

20

AD-A270 810



# A TRIDENT SCHOLAR PROJECT REPORT

NO. 202

"ESSENTIAL SHIFT:  
SCIENTIFIC REVOLUTION IN THE 20<sup>TH</sup> CENTURY"



DTIC  
ELECTE  
OCT 19 1993  
S E D

UNITED STATES NAVAL ACADEMY  
ANNAPOLIS, MARYLAND

This document has been approved for public  
release and sale; its distribution is unlimited.

93-24560



93 1013 001

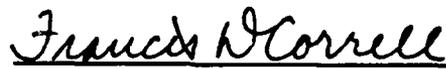
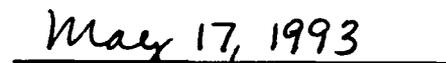
U.S.N.A.— Trident Scholar project report; no. 202 (1993)

"ESSENTIAL SHIFT:  
SCIENTIFIC REVOLUTION IN THE 20<sup>TH</sup> CENTURY"

by  
Midshipman David K. Ismay, Class of 1993  
U.S. Naval Academy  
Annapolis, Maryland

  
Advisor: Professor Robert Artigiani  
History Department

Accepted for Trident Scholar Committee

  
Chair  
  
Date

USNA-1531-2

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB no. 0704-0188

Public Reporting Burden for this collection of information is estimated to average 1 hour of response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE <b>May 17, 1993</b>	3. REPORT TYPE AND DATES COVERED	
4. TITLE AND SUBTITLE <b>Essential shift : scientific revolution in the 20th century</b>			5. FUNDING NUMBERS	
6. AUTHOR(S) <b>David Keringer Ismay</b>				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>U.S. Naval Academy, Annapolis, MD</b>			8. PERFORMING ORGANIZATION REPORT NUMBER <b>U.S.N.A. - Trident scholar project report ; no. 202</b>	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES <b>Accepted by the U.S. Trident Scholar Committee</b>				
12a. DISTRIBUTION/AVAILABILITY STATEMENT <b>This document has been approved for public release; its distribution is UNLIMITED.</b>			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) <p>With the publishing of Sir Isaac Newton's <u>Principia Mathematica</u> in 1687, a scientific paradigm was established that clearly dominated society for two and a half centuries. Many historians of science have identified the Copenhagen interpretation of the quantum theory, formulated c.1927, as having completed a scientific revolution that ended the reign of classical Newtonian science. A rival claim to contemporary scientific revolution, however, has been put forward by Ilya Prigogine and the Brussels school of thermodynamics based on Prigogine's work in non-equilibrium thermodynamics.</p> <p>Using the historical consensus model of scientific revolution first articulated by Thomas S. Kuhn in 1962, this analysis examines the extent to which the Copenhagen interpretation of the quantum theory and the work of Ilya Prigogine complete the conceptual, scientific paradigm-shift necessary for a scientific revolution. The resulting historical evidence shows that the Copenhagen interpretation did not complete a paradigm-shift; instead, it was a self-revelation by the scientific community which revealed the essence and fundamental limitations of Newtonian science. Evidence further indicates that the valid claim to scientific revolution in the 20th century lies with the contemporary work of Prigogine and the Brussels school. By abandoning the deterministic, mechanical world-view of the Newtonian paradigm and accepting a new reality of process and irreversible time, Prigogine and his associates have established the foundations for a revolutionary new scientific paradigm.</p>				
14. SUBJECT TERMS <b>Dissipative structures; Kuhn, Thomas S.; paradigm; Prigogine, Ilya; quantum theory; scientific revolution</b>			15. NUMBER OF PAGES <b>81</b>	
17. SECURITY CLASSIFICATION OF REPORT <b>UNCLASSIFIED</b>			16. PRICE CODE	
18. SECURITY CLASSIFICATION OF THIS PAGE <b>UNCLASSIFIED</b>		19. SECURITY CLASSIFICATION OF ABSTRACT <b>UNCLASSIFIED</b>		20. LIMITATION OF ABSTRACT <b>UNCLASSIFIED</b>

## ABSTRACT

With the publishing of Sir Isaac Newton's Principia Mathematica in 1687, a scientific paradigm was established that clearly dominated society for two and a half centuries. Many historians of science have identified the Copenhagen interpretation of the quantum theory, formulated c.1927, as having completed a scientific revolution that ended the reign of classical Newtonian science. A rival claim to contemporary scientific revolution, however, has been put forward by Ilya Prigogine and the Brussels school of thermodynamics based on Prigogine's work in non-equilibrium thermodynamics.

Using the historical consensus model of scientific revolution first articulated by Thomas S. Kuhn in 1962, this analysis examines the extent to which the Copenhagen interpretation of the quantum theory and the work of Ilya Prigogine complete the conceptual, scientific paradigm-shift necessary for a scientific revolution. The resulting historical evidence shows that the Copenhagen interpretation did not complete a paradigm-shift; instead, it was a self-revelation by the scientific community which revealed the essence and fundamental limitations of Newtonian science. Evidence further indicates that the valid claim to scientific revolution in the 20<sup>th</sup> Century lies with the contemporary work of Prigogine and the Brussels school. By abandoning the deterministic, mechanical world-view of the Newtonian paradigm and accepting a new reality of process and irreversible time, Prigogine and his associates have established the foundations for a revolutionary new scientific paradigm.

### Key Words:

Dissipative Structures  
Kuhn, Thomas S.  
Paradigm  
Prigogine, Ilya  
Quantum Theory  
Scientific Revolution

Accession For	
NTIS	<input checked="" type="checkbox"/>
CRA&I	<input checked="" type="checkbox"/>
DTIC	<input type="checkbox"/>
TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

DTIC QUALITY INSPECTED 2

## TABLE OF CONTENTS

ABSTRACT .....	1
Chapter	
1. INTRODUCTION .....	3
2. NEWTON AND THE CLASSICAL PARADIGM OF SCIENCE .....	7
3. THE COPENHAGEN INTERPRETATION OF THE QUANTUM THEORY .....	16
4. FROM NATURE TO SCIENCE .....	27
5. PARADIGMATIC BANKRUPTCY .....	33
6. BEYOND THE CLASSICAL FRINGE .....	36
7. PRIGOGINE AND THE BRUSSELS SCHOOL .....	45
8. THE CONTEMPORARY CLAIM TO REVOLUTION .....	53
9. CONCLUSION .....	60
NOTES .....	68
SELECTED BIBLIOGRAPHY .....	77

## CHAPTER 1

### INTRODUCTION

In the late seventeenth century, the discoveries of Sir Isaac Newton completed a scientific revolution. His theories established a paradigm that determined what nature looked like, and at the same time, the method by which we should make that determination. This new picture of nature was a mechanistic one in which universal laws governed the behavior of matter and energy and in which scientists illuminated these laws from the darkness of human ignorance by mathematical analysis and derivation based solely on experiment. Newton's paradigm, originally based on mechanics, met with great success in virtually all applications as it dominated the science of the eighteenth, nineteenth and twentieth centuries.

With their publication of the Copenhagen interpretation of the quantum theory in 1927, however, physicists Werner Heisenberg and Niels Bohr appeared to challenge Newton's science in a revolutionary way. The quantum theory's apparent rejection of causal space-time<sup>1</sup> and its principle of fundamental indeterminacy shook the foundations of classic Newtonian science and resulted in the reformulation of certain portions of the mechanics that Newton created. The quantum theory did not, however, fundamentally change the Newtonian paradigm. The success of the theory was the revelation of the limitations of practicing the science defined by the classical Newtonian paradigm. No longer was science capable of a complete description of the

universal laws by which the universe operated. For the first time since the paradigm's inception, the science of mathematics and experimental results was an obstacle to rather than a vehicle for yielding a complete knowledge of nature. It was this self-conscious revelation forced by the quantum theory that accounted for the philosophical crisis within the scientific community which appeared as an indicator of scientific revolution.

Although it did not in fact complete a revolution, the quantum theory did help bring about the necessary conditions for one. The Copenhagen interpretation of the quantum theory was an anomaly within the Newtonian paradigm that revealed to the classical scientists a limitation on the science they were practicing. If examined with the two other major anomalies that appeared within the Newtonian paradigm in the nineteenth century, the science of thermodynamics and Charles Darwin's theory of biological evolution, a scientific revolution in the twentieth century appears not only possible, but probable. Taken together, these three anomalies show a paradigm in crisis, unable to adequately map the world that twentieth century humanity was experiencing.

