pegged this as a difference between the two sets of scientists, it is not necessarily the case since measurements are generally a part of experimental facts. The London brothers concerned themselves with the experimental results of the existence of the Meissner effect. While Fritz London may have tried to distance himself from solely relying on measurement related results, Cartwright and Suarez argue that he focused first and foremost on the entirety of experimental results including a phenomenal view of resistanceless expulsion of magnetic fields in the Meissner effect. Without knowing Bardeen's views toward the measurement related subset of experimental results, I cannot comment on whether this point was truly a difference in problem solving technique.

Through [2] and [3], we can see the parallel problem solving methods more clearly.

[2] was developed through Bardeen developing a description of strong interactions between electrons and phonons for *Handbuch der Physik* of 1955. Bardeen had encouraged Pines to pursue this line of inquiry, where Pines began to study polar crystals where electrons are strongly coupled to high-frequency phonons. [3] can be seen through Pines developing a technique which had already been used in the study of mesons, and applied it to electron-phonon coupling (Matricon and Waysand 149). The lack of prior theoretical baggage also

presented itself in Bardeen's confirmation of the effects of Coulomb repulsion between electrons in electron-phonon interactions. His model yielded the prediction that two electrons in a solid need not always repel each other, rather, in certain conditions, they might attract each other (Matricon and Waysand 149).

### 3.5.1 Concrete but not Phenomenological

It is important to note that even though Pines reported Bardeen developing a phenomenological description of electron-phonon interactions to deal with the issue of superconductivity, I argue that this does not entirely map up with the terminology of a phenomenological model presented by Cartwright et al.

A phenomenological model is constructed via reliance on experimental facts. Electron-Phonon interactions in BCS theory, however, are not empirically accessible. This does not change its classification of relying on the concrete since Pines reports that Bardeen approached the problem without first focusing on the theory. The London-London model was considered phenomenological by Cartwright et al. since the model developed was predominantly based on the experimental facts gathered regarding the phenomenon of the Meissner effect. Unlike BCS, this model remained phenomenological since it did not lend itself to a connection with quantum theory of the time.

The BCS model, however, ultimately lent itself to a connection with the abstract, quantum theory of the time. The BCS model is considered concrete since it can only be applied to a specific case of superconductivity. The concrete refers to singular phenomenon. This is the same difference as the formula for Hooke's law vs. Newton's second law of motion.

Hooke's law applies specifically to springs, whereas, $F = ma$ applies to a range of topics that includes springs. Since current quantum theory applies to a range of topics including superconductivity, the abstract level of Newton's second law is used in a similar manner as the abstract level of current quantum theory. Ultimately, the BCS model supplied a better articulation to quantum theory in the specific case of superconductors by showing the possibility of electron pairing. The discoveries of BCS theory assisted in fitting out quantum theory to the phenomenon of superconductivity. As such, the BCS model is concrete under Cartwright's classification. However, in its ultimate connection to quantum theory, it is not phenomenological in the same sense as the London-London model. The electron coupling described by BCS advances our knowledge of quantum theory due to its application in superfluidity. In this manner, discoveries in BCS can expand the fundamental abstract theory.

### 3.6 The Shift from Abstract to Concrete

Similar to the move from the abstract to the concrete during a time of crisis at the London-London account, reliance on the concrete in problem solving can once again be seen in the development of BCS theory.

As pointed out in a previous section about experimentalists in light of BCS, the focus on the concrete gained traction as a problem solving method when theory did not suffice. The issue of explaining the energy differential via prior quantum theories was an anomaly in the progress of work in superconductivity. The lower energy state of superconducting materials after phase transition could not be explained given Frohlich's theory. As such, the workings of normal science were interrupted, and a crisis ultimately resulting in the discovery of Cooper-pairs as an explanation of the energy differential arose.