With a reliance on directed time, complexity and fundamental, stochastic analysis, thermodynamics and Darwinian evolution stood in stark opposition to the simple, reduction of time-reversible Newtonian force laws. Like quantum theory, they were serious anomalies that were initially considered by the classical scientist to be immature fields of study. With increased accuracy of measurement and further study, they could be reduced to and explained by the deterministic, force-particle laws of the

Newtonian paradigm. In order to use the already successful applications in science and technology of these "immature" sciences, scientists had to overlook their logical and philosophical implications within the old paradigm.

In the late twentieth century, however, a portion of the world scientific community has begun to reevaluate the role of evolution and thermodynamics in nature. Led by the pioneering work of the Belgian, Nobel-Laureate chemist Ilya Prigogine, the Brussels school of thermodynamics has developed a science that has the potential to complete a twentieth century scientific revolution. Anchored in a belief in randomness, self-organization, complexity, symmetry breaks and directed time, the dissipative structures theory constitutes a total paradigmatic break with that of Newton. Convinced that nature is too complex to describe with one language or theory,<sup>2</sup> Prigogine suggests that a new understanding of the way nature works, based on dissipative structures theory, has the potential, in fact, to end the schism between the "soft" and "hard" sciences created by the Newtonian paradigm.<sup>3</sup> Fundamental to this proposition is the reality that within this new paradigm, life is not a statistical miracle, but instead, a necessary and natural occurrence.<sup>4</sup>

The following is a comparative analysis of the developments of the quantum and dissipative structures theories which seeks to determine the historical viability of their claims to a twentieth century scientific revolution. Using the architecture of Thomas S. Kuhn, this study relies on precise definitions and an understanding of historical theory, much like the science with which it deals. In this sense it is different from the history of other disciplines, people, or phenomena. The history of

science is, however, a valid historical pursuit. I present in defense of the nature and focus of this analysis, what Kuhn wrote in defense of his own work. "What historians generally view as historical in the development of individual creative disciplines," he wrote, "are those aspects which reflect its immersion in a larger society. What they all too often reject, as not quite history, are those internal features which give the discipline a history in its own right."<sup>5</sup>

## CHAPTER 2

### NEWTON AND THE CLASSICAL PARADIGM OF SCIENCE

Since ancient times, people have attempted to understand the world around them through the powers of observation and logical thought. Historically, the first scientists were the Greeks, and their first scientist was Thales of Miletus. In the sixth century B.C., Thales attempted the first description of the world free of religious and mythic explanation, as he attempted to discover natural causes for the workings of the universe. By excluding mythopoetic explanations from his reasoning, Thales's postulates lacked any but human authority, thereby exposing them to criticism and in turn to rejection and later replacement. Thus began man's practice of science, which was characterized by the desire for an ever increasing ability to understand the world.

Until the seventeenth century, this "progress" within the scientific community continued with little effect on the human condition. Science and technology developed along primarily separate paths. Science remained in the abstract and technology arose out of practical experience and craft knowledge "in the hands" of workers or artisans. The science of the medieval and Renaissance periods in particular were mired in the influence of religion and remained full of theories and postulates resting largely on speculation and independent of experience. In the latter part of the seventeenth century, however, there was a revolution in science whose effects are still felt today. With the publication of Principia Mathematica in 1687, Sir Isaac Newton changed the

nature and practice of science so profoundly that his system of science remained unchallenged for nearly four centuries.

Consistent with the trend of experiential science of Bacon, Boyle and other natural philosophers of the seventeenth century, Newton's new science rested on two principal foundations, experiment and the prescriptive authority of universal mathematical law. For Newton, scientific knowledge was fully dependent on experimental results and deductions therefrom. Equally important was his discovery of general or universal force laws, such as gravitation and inertia, which could be expressed mathematically. This combination of method and intended mathematical results produced a completely new and revolutionary system of science.

Simultaneously, Sir Isaac had found in his method the key to unlocking the secrets of the universe and, in his universal mathematical laws, he had actually discovered those secrets. So pervasive and influential were his ideas and method that the eighteenth century historian Jean-Sylvain Bailly wrote that "Newton overturned or change[d] all ideas," he "brought about a revolution." He "alone, with his mathematics, divined the secret of nature."<sup>6</sup> His revolution quickly spread from the practice of physical science to all sciences including the so called "soft" sciences.<sup>7</sup> Thus, for scientists of all disciplines, Newton had created a completely new way of looking at the world as well as the rules for that examination.

The Newtonian system of science dominated all of science during the eighteenth and nineteenth centuries. Even the work of James Clerk Maxwell that established the field and theories of electromagnetism was Newtonian in nature. In his

exploration of electricity and magnetism, Maxwell sought universal mathematical laws governing their behavior and verifiable by experiment. Similar to the development of thermodynamics in the nineteenth century, Maxwell was studying a science whose subject was not Newtonian mechanics, but he was still practicing Newton's science within the Newtonian system. The process that Newton had discovered seemed to be capable of explaining nature in its entirety. As the physicist and historian of science Alistair Rae wrote, "by the end of the nineteenth century it seemed that the basic fundamental principles governing the behavior of the physical universe were known: everything appeared to be subject to Newton's mechanics and Maxwell's electromagnetism."<sup>8</sup>

The practice of science within the Newtonian system, however, experienced an irreversible change in form during the early years of the twentieth century. With the combination of Werner Heisenberg's uncertainty principle, Niels Bohr's complementarity principle and Max Born's statistical interpretation of Erwin Schrödinger's wave equations, a new body of theory emerged from within the scientific community of the late 1920s. This theory, as expressed by Heisenberg and Bohr at the Fifth Physical Conference of the Solvay Institute in Brussels in October 1927, became solidified and popularized among most practicing scientists as the Copenhagen interpretation of the quantum theory. Fundamental to this theory was an illumination of the relationship between the observer and the observed which undermined the authority of scientific measurement.

Accompanying this illumination was a revelation within the community of

physical scientists that shook the Newtonian foundations upon which that community was founded. For the first time scientists were faced with a mathematically indisputable limitation on the amount of knowledge that they could know about the universe around them. The confusion and shock felt by scientists of this period as a result of this newly formulated quantum theory has been mistaken by most within and outside of the scientific community as having accomplished a revolution in science.<sup>9</sup> An examination of the development of the Copenhagen interpretation of quantum theory, however, reveals that the theory did not replace the modern Newtonian science with a new system. Instead of constituting a scientific revolution, the Copenhagen interpretation represented a realization and subsequent mathematical formulation of the limitations of Newton's system.<sup>10</sup> It was an emotional and defining period in science, but it was not a revolutionary one.

Fundamental to this analysis of the Copenhagen interpretation is a common understanding of the nature of science, scientific "progress" and scientific revolution. The historian and philosopher of science Thomas S. Kuhn articulated a theory of the nature and process of scientific revolutions that became the leading model for revolution in science. In his 1962 book The Structure of Scientific Revolutions, Kuhn described an understanding of scientific revolution based on the existence of "paradigms" of knowledge within the scientific community. A clear rejection of the positivist theory of accumulated "Truthful" scientific knowledge, his theory instead explained revolution in science in terms of the dynamics of scientific communities and the nature of scientific knowledge. In rejecting the positivist accumulation, he

redefined the practice and purpose of the scientist within science.

As historians have studied science, they have recognized a multitude of theories and constructs of the world developed by scientists throughout the ages. Most have presumed that this succession of theories and formulas has represented progress towards a "true" description of nature<sup>11</sup>. From Thales to Einstein, scientists in every era have sought to understand nature and the world, for themselves, through theoretical conjecture and experimental verification. Throughout history, science became more accurate and better able to describe the world. With each discovery, a little more light was thought to have been shed on the darkness of humanity's collective ignorance. The prevailing science was considered to be the correct body of knowledge but, once disproved, a theory was relegated to myth or discarded as the product of ignorance in light of the newest findings, theories or experimental results. Through this process, scientific knowledge has been presumed by many to increase in volume, correctness and accuracy in describing the world.<sup>12</sup> It is this positivist "development by accumulation"<sup>13</sup> that Kuhn rejected and sought to replace.

In its place, Kuhn proposed a theory of scientific activity that not only defined revolution but also explained the daily activity of science. This distinction in turn elucidated the nature of science itself. Kuhn based his understanding on the existence of scientific communities which subscribe to paradigms or models by which members see and interact with the reality of their world. The community consists, he wrote,

of the practitioners of a scientific specialty...bound together by common elements in their education and apprenticeship...responsible for the pursuit of a set of shared goals, including the training of their successors. Such communities are characterized by the relative fullness

of their communication within the group and by the relative unanimity of the group's judgement in professional matters.<sup>14</sup>

Science, by its nature, is a shared experience much akin to language. It is a relational description or understanding of the world shared by a group rather than that held by an individual.<sup>15</sup> Kuhn proposed that for such a group, the basis of a professional education is the indoctrination into the community paradigm by which the student scientist is given the "conceptual boxes" into which to "attempt to force nature."<sup>16</sup> Contained within, or perhaps forming the walls of these boxes, are the preliminary answers to the very basic questions of the composition and operation of the universe as understood by the scientific community. This paradigm allows the scientists who accept it to make certain assumptions as to the workings of the universe and the nature of the knowledge they seek, so that they no longer have to create or build, with every work, their foundational beliefs. Importantly, the paradigm is also prescriptive, shaping the way in which scientists apply their model to nature. It is the commonly held paradigm that makes scientific study itself possible in that it gives relevance and importance to specific data and observation out of the infinity of sensational existence. Kuhn related his idea of a paradigm to that of a judicial decision that is simultaneously a descriptive piece of law and a prescriptive legal "object for further articulation and specification under new or more stringent conditions."<sup>17</sup>

Kuhn described the daily activity of a scientific community as "normal science," that is, the "mopping up" procedure to fit small inconsistencies into the paradigm or to increase the precision with which the paradigm predicts or explains observations.<sup>18</sup> According to Kuhn, this work is essentially the solution of puzzles,

albeit important and often complex ones, but little more. With a puzzle, one attempts to create or recreate a visual or conceptual picture by a certain set of rules with a predicted and expected outcome. Similarly, "bringing a normal research problem to a conclusion is achieving the anticipated in a new way."<sup>19</sup> Thus, in experimentation, "anomaly appears only against the background provided by the paradigm," that is, without the expectations of the model, all results and observations would appear equally relevant or, more importantly, irrelevant.<sup>20</sup>

From where, then, does scientific revolution appear? The answer, for Kuhn, lies within the practice of normal science and the cultural development of the scientific community. With the "generally cumulative"<sup>21</sup> work of normal science, anomalies and an increasing complexity or inability to fit nature into an existing paradigm may arise. This phenomenon, combined with changes in the way that a community perceives itself or the world, must lead to a crisis in the scientific community. This crisis represents a general feeling that the operating paradigm is somehow no longer adequate or sufficient to describe nature and that an alternative may do so more successfully or more completely.

For Kuhn, the existence of a paradigm for a scientific community is essentially necessary in order to have the discovery that leads to scientific revolution. Both the crisis and the alternative are necessary, for "the decision to reject one paradigm is always simultaneously the decision to accept another, and the judgement leading to that decision involves the comparison of both paradigms with nature and with each other."<sup>22</sup> "To reject one paradigm without simultaneously substituting another," he

continued "is to reject science itself."<sup>23</sup>

The resolution of the scientific crisis in revolution is very revealing of the nature of Kuhn's paradigm and the impact that a revolution has on a scientific community. We must realize, he reasoned, that when we look at the supporters and detractors of a new paradigm, their experience of reality is governed by the paradigm. It is a fundamental element of their rational thought and a key to their communication within the community. With the acceptance of a new or different paradigm, Kuhn argued, a person enters a different world. All of the data and experiences of the old paradigm are no longer the same because they mean something completely different. It is possible with a real Kuhnian paradigmatic change that what before was relevant and important no longer is, and conversely what was superfluous or foolish becomes paramount.

Fundamental to Kuhn's theory is the nature of the choice between paradigms. He described it as a "shift in scientific vision or some mental transformation,"<sup>24</sup> that occurs as an "all at once or nothing...conversion experience that cannot be forced."<sup>25</sup> This is not to deny at all the importance of critical, rational thought for the scientist in crisis, but evidence and observation do not in fact lead to a paradigm choice based on logic. Utilizing the parallel to language once more, between two paradigms, as between two languages, there can be no actual translation from one to the other. In any attempt to do so, information is lost and a compromise is made to provide some level of translational understanding. Similarly, there is a certain inability to communicate between or compare opposing paradigms of science. While logic, reason

and evidence easily follow and support a paradigm, the choice of a paradigm must come first. Thus, any accurate explanation of the paradigm choice "must, in the final analysis, be psychological or sociological. It must...be a description of a value system, an ideology, together with an analysis of the institutions through which that system is transmitted and enforced."<sup>26</sup>

The anti-positivistic nature of his theory, its new language of paradigms and its reliance on history, psychology and sociology earned Thomas Kuhn many critics and several volumes of criticism<sup>27</sup>. Frequently attacked were his use of the word paradigm, his recognition of the community nature of science and his theory of paradigm choice. This scrutiny forced Kuhn to both clarify and eventually dilute his original theorem. In an apparent effort to provide examples in the defense of his theorem, Kuhn applied it to several thematic, instead of paradigmatic, shifts in science in the nineteenth century.<sup>28</sup> Such thematic changes in science are Maxwell's development of the science of electromagnetism and the development of the study of thermodynamics. As mentioned earlier, these were changes in theme within the Newtonian paradigm. The scientific method and the desired goals were Newtonian. As defined in his original treatise, The Structure of Scientific Revolution, Kuhn's theory of revolution was clearly intended to address fundamental change in the structure and conceptualization of science. His theory is particularly relevant to the Newtonian paradigm within which the scientific community operated since the late seventeenth century. This study uses the concepts of paradigm and scientific revolution as defined by Kuhn in this manner.

### CHAPTER 3

#### THE COPENHAGEN INTERPRETATION OF THE QUANTUM THEORY

Historical support for this interpretation of Kuhn's theory can be found within the modern scientific community in the period just preceding the development of the quantum theory. For the early twentieth century scientists involved in developing the quantum theory, their vision and understanding of Newtonian science and the Newtonian paradigm came through the filter of the Austrian scientist and philosopher Ernst Mach. It is clear from the writings of Bohr, Heisenberg and Einstein that they and their contemporaries were the disciples of Mach's philosophy in their early years as students.<sup>29</sup> They learned from Mach to recognize the essential dominance and importance of the Newtonian paradigm as postulated in Kuhn's theory. In his major work The Science of Mechanics (1883) Mach demonstrates the commitment that Kuhn attributed to a paradigm. He wrote

the principles of Newton suffice by themselves, without the introduction of any new laws, to explore thoroughly every mechanical phenomenon practically occurring, whether it belongs to statistics or to dynamics. If difficulties arise in any such consideration, they are invariably of a mathematical (formal) character, and in no respect concerned with questions of principle.<sup>30</sup>

For Mach, the theories of Newton provided the inclusive explanation for the workings of the universe and all science since had been a largely mathematical operation to eliminate anomaly or extend their application. Mach further reiterated the dominance

of the Newtonian paradigm when he wrote

Since his [Newton's] time no essentially new principle has been stated. All that has been accomplished in mechanics since his day, has been a deductive, formal, and mathematical development of mechanics on the basis of Newton's laws.<sup>31</sup>

This is precisely the operation of a paradigm and its subsequent "normal science" as described by Kuhn. Mach's own contribution to the "mopping up"<sup>32</sup> effort within the Newtonian paradigm was to make the paradigm as he saw it, more fundamentally Newtonian than it had become in practice. For Mach, the essence of the Newtonian revolution of the eighteenth century, was the removal from science of all non-experiential, non-sensationally based theory. "Starting from his analysis of Newtonian presuppositions, Mach proceeded in his announced program of eliminating all metaphysical ideas from science."<sup>33</sup> This understanding of the paramount importance of the Newtonian paradigm and the purely sensation based, experiential science that the early twentieth century scientists inherited from Mach becomes key to an understanding of their development of and subsequent reaction to the quantum theory.