According to Kuhn's stages of a scientific revolution, a revolution only ends when a new paradigm is accepted. This new paradigm must include theoretical components that can solve the anomalies the previous paradigm could not (Kuhn 152). BCS theory supplied a key piece of information to be incorporated within quantum theory in the form of Cooper pairs. Since this had application outside of BCS theory, it can be seen as the articulation of a new paradigm of quantum theory – different from the old quantum theory in that it is now microphysically possible to explain surprisingly low energy levels of a material in superconducting or superfluid states. In this manner, we can see that, while a reliance shift to the concrete level can assist in problem solving, creating a model that can ultimately connect to the abstract level of a paradigm is necessary to end the stage of crisis. This also shows that a model developed through reliance on the concrete level is indeed temporary, but its temporariness does not conflict with its necessity.

### 3.6.1 Problem Solving

The need for focusing on the concrete in the case of the BCS theory shows a crisis since the normal science paradigm of quantum theory could not account for the energy differential present in superconductors during phase transition. This perpetuated a crisis in the sub field of superconductivity where it seemed as though the Meissner effect still could not be accounted for with quantum theory of the time. While fundamental quantum theory may have provided a greater number of predictions to be tested, these predictions did not include the phenomenon of electron coupling.  In this manner, the focus on the concrete rather than the results of the theory allowed for the positing of electron coupling in BCS theory.

The focus on the concrete aligns with the instrumental method presented by Cartwright in “Tool Box” even though there is no outright dismissal of the abstract.  Critics may argue that since BCS ultimately lends itself to the modification of quantum theory, the distinction between the abstract and the concrete is muddled.  This would be an issue since I argue that the distinction leads to the possible reliance on the concrete during times of crisis, and reliance on the abstract during times of normal science.  It may be the case that the distinction became muddled after the full development and acceptance of BCS since BCS theory ultimately connects to modern day quantum theory.  However, this distinction stands during the time of problem solving for the anomaly of electron energy differential.

This distinction also aligns with the instrumentalist method outlined in “Tool Box”.  It can be realized through distinguishing parts of the timeline of development of BCS to show that the abstract and concrete may have become muddled after the findings of the theory were applied to the larger quantum theory.  We first have Frohlich’s theory gaining traction in accounting for the relation between the critical temperature of a superconductor and the atomic mass of the superconducting material.  Then this theory encountered the issue of explaining the energy difference between the material’s normal state and superconducting state.  Bardeen, Cooper, and Schrieffer utilized the phenomenon of the energy difference to posit condensation of electron pairs.  Cooper pairs also connected to other areas of quantum theory including an explanation of superfluidity of helium-3 at low temperatures.

The application of Cooper pairs to areas outside of superconductivity, though still within low temperature physics, shows the end of the anomaly in superconductivity. It also shows how reliance on the concrete may ultimately be temporary, but this temporariness is not a problem in itself.

### 3.7 Summary of the Differences in Philosophical Assessments between BCS and the London-London Model

As presented in the previous chapter, the London-London model has been topic of philosophical conversation regarding model creation strategies. BCS theory, however, has seen less discussion in the literature in the context of the distinction between abstract and concrete levels. This difference can be seen through the naming of the London-London solution a model, and BCS as a theory. The London-London model was a phenomenological model that relied on the experimental facts of the Meissner effect to create an equation which reflected the expulsion of a magnetic field inside the superconductor. BCS theory, even while focusing on the concrete issue of the energy differential, posited electron interactions that were not confirmed by experimental facts of the time.

The London-London model also remained autonomous from theory as it did not add to the development of quantum theory of the time. The equation merely applied to the case of superconductors. BCS theory, however, ultimately connected the solution of the electron differential issue to other areas of quantum theory.

# Chapter 4

# Summary and Conclusion

In chapter 1, I exposited the presence of the abstract/concrete distinction in various pieces of philosophy of science literature. I presented Kuhn's outline of the distinction between symbolic generalizations and manipulations along with his outline of a scientific revolution as well as Cartwright's argument about the abstract and the concrete in model construction. Terminologies were clarified to argue that the abstract refers to a fundamental theory and the concrete refers to the phenomenon in occurrence. Lastly, other views on the distinction by Nugaev and Schindler were exposited and contrasted with both Kuhn and Cartwright's views.