The quantum theory was born in the work of the German physicist Max Planck. When he entered the field of physics as a young college student, Planck was faced with the prospect of a science that had almost completely mapped nature, with little left to explain. When he entered school in 1875, one of his professors told the eager Planck that "physics is a branch of knowledge that is just about complete...the important discoveries, all of them, have been made."<sup>34</sup> Discouraged but not defeated, Planck began his studies and was soon attracted to the relatively new field of thermodynamics.

In 1895, Plank began to attack the puzzling problem of black-body radiation.<sup>35</sup>

Black-body radiation is the emission of radiation as the result of heating a metal to high temperatures. The theory suggested by classical physics was that the radiation's frequency is directly proportional to the temperature of the radiating body in a continuous way over the entire electromagnetic spectrum. At low temperatures, the metal would emit low frequency radiation in the infra-red region of the spectrum, and vary continuously, with the frequency decreasing as the temperature increased. The great "catastrophe"<sup>36</sup> surrounding the theory was that at the higher end of the spectrum, the energy radiated would be infinite. Experimentation had revealed a sharp drop-off in the frequency spectrum at its high end and infinite energies were a physical impossibility.

After much theoretical and mathematical manipulation, Planck proposed a solution to the problem. Borrowing an idea from Ludwig Boltzman's thermodynamic equations, Plank postulated that the energy emitted by the metal was not continuous but instead was released discontinuously in discrete packages which he named quanta. The energy emitted was directly related to its frequency by the constant  $h$ , which equaled  $6.6E-34$  Joules-seconds, and could only exist in whole number multiples of the quantum unit,  $hf$ , with  $f$  being the radiation wave frequency in cycles per second. Not only did his theory and equations solve the problem of infinite energy, they accurately predicted the experimentally observed high frequency behavior. Planck quickly presented his findings at the October 9, 1900 meeting of the Berlin Physical Society and met with immediate success as he found support and correlation from the

work of a contemporary also involved in black-body theory, Heinrich Rubens.<sup>37</sup>

The idea of energy quantized in discrete discontinuous packages was new to classical physics which placed a premium on continuity and linearity. Planck's quanta received great support five years later when Albert Einstein published his Nobel Prize winning work on photoelectric emission. In his theory he postulated that light, too, was quantized in energy packets which he named photons.<sup>38</sup> The great success with which both Planck's and Einstein's theories predicted and explained experimental results lent great credence to Planck's concept of quantized energy and its discrete discontinuity. The quanta soon intrigued a young Danish physicist, Niels Bohr, who was exploring the nature and structure of the atom.

Bohr had been studying the line emission spectra of atoms trying to find a law by which the location of the emission lines along the frequency spectrum could in fact be understood and predicted. In 1913, following the suggestion of a friend who specialized in spectroscopy, Bohr looked again at the mathematical relationship developed in 1885 by Johann Jakob Balmer for the spectral lines of hydrogen.<sup>39</sup> In his analysis of the Balmer series, Bohr recognized that the mathematical relationship could be rewritten using Planck's constant,  $h$ , which maintained its exact prediction of the spectrum.<sup>40</sup> With this quantum analysis of the hydrogen atom, Bohr began a commitment to the quantum and its primacy that was to dominate the rest of his life.

The first implication of this analysis of hydrogen was no less than a complete change in the way physicists described the atom. In 1911, Ernest Rutherford had developed a model of the atom in which electrons circularly orbited the atom's

nucleus. This model, though, like black-body radiation, had its own catastrophe. According to classical mechanics, such orbits would be unstable, as the electron would continuously lose energy and therefore be a continuous emitter of radiation. Experience and experiment, however, showed that the atom was stable and free of such continuous emission. The model also claimed that the possible electron orbits were infinite in number, varying in size and location about the nucleus according to electron energy.<sup>41</sup> This energy, like that in the classical black-body theory, was assumed to be continuous with all levels equally possible in theory. To Rutherford's model, Bohr applied the quantum. In his resulting new model, the electrons were restricted to orbits by the amount of energy that they possessed and did not give up any energy within an orbit. No longer were all orbits possible.<sup>42</sup> In addition, an electron absorbed or emitted energy only in Planck's quantum packets of  $hf$ . Emission or absorption represented a discontinuous, discrete movement between orbits. Eager for acceptance and recognition, Bohr sent his findings to Rutherford for review and after slight alterations, it was published in an English scientific journal, *The Philosophical Magazine*.<sup>43</sup>

Between his first publication of the quantum atomic model in 1913 and the 1927 formulation of the Copenhagen interpretation of quantum mechanics, Bohr experienced many setbacks and successes concerning the quantum and its application in light of classical mechanics. During this confused period of development, though, he was not alone as the pursuit of the quantum became a community effort centered in Copenhagen at Bohr's institute. Present at the institute was the young physicist,

Werner Heisenberg who was to join Bohr as a pillar of the Copenhagen interpretation with his determination of the uncertainty principle. During his study of the quantum theory at the institute, Heisenberg recognized a relationship between a particle's momentum and position that resolved the problem of measurement within the quantum theory. Experiments at the atomic level had resulted in an imprecise measurement in the value of a particle's energy at any particular moment in time and space, as determined by momentum and position. An experiment that determined position with high accuracy, resulted in an inaccurate measurement of momentum and vice versa. Heisenberg's principle stated that for any measurement involving noncommuting properties such as position and momentum at a specific time, the measured result may be equal to, but no less than,  $h$ , Planck's constant.<sup>44</sup> Energy too was quantum in nature and measurement of it could not surpass the quantum magnitude,  $hf$ , in accuracy. The absolute measurement for which scientists had been striving was suddenly impossible. Heisenberg's theory discovered a universal, mathematical limitation to its accuracy. This formulation of the uncertainty principle in March 1927<sup>45</sup> was to become one of two fundamental principles of the Copenhagen interpretation of the quantum theory. The other principle, that of complementarity, followed a separate but simultaneous development and hinged on a resolution of the wave-particle duality of quantum phenomena.

The resolution of the duality began with the work of Louis de Broglie in 1923. In his Nobel Prize winning work, de Broglie took an assertion made by Albert Einstein and gave it substance and mathematical form. When Einstein introduced the

photon of light in 1905, he succeeded in explaining the question of photoelectric emission, but created as well great confusion in the understanding of the nature of light. In his theory light behaved as a packet or particle of energy, but within the rest of classical physics it behaved as an energy wave. At the time, Einstein had proposed that for radiation like his photoelectric emissions there somehow existed a dual wave-particle nature, but he left his postulate without form. De Broglie applied Einstein's idea for photon behavior to the electron, asserting that the electron particle moved in a so-called "particle wave".<sup>46</sup>

In 1926, Erwin Schrödinger took de Broglie's work and further developed it with his formulation of a system of wave mechanics. An opponent of the quantum and its uncertainty, Schrödinger had hoped to eliminate the quantum discontinuities or "jumps" that electrons in Bohr's model made between stable states. Initially, it appeared that his wave equations did just that.<sup>47</sup> After the analysis and work of Max Born later that year, however, the quantum jumps still remained. In fact, Born had shown that Schrödinger's waves were waves of probability. They gave the probability that a particle would be at a certain position at a specific time rather than the deterministic description of exact position that Schrödinger had hoped for.<sup>48</sup>

As the year 1927 approached, then, the duality of wave and particle remained. Schrödinger and Born had created equations that explained the behavior of electrons as waves but the Bohr model and its equations showed the electron to be a particle that obeyed the  $hf$  quantum of discontinuous energy measurable to Heisenberg's limit of certainty. The answer to the duality, and the second fundamental principle of the

quantum theory was what became known as Bohr's principle of complementarity.

Shortly after Heisenberg's formulation of the uncertainty principle in the spring of 1927, Bohr articulated his ideas. He realized that quantum entities, like the electron and the photon, were simultaneously both particles and waves, but neither was ever one or the other alone. The behavior that was measured in any one experiment was only one facet of the quantum entity's nature. A recognition of the effect that an observer had on an observed object was the key, for Bohr, that linked the two seemingly contradictory behaviors. The behavior observed in the course of any one experiment was dependent on the action of the experiment. That is, the action of observing a quantum object substantively affected that object in such a way as to produce an experimentally dependent result. An experiment such as a double slit diffraction that looks for the wave nature of light (by constructive and destructive wave interference), for example, will always produce as its result a measurement of light behaving as a wave. Similarly, an experiment using photoelectric emission to measure the determinants of a "particle" of light will always reveal the particle behavior of the light. An experiment capable of determining exactly both at the same time is impossible by Heisenberg's uncertainty principle. Any such measurement is a measurement of the quantum entity's energy and is therefore restricted, as is any energy measurement, to the accuracy of the quantum,  $hf$ . A complete knowledge of a quantum entity, then, could only be discovered by accepting all complementary descriptions gained from different experiments as equally revealing of its actual nature under different circumstances.

The principles of complementarity and uncertainty were brought together and publicly revealed as a coherent theory by Bohr and Heisenberg at the Fifth Physical Conference of the Solvay Institute in Brussels in October 1927. The twenty-eight men and one woman present at the conference were among the brightest and most accomplished scientists of the day. Many who had been involved in some way with the development of the quantum theory, such as Max Planck, Wolfgang Pauli and Paul Dirac, were in attendance as were two of the theory's greatest critics, Erwin Schrödinger and Albert Einstein.<sup>49</sup> The dialogue that took place between Einstein and Bohr during the course of the conference was perhaps one of the most significant in the development of the quantum theory. Einstein was an open critic of the theory. He regularly corresponded to his close friend Max Born and expressed his reservations about the completeness and validity of Bohr's theory.<sup>50</sup> He was reluctant to accept any implication of a renunciation of causality. In a December 1926 letter to Born he wrote that

quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but it does not really bring us any closer to the secret of the 'old one.' I, at any rate, am convinced that *He* [God] is not playing at dice.<sup>51</sup>

Einstein clung to the classical physical science belief that the world, as Newton described it, was determined by forces and laws by which total knowledge could be discerned. He could not accept Heisenberg's fundamental uncertainty that Bohr's complementarity required. With each day at the conference came a new round of argument between Bohr and Einstein. Einstein created thought experiments to challenge the quantum theory (most commonly a theoretical apparatus to make a

perfect measurement of energy more accurate than Heisenberg's uncertainty,  $h$ ), and each morning brought a rebuttal from Bohr. With every "experiment," Bohr sought to find a flaw in Einstein's reasoning and thus maintain the validity of the quantum theory. With this debate, Bohr strengthened the quantum theory but never convinced Einstein of its legitimacy. While he would never feel comfortable with the theory and would always be troubled with its lack of determinacy, Einstein did admit its consistency as a serious, though not complete, scientific theory.<sup>52</sup>

After the Solvay Conference and the Bohr-Einstein debate, the quantum theory quickly gained widespread acceptance throughout most of the scientific community. While Einstein, Schrödinger and others were never fully satisfied, the theory proved to be one of the most successful in the history of science. Its explanation of experimental results and observations was comparable to that with which Newton's laws of force and gravity had achieved three centuries before.<sup>53</sup> Bohr wrote, "in the history of science there are few events which, in the brief span of a generation, have had such extraordinary consequences as Planck's discovery of the elementary quantum of action."<sup>54</sup> Also, like Newton's science, the science of quantum theory with its own accompanying philosophy appeared to spill out of science proper into the rest of human experience. Bohr in particular was convinced that his complementarity had greater implications than for quanta alone.<sup>55</sup>

There is little doubt, in fact, that the formulation of the quantum theory shook the foundations of physical science in the early twentieth century.<sup>56</sup> Its suggestion that there was a limit to the accuracy of measurement, and therefore the amount of

knowledge about the world that scientists could discover, was startling. Many, like Einstein, would never fully accept the theory as complete, tolerating it only until a deterministic universal could take its place. For most, though, the quantum theory proved a complete, revolutionary abandonment of the classical physics that preceded it.<sup>57</sup>

A close examination of the writings of Bohr and Heisenberg, however, reveals that the theory was not an exercise in revolutionary science, but instead, one of the most brilliant pieces of "normal" science, as described by Thomas Kuhn, that the world has ever seen.

## CHAPTER 4

### FROM NATURE TO SCIENCE

As explained earlier, Thomas Kuhn's theory of scientific revolution supposes that there exist paradigms of knowledge within scientific communities. These paradigms are both descriptive, giving a basic understanding of the workings of the universe, and prescriptive, providing the framework and method for further discovery. For Kuhn, a revolution in science is achieved with the replacement of paradigm and by nothing less. Though startling in its suppositions and implications, the Copenhagen interpretation of the quantum theory did not achieve such a revolution. It was a product of the Newtonian paradigm which, instead of creating a new paradigm of science, incorporated new refinements into the old. This conclusion is not an obvious one. The question of the nature of the quantum theory is one that both Niels Bohr and Werner Heisenberg struggled with and sought to explain to the rest of the world.

The two fundamental aspects of the quantum theory that provided the classically trained scientist (and the non-scientist brought up in the shadow of the Newtonian paradigm) with such trouble were its redefinition of the relationship between the observer and the observed and its reliance on stochastic, non-deterministic mathematics. These principles formed the heart of the challenge because they were directly related to two precepts to which classical science dearly clung: that of observer independence and the fundamental determinism of reality. Because these

foundations remained in the world-view of the scientific community, their reformulation for the practice of science by the quantum theory did not achieve a replacement of the Newtonian paradigm and was therefore, not a revolution.

As introduced earlier, the quantum theory which Bohr and Heisenberg described recognized that the method of observation was not only critical to an observation, but was part of the observational phenomenon itself. An important part of Bohr's formulation of his theory was the use of the word phenomenon to describe the event and result of observations. He wrote that "as a more appropriate way of expression...[he] advocated the application of the word phenomenon exclusively to refer to the observations obtained under specified circumstances, including an account of the whole experimental arrangement."<sup>58</sup> This choice of wording was important for the understanding of his theory. No longer could the scientist suppose that he or she was an observer completely independent, in observation, of the event or object being studied. The action of measurement or observation changed the pre-measurement state of the observed object according to the nature or structure of the observation. The scientist could deal only with the totality of the phenomena: the observer, the observed and the instrument of observation together. As explained earlier for the wave-particle duality of light, this realization of quantum observational phenomena required Bohr's complementarity. Different sorts of measurements would produce different data sets according to the measurement apparatus used, and all sets would be partially indicative of the nature of the observed.

Bohr recognized that "the feature which characterizes the so-called exact

sciences is, in general, the attempt to attain uniqueness by avoiding all reference to the perceiving subject."<sup>59</sup> This independence formed, according to Bohr, the scientists' ideal of objectivity. For the quantum theory to state, then, that any observation or measurement resulted in a set of data imbedded in the apparatus of observation was to say that the long sought after independence was impossible. For the classically trained scientist, the ideas of independent observation and objectivity were closely linked, and their apparent separation by quantum theory was fundamentally disturbing. Of this connection, Heisenberg wrote that the "mechanics of Newton and all other parts of classical physics constructed after its model started from the assumption that one can describe the world without speaking about God or ourselves,"<sup>60</sup> and with this approach, the scientist aimed for the "'objective' description or explanation" of nature.<sup>61</sup> With the quantum theory, this goal suddenly appeared unattainable. As Bohr wrote, "an independent reality in the ordinary physical sense [could] neither be assigned to the phenomena nor to the agencies of observation."<sup>62</sup> Therefore, there was only one option left for the scientist who held on to the goal of absolute independence in observation, the observation of nothing "natural" at all.<sup>63</sup>

As fundamental to the Copenhagen interpretation of the quantum theory as observer independence was its formulation in the language of statistical mathematics. By its statistical nature, the theory forced a break with the determinism on which classical scientists had relied.<sup>64</sup> As developed earlier, the science developed in the Newtonian paradigm placed a premium on continuity, linearity and exact knowledge. For the classically trained scientists, the world was composed of material particles that

universally obeyed the force laws of Newton. As Heisenberg explained, "what is important for the materialistic world-view is simply the possibility that such small building stones of elementary particles exist and that they may be considered the ultimate objective reality."<sup>65</sup> The result of this view was that science, for the most part, became an attempt to gain perfect knowledge of these particles, and therefore, a complete knowledge of "objective reality." The scientists, then, were to gain knowledge of this particle reality through experiment, and because the particles were ruled by knowable laws, determine the future or reconstruct the past for that small piece of the world. Coupled with the observer dependence recognized and required by the quantum theory, the apparent rejection of this causal determinism, struck a major blow at the philosophy of the classical scientists. This, perhaps more than any other feature of the quantum theory, caused a feeling that the scientific community was revolting against the Newtonian paradigm.