Chapter 2 focused on showing how the development of the London-London model of superconductivity utilized a shift in reliance from the abstract to the concrete as the main tool for model construction. This was shown with a discussion of previous philosophical literature by Cartwright et al. and French, Ladyman, Bueno, and Da Costa, where Cartwright argued that the London-London model was created phenomenologically. I then argued in the same vein as Cartwright using the areas of reliance on both the abstract and the concrete in the development of this model to conclude that the London-London model was indeed both concrete and phenomenological. Furthermore, I placed the London-London model within Kuhn's framework for scientific change to extend Cartwright et al.'s argument of the usefulness of phenomenological models and show that its reliance on the concrete level assisted in problem solving when the abstract level of a pre-existing paradigm failed.

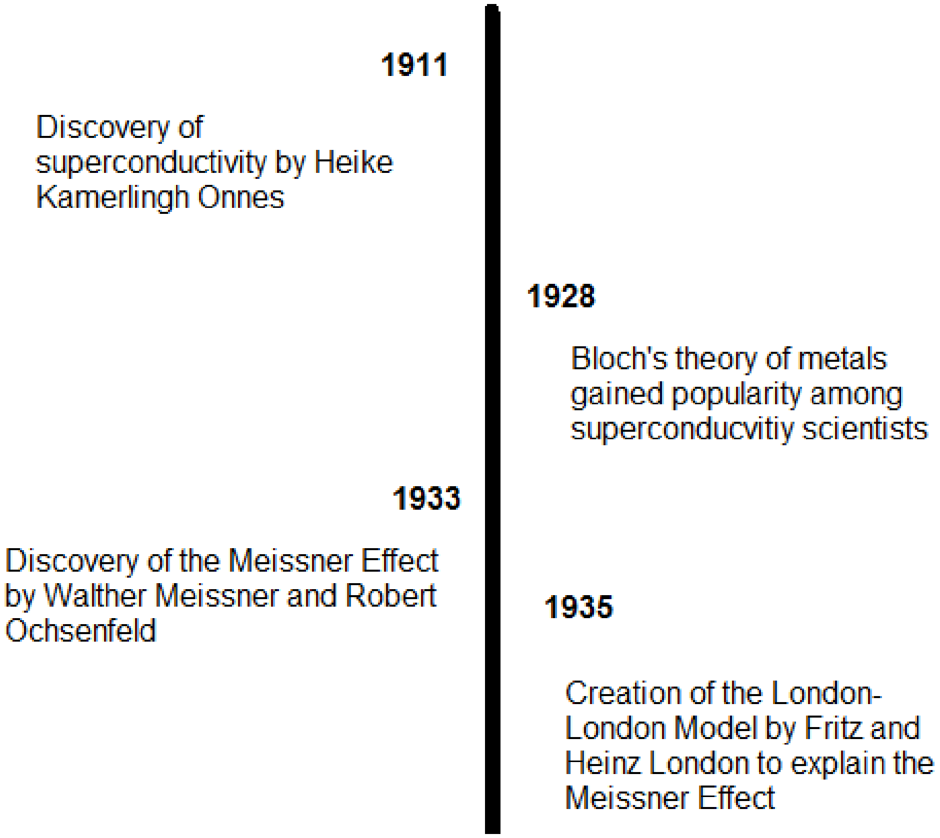
Chapter 3 focused on the concrete development of BCS theory as a major successor to the London-London model. I argued that despite BCS theory seeming to be more “theory-like” to the scientific community, it developed with heavier reliance on the concrete than the abstract due to Frohlich’s theory not being able to account for the energy difference between a material’s superconducting and non-superconducting states. This is similar to the development of the London-London model. Both methods resolved anomalies in previous theories by focusing on the phenomenon causing the anomaly rather than deferring to theory.

Furthermore, I argued that BCS theory ultimately resolved the crisis by ultimately providing a link to larger quantum theory through the application of Cooper pairs outside of superconductivity. This extended Cartwright et. al.’s argument by utilizing a unique case study and framing it under the more comprehensive notion of Kuhnian paradigms.

Both chapters 2 and 3 showed the importance of a model developed through a reliance on the concrete level. These models allowed scientists to continue problem solving at times when the abstract level of a paradigm could not account for occurring phenomenon. Within a Kuhnian framework, we can now see that concrete models have a temporary but needed role in problem solving during paradigm shifts.