Clearly, the quantum theory departed from classical, mathematical determinism. Bohr repeatedly emphasized this departure and it was the most repulsive aspect of the theory for Albert Einstein. In an April 1924 letter to Max Born, he wrote, "I should not want to be forced into abandoning strict causality without defending it more strongly than I have so far. I find the idea quite intolerable," and if it were to be true, "[I] would rather be a cobbler, or even an employee in a gaming-house, than a physicist."<sup>66</sup> Of the quantum theory, Bohr wrote, it "has not been attained...without a *renunciation of the causal space-time mode of description* that characterizes the classical physical theories [emphasis added]."<sup>67</sup> Because the observer effected the

object being observed in the quantum phenomena, the "chain of causality" was broken. That is, whatever was occurring in the particle reality of the outside world was disturbed and changed by the act of observation. Thus, the scientist could no longer get any independent picture of the deterministic causality which described the life of a particle. Again, Bohr explained that theory

implies a *renunciation* as regards to the causal space-time co-ordination of atomic processes. Indeed, our usual description of physical phenomena is based entirely on the idea that the phenomena concerned may be observed without disturbing them appreciably [emphasis added].<sup>68</sup>

Admittedly disturbing to the classically trained mind, this renunciation of the determinism upon which Newton's paradigm was in part based was in fact only an apparent one, and the above quote from Bohr's essay collection begins to reveal the critical defining factor.

Although the scientific advocates of the Copenhagen interpretation of the quantum theory recognized the observer-observed interdependence and the inability to describe events deterministically, they *did not* give up their belief in the fundamental determinism of the reality of the world. As Bohr wrote, it was the *description* of the world that was indeterministic, not the actual reality of the world. The great realization that the Copenhagen scientists made, then, was that the scientist was unable to measure or describe quantum phenomena in an independent, deterministic manner. They still implied, however, that the material particle reality of the world continued to operate in a deterministic manner independent of their existence. That is, they recognized that there was a fundamental amount of knowledge that they would not be

able to attain. Their renunciation concerned the science that they were practicing. It said nothing about the way in which the world being observed actually operated.

Heisenberg explained in a later essay that "determinism was...preserved in principle," but "in practice...we took account of our incomplete knowledge of physical systems."<sup>69</sup> Addressing this point further, he wrote that the quantum theory

*which is based on Newtonian mechanics...is in principle not a renunciation of determinism. While it is held that the details of events are fully determined according to the laws of Newton's mechanics, the condition is added that the mechanical properties of the system are not fully known.*<sup>70</sup>

The descriptive mathematical determinism was replaced, then, by the statistical probabilistic mathematics of the quantum theory. The language of the scientists changed, but their belief in how the world operated did not. Classical physics was essentially updated or revised. Heisenberg explains that

*the probability function obeys an equation of motion as the co-ordinates did in Newtonian mechanics; its change in the course of time is completely determined by the quantum mechanical equation, but it does not allow a description in space and time.*<sup>71</sup>

Therefore, rather than discovering or articulating a new description of the reality of the world of particles and force laws, the Copenhagen interpretation revised its mathematical language and introduced into science a self-realization of the limitations of the Newtonian paradigm's ability to describe the world.

## CHAPTER 5

### PARADIGMATIC BANKRUPTCY

The significance of the rise of the quantum theory in the twentieth century, then, was not an achievement of a revolution in science. Instead, it was a reformulation of the Newtonian paradigm in a different (statistical) mathematical language and the self-recognition of the limits of the paradigm's ability to gather knowledge of the world. Kuhn's theory of scientific knowledge paradigms stated that the paradigm described the basic world-view of the scientists and gave them the method for completing or exploring the world according to the premises of that world-view. Once the foundations of the paradigm were established, the work of the scientists within the paradigm was Kuhn's "normal science" of applying the vastness of experience in all areas to those foundations.

A revolution occurs, then, only when the paradigm, in its totality, is changed and is replaced with another.<sup>72</sup> The Copenhagen interpretation of the quantum theory did not accomplish this revolution in paradigm. It instead represented the culmination of the paradigm's normal science in its efforts to fit all aspects of nature (in this case nature at the sub-atomic level) into the paradigm. Its recognition of observational dependence and the descriptive non-determinism of the science practiced, illuminated the limits of the paradigm. It represented an emotional revelation to the classically trained scientists who considered their potential for knowing the "objective reality" of

the materialistic world unlimited, but it was not a revolution.

The writings of both Bohr and Heisenberg confirm, in fact, that Newton's paradigm remained intact through the development and eventual, general acceptance of the quantum theory.<sup>73</sup> In his essays, Bohr made this point clear. He wrote,

Indeed, there is no question of a failure of the general fundamental principles of science within the domain where we could justly expect them to apply. The discovery of the quantum of action shows us, in fact, not only the natural limitation of classical physics, but...confronts us with a situation hitherto unknown in natural science...the limit, which nature herself has thus imposed upon us, of the possibility of speaking about phenomena as existing objectively finds its expression, as far as we can judge in the formulation of quantum mechanics.<sup>74</sup>

The paradigm was not attacked by the quantum theory, but the accuracy of its methodology and the mathematical language of its expression were refined.

Heisenberg described this refinement as well when he wrote,

When one considers the basis of the modern [quantum] physics, one finds that it really *does not infringe on the validity* of classical physics. Rather has the necessity, and indeed the possibility, of a *revision* been raised by the *limits encountered in the application of the system of concepts of classical physics* [emphasis added].<sup>75</sup>

In a sense, the quantum theory, particularly in light of the Heisenberg uncertainty principle and the quantum,  $hf$ , of energy measurement, provided a "maximum sharpness of definition of the space-time and energy-momentum"<sup>76</sup> quantities knowable by scientific measurement. Heisenberg explained that "the scientific method of analyzing, explaining and classifying has become conscious of its limitations which arise out of the fact that by its intervention, science alters and refashions the object of investigation."<sup>77</sup>

Thus, it was the recognition of this limit "maximum sharpness" which was so

unsettling to the classically trained scientists and which, with the apparent renunciation of determinism, caused such a feeling of loss and uncertainty within the scientific community that so many believed the theory to be revolutionary. Heisenberg recognized the psychological and emotional implications when he wrote,

Hopes that the extension of man's material and spiritual powers would always spell progress are limited by this situation, if at first somewhat vaguely, and the dangers increase as the optimistic wave of faith in progress dashes against this limitation.<sup>78</sup>

It was a self-conscious recognition about the nature of the science that the classically trained scientists were practicing, not about the way the world worked. Again, Heisenberg wrote of the theory's impact. "When we speak of the picture of nature in the exact science of our age," he wrote, "we do not mean a picture of nature so much as a *picture of our relationship with nature* [original emphasis]."<sup>79</sup>

## CHAPTER 6

### BEYOND THE CLASSICAL FRINGE

Although it did not complete a scientific revolution in the early twentieth century, the Copenhagen interpretation of the quantum theory laid the foundation for one in the late twentieth century. While it revealed the inability of the classical, Newtonian paradigm of science to give a self-consistent explanation for sub-atomic behavior, the quantum theory did not provide the new description of nature, the new paradigm, required for a scientific revolution.

For the scientists of the Copenhagen interpretation, the quantum theory was a negative statement concerning the classical paradigm's limited ability to describe the world. While they believed that the world was fundamentally deterministic and operated independently of humankind, the quantum theory showed them by way of experimentation that the *science* of the paradigm was in fact dependent upon the observer and, moreover, fundamentally indeterministic. That is, the practice of science was a human interaction with nature that had fundamental operational limitations. Heisenberg's uncertainty principle limited the measurement of non-commutating deterministic properties, such as position and momentum, to the accuracy of  $h$ . Bohr's complementarity revealed that the way a scientist looked at, or measured nature influenced and therefore limited the experimental results. Classical science had fundamental limitations against which its practitioners continually fought in the pursuit

of a complete description of the Newtonian force-particle universe.

The theories articulated by the Belgian chemist Ilya Prigogine and the Brussels school of thermodynamics, however, have the potential to complete a scientific revolution because they constitute an entirely new paradigm. Termed dissipative structures theory, his work provides a different view of how and why the world operates, and that view entails a new focus for all science. An important result of Prigogine's theories is the way in which they deal with the existence and results of the quantum theory. In direct contrast with the Copenhagen interpretation of the quantum theory's negative statement, Prigogine makes a revolutionary step by reconceptualizing the quantum theory as a positive statement for the reformulation of a new science. He is able to do this because of the new world picture that his theory incorporates. As developed earlier, the Newtonian force-particle world was a deterministic one which operated independently of the actions of humankind. The classical scientist's job in explaining nature was to remain objectively independent from observation. Prigogine's science, however, assumes a fundamentally random rather than deterministic world in which human scientists are participants.

Within this new paradigmatic framework, the results of the quantum theory appear in a new light. What were *limitations of science* that represented the loss of information and inability to describe nature for Bohr, Heisenberg and Born become, for Prigogine and the dissipative structures theorists, the *attributes of nature*.<sup>80</sup> For the Copenhagen scientists constrained by the classical paradigm, the indeterminacy and observational dependence revealed by the quantum theory forced them to speak no

longer of nature, but of man's relationship with nature.<sup>81</sup> That is, within the classical paradigm, the quantum theory could only describe the practice of science. Heisenberg wrote that, "the mathematical formulas indeed no longer portray nature, but rather our knowledge of nature."<sup>82</sup> No longer able to reveal nature's secrets completely, science had become humankind's "argument with nature."<sup>83</sup> The paradigm established by dissipative structures theory, however, incorporates the quantum theory as not only a description of science, but a key insight into how nature itself works. With a new paradigm, Heisenberg's negative argument with nature becomes Prigogine's positive "dialogue with nature."<sup>84</sup>

Kuhn recognized in his theory of scientific revolution that a paradigm shift requires a change in the entire world perception of its practitioners. With such a shift, what was meaningless, insignificant or anomalous is likely to take on new meaning and importance. In addition, Kuhn's theory implies that what were limitations on science are likely to become key factors in its redefined practice. With the paradigm shift suggested by Prigogine's theory, the quantum theory undergoes such a reversal in meaning. But the quantum theory is not the only major theoretical body of work affected. Dissipative structures theory also appears to successfully address the science of thermodynamics and Darwin's theory of evolution, both of which remained outside of the classical paradigm as inexplicable contradictory anomalies. In order to best understand Prigogine's work, it is necessary to briefly examine histories of thermodynamics and evolution, their relationship with the Newtonian paradigm and with each other.

Charles Darwin developed his theory of biological evolution in the mid-nineteenth century building on the work of his grandfather Erasmus, the French biologist Jean Baptiste Lamarck, and the Scottish geologist Charles Lyell.<sup>85</sup> Based on the extensive observational research that he conducted on his 1831-1836 voyage on *HMS Beagle*, Darwin identified the process of natural environmental selection in speciation. Natural selection was the mechanism which "preserves beneficially varying forms of existing species, while...continued selection,...compounds some of them into new species."<sup>86</sup> Published in *The Origin of Species* (1859), Darwin's theory of evolution had immediate and substantial impact.<sup>87</sup>

While classical science was searching for simplicity through reduction by means of time-reversible mechanical laws, Darwinian evolution placed the existence of life's variety and complexity in a time-directed process of increasing organization. Attempting to practice strictly modern science, Darwin identified the mechanism of natural selection, the environment acting like a Newtonian force on members of different species, in the process of evolution. Though similar to Newtonian universals, natural selection and evolution revealed significant differences between the biological and mechanical worlds. Local, *random* variation, directional time, and system process were the non-Newtonian features of nature that evolution demanded.

Such differences clearly placed the theory of evolution outside of the classical scientific paradigm. But unlike the quantum theory, evolution did not cause great opposition in the scientific community. In the mid-nineteenth century, classical science had yet to be successful in its attempt to explain the study of biology in terms

acceptable to the classical paradigm. Evolution had made life a valid scientific question, and Darwin was attempting to explain life in the Newtonian paradigm. Natural selection was the mechanical process acting on the matter of biological organisms. For most scientists, then, evolution was a necessary if not yet sufficient explanation for a body of experience that could be, but had not yet been fully explained in terms of Newtonian force-particle laws.<sup>88</sup> The attempt to fit life into the paradigm, however, failed.

As classical science continued to address biology and life in a more rigorous fashion, the science of genetics was created (c. 1900).<sup>89</sup> With its reducible molecular chemistry and discovery of genes, genetics gave much insight into certain aspects of living organisms and eventually identified the record of Darwinian evolution in DNA structure.<sup>90</sup> Although this application of the classical paradigm to life resulted in spectacular applicative advances like those of quantum science, it failed to consistently explain the phenomenon of life. Evolution was shaping life with a non-reducible, irreversible sequence of increasing order, and biological organisms displayed system properties that reduction could not explain. Despite their confidence in the science, moreover, genetic reduction identified certain component parts of living organisms but failed to explain their origin or their totality.

In a similar way, thermodynamics developed outside of the Newtonian paradigm during the mid-nineteenth century. Historically an almost entirely experimental pursuit with little attention having been paid by its earliest practitioners to the development of a complete theory, the theoretical science of thermodynamics

was founded by Rudolf Clausius in 1850.<sup>91</sup> With the publication of his first paper, "*On the motive power of heat and on the laws which can be deduced from it for the theory of heat*," in that year, he established the science of thermodynamics out of the historical jumble of experimental record and incomplete theory.<sup>92</sup> Building on the work of great experimentalists such as Carnot, Kelvin and Joule, Clausius unified "previously disparate theories"<sup>93</sup> into two coherent theoretical laws, later named the first and second laws of thermodynamics. In 1854, he identified the "property now called entropy,"<sup>94</sup> completing the science's foundation.

Successful particularly in its technological applications, thermodynamics, like the quantum theory, was validated by experience but was inexplicable within the classical paradigm. Based fundamentally on the behavior of large numbers of particles and their macroscopic group properties such as heat, pressure and density, thermodynamics failed to provide a specific and deterministic explanation of experience by means of Newtonian forces and reducible particles. It was viewed by scientists of the day as a non-rigorous, somehow incomplete science which, by increased accuracy of experiment and new theory, could later be reconciled with classical physics.<sup>95</sup>

A "phenomenological" science, thermodynamics gave "no intuitive feeling of causality," leaving classically trained "science students brought up to analyze all experiences in terms of their causes" feeling uncomfortable.<sup>96</sup> In addition to its non-reducible, macroscopic nature, the second law of thermodynamics presented the classical paradigm with an equally unsolvable problem. Although it was originally

articulated with respect to the efficiency of heat engines, the essence of the second law stated that for any process, there is an irreversible change in energy such that the total measure of entropy increases. As originally conceived by Clausius, entropy was to be a measure of available energy in a system;<sup>97</sup> more generally, however, it is "a measure of disorder or randomness".<sup>98</sup> As one of the fundamental laws of thermodynamics, the second law, describing nature's irreversible movement towards disorder, helped to place the science even further outside the reversible classical paradigm. Moreover, it appeared to absolutely contradict the ever increasing order and structure of Darwin's evolution.

After the advances of Clausius's laws, thermodynamics made steady progress in the explanation of experience but was still unsuccessful in terms of the classical paradigm. Near the turn of the century, as the foundations for the quantum theory were being laid, Ludwig Boltzman developed his explanation of the behavior of large groups of particles with his statistical mathematics and now famous distribution curve. Though his attempt was to explain thermodynamic "group" properties in terms of their constituent particles with Newtonian mechanics, he succeeded instead in showing, as did the quantum theory, what the paradigm could *not* successfully explain through its process of reduction. His results, in fact, created a new anomaly for the classical paradigm, statistical thermodynamics.<sup>99</sup> Peter Atkins wrote in The Second Law that Boltzman "traveled to thermodynamics from the atom, the symbol of emerging scientific fundamentalism."<sup>100</sup> Because he could not reduce his explanations of thermodynamic properties to the individual particle and further introduced probability

instead of determinism, Boltzman's attempt within the classical mechanical paradigm failed.