# Appendix A

## Timeline of the London-London Model



**1911**

Discovery of superconductivity by Heike Kamerlingh Onnes

**1928**

Bloch's theory of metals gained popularity among superconducvitiy scientists

**1933**

Discovery of the Meissner Effect by Walther Meissner and Robert Ochsenfeld

**1935**

Creation of the London-London Model by Fritz and Heinz London to explain the Meissner Effect

# Appendix B

## Timeline of BCS theory

**1951**

Anti-theoretical tone develops amongst experimentalists including Bernd Matthias

**1954**

Creation of Frolich's theory regarding the isotope effect and electron-lattice interactions

**1954**

Higher temperature (critical temperatures as high as 18K) superconductors discovered experimentally by Matthias.

**1955**

John Bardeen writes a phenomenological description of the main experimental facts of a material's transition to a superconducting state

**1957**

Publication of the paper on BCS theory

**1972**

Bardeen, Cooper, and Schrieffer win the Nobel Prize in Physics for their work in superconductivity

# Bibliography

Bardeen, J., L. N. Cooper, and J. R. Schrieffer. "Microscopic Theory of Superconductivity." *Phys. Rev. Physical Review* 106.1 (1957): 162-64. Web.

Bromberg, Joan L. "Experiment Vis-a-fis Theory in Superconductivity Research. The Case of Bernd Matthias." *Physics, Philosophy, and the Scientific Community: Essays in the Philosophy and History of the Natural Sciences and Mathematics in Honor of Robert S. Cohen*. Ed. Kōstas Gavroglou, John J. Stachel, and Marx W. Wartofsky. Dordrecht: Kluwer Academic, 1995. 1-10. Print.

Bueno, Otávio, Steven French, and James Ladyman. "Empirical Factors and Structure Transference: Returning to the London Account." *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 43.2 (2012): 95-104. Web.

Bueno, Otávio, Steven French, and James Ladyman. "Models and Structures: Phenomenological and Partial." *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 43.1 (2012): 43-46. Web.

Bueno, O., S. French and J. Ladyman, (2002). On Representing the Relationship between the Mathematical and the Empirical. *Philosophy of Science*, 69, pp. 497-518.

Cartwright, Nancy. "How We Relate Theory to Observation." *World Changes: Thomas Kuhn and the Nature of Science*. By Paul Horwich. Cambridge, MA: MIT, 1993. 259-73. Print.

Cartwright, N., T. Shomar and M. Suárez (1995). The Tool Box of Science. In Herfel, W., W. Krajewski, I. Niiniluoto and R. Wojcicki (eds.), *Theories and Models in Scientific Processes* (pp. 137-149). Amsterdam: Rodopi.

Hacking, Ian. "Working in a New World: The Taxonomic Solution." *World Changes: Thomas Kuhn and the Nature of Science*. By Paul Horwich. Cambridge, MA: MIT, 1993. 275-310. Print.

Hoddeson, Lillian. *Out of the Crystal Maze: Chapters From the History of Solid State Physics*. New York: Oxford UP, 1992. Print.

Kragh, Helge. *Quantum Generations*. Princeton, NJ: Princeton UP, 2002. Print.

Kuhn, Thomas S. *The Structure of Scientific Revolutions*. Chicago: U of Chicago, 2012. Print.

Matricon, Jean, and Georges Waysand. *The Cold Wars: A History of Superconductivity*. Trans. Charles Glashausser. New Brunswick: Rutgers UP, 2003. Print.

Nugaev, R. M. "Basic Paradigm Change: The Conception of Communicative Rationality." *Russian Studies in Philosophy* 41.2 (2002): 23-36. *JSTOR [JSTOR]*. Web.

Schindler, Samuel. "Theory-laden Experimentation." *Studies in History and Philosophy of Science Part A* 44.1 (2013): 89-101. *JSTOR [JSTOR]*. Web.

Suárez, Mauricio, and Nancy Cartwright. "Theories: Tools versus Models." *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 39.1 (2008): 62-81. Web.

"The Nobel Prize in Physics 1972". *Nobelprize.org.* Nobel Media AB 2014. Web. 4 Aug 2015. <http://www.nobelprize.org/nobel_prizes/physics/laureates/1972/>