Describing Boltzman's effort, Atkins noted, "many of his contemporaries doubted the credibility of his assumptions and his argument, and feared that his work would dethrone the purposiveness which they presumed to exist within the workings of the deeper world of change, just as Darwin had recently dispossessed its outer manifestations."<sup>101</sup> Statistical thermodynamics posed a threat to the determinism of nature as seen by the Newtonian paradigm and revealed one of the paradigm's weaknesses. What thermodynamics showed, in fact, was another failure of self-consistency within classical science. Percy Bridgman wrote in The Nature of Thermodynamics that thermodynamics' "guiding motif is strange to most of physics: namely a capitalization of the universal failure of human beings to construct perpetual motion machines." While perpetual motion machines were not the goal of classical mechanics, their existence by strictly classical Newtonian theory, should have been a possibility.<sup>102</sup> The second law had shown that they were instead an impossibility. In much the same way Einstein and Schrödinger justifiably saw acceptance of the Copenhagen interpretation as a recognition of a failure of the Newtonian paradigm, full acceptance of thermodynamics without further reduction would have signaled another failure for classical science.

At the beginning of the twentieth century evolution and thermodynamics represented two large and coherent bodies of scientific work that apparently could not be reconciled with each other or with the Newtonian paradigm. Both were the results

of attempts to extend classical science into previously unaddressed areas of experience, life and heat flow. Both required a temporal direction but toward apparently irreconcilable ends, the ever increasing thermodynamic disorder of entropy and the continual progression of evolutionary order. An examination of these phenomena from within the classic paradigm revealed aspects of nature which could not be exclusively reduced to and fully explained by Newtonian force-particle laws alone. It is in this sense that they joined the Copenhagen interpretation of the quantum theory as anomalies, that is as unclassifiable experiences within the classical paradigm. Of the three, the quantum theory was the most disturbing to the scientific community, and most revealing of the anomalies because it failed to explain the very essence of the Newtonian paradigm, fundamental particle reality, in a manner consistent with the paradigm itself.

## CHAPTER 7

### PRIGOGINE AND THE BRUSSELS SCHOOL

While the dissipative structures theory of Ilya Prigogine addresses the microscopic world sought by classical physics, it did not begin in or rely on the microscopic realm for a scientific understanding of nature. Instead, Prigogine's work was born in thermodynamics, the "anomalous" science of the macroscopic. In direct contrast to the Copenhagen scientists who resigned themselves to speaking only of the science they were practicing, Prigogine sought once again to describe nature.

Thermodynamics provided a different conceptual framework from which to begin a new study of the world, a study which fundamentally *included*, rather than excluded, time, irreversibility and humanity from nature. It is not surprising that a new science which was fundamentally different from the Newtonian paradigm should have arisen from one of its major anomalies. As anomalies, they attracted further study, both scientific and philosophical. Of thermodynamics, Bridgman wrote, "it must be admitted, I think, that the laws of thermodynamics have a different feel from most of the other laws of the physicist. *There is something more palpably verbal about them - they smell of their human origin* [emphasis added]."<sup>103</sup>

The more human aspect of nature that Bridgman and later Prigogine recognized in thermodynamics was similar to that relationship recognized by Bohr and Heisenberg in the quantum theory. Bohr repeatedly emphasized science's dependence upon

language<sup>104</sup>, and Heisenberg noted that, "in science....the object of research is no longer nature in itself but rather nature exposed to man's questioning, and to this extent *man here also meets himself* [emphasis added]."<sup>105</sup> Prigogine's theory of dissipative structures reveals that both the science of thermodynamics and the observer dependence of the Copenhagen interpretation of the quantum theory had recognized the same attribute of nature. Science and nature were part of a system and therefore, by definition, dependently interactive. The difference in appreciation of this point arises, then, because Prigogine and the Copenhagen scientists approached it from two different conceptual vantage points, two different paradigms.

Prigogine recognized that the world of human experience was one of constant system interactions and complexity and that classical laboratory idealizations were just that, idealizations. Scientific reality for Prigogine would lie in the attempt to understand nature as it actually worked, as a self-consistent whole without idealizations and exceptions. F.C. Andrews wrote in Thermodynamics: Principles and Applications that, "it must be emphasized that thermodynamics treats *real* systems made up of *real* matter. There is nothing idealized about the subject thermodynamics studies."<sup>106</sup> Andrews, a classically trained thermodynamicist, refrained from addressing the philosophical implications of this statement, simply recognizing that "the main reason a macroscopic science is useful is that we live in a macroscopic world."<sup>107</sup>

Though Prigogine would agree with Andrew's analysis of the utility of thermodynamic science, his theories force the philosophical discussion of reality that

Andrews avoided. The potential of his dissipative structures theory to cause a philosophical realignment concerning the nature of scientific reality give Prigogine's science a legitimate claim to initiating paradigmatic scientific revolution.

Prigogine's theories are in part a reflection of the temporal and physical scientific environment in which he was a student. Having fled from the Bolsheviks in his native Russia and later from the Nazis in Germany, Prigogine settled in Belgium as a young man. There, as a university student, he was exposed to the applications-oriented thermodynamic science of the Brussels community. His mentor and professor was Theophile De Donder, who developed the concept of chemical affinity<sup>108</sup> and the early mathematical formulations for non-equilibrium states that defined the Brussels school of thermodynamics.<sup>109</sup> Under his direction, Prigogine pursued the study of non-equilibrium thermodynamics.<sup>110</sup> Building on De Donder's work with his colleague Raymond Defay, Prigogine laid the mathematical and theoretical foundation for his dissipative structures theory.<sup>111</sup> Apparently influenced by the paradoxes raised by the quantum theory and the seeming incapacity of classical dynamics to explain biological systems,<sup>112</sup> he continued theoretical work on non-equilibrium thermodynamics. Shortly after the end of the second World War, he developed the early mathematical models of ordered systems within non-equilibrium thermodynamic flows later termed "dissipative structures."<sup>113</sup>

The philosophical foundations of dissipative structures rest with Prigogine's recognition that classical science, by essentially ignoring irreversibility and non-equilibrium states, was operating with assumptions that ran contrary to fundamental

human experience. The classical treatment of time was one such pivotal assumption. Within the Newtonian paradigm, time was not an attribute of nature, but a convenience of record. Despite the reality of time in human experience, it was, for the scientist, only the marker by which one could measure the action of a force on a particle. Albert Einstein was convinced of time's reversibility and referred to time itself as a subjective "illusion."<sup>114</sup> Prigogine was convinced otherwise. He wrote that

great thinkers such as Einstein, Bergson and Heidegger, in spite of their differences, hold as a common belief that time irreversibility is not and cannot be the object of science proper...[this] has always amazed me: time is for us the main phenomenological and existential dimension; to say that it is an illusion is, in a sense, an extraordinary expression of faith in symbolic thinking.<sup>115</sup>

It was an extraordinary expression of faith that Prigogine was unwilling to make. For him time was essentially real and therefore irreversible, and his science has pursued in part, a "rediscovery of time."<sup>116</sup>

Prigogine's paradigm shift began with a reexamination of the second law of thermodynamics. Where the second law before had been considered an approximation or even subjective, Prigogine recognized that Clausius's statement of entropy increase was in fact a universal law in application concerning the entirety of the natural universe.<sup>117</sup> That is, it is the entropy of the *universe* as a whole that must always tend to a maximum. Prigogine's theoretical confidence in Clausius's law was key to his claim that dissipative structures theory had the potential to unify the previously contradictory statements of entropy and evolution, and irreversible time is its logical by-product. If the entropy of the universe is constantly progressing in an irreversible

direction of increasing magnitude, then it becomes the measure or indicator of an irreversible progression that humankind has recognized as time. The past and future are not simply distinguished by the replacement in a classical equation of  $t$  with  $-t$ ,<sup>118</sup> but instead are the reality of the universe's own development. The second law, Prigogine said, prohibits the reversal of time in theory and practice because it creates an "infinite entropy barrier."<sup>119</sup> For a reversal of time, which for classical physics was theoretically as easy as a sign change, the entire universe would have to be replaced in exactly the same prior entropic state. No longer would only dynamic trajectories have to be reversed, but in addition all entropic energy conversions. For an infinite universe filled with fundamentally irreversible energy conversions, with frictional heat loss as the simplest of examples, entropic reversal becomes an infinite, and therefore impossible, requirement to overcome.

Prigogine provided a revised role for the second law. Obviously, he continued to recognize entropy as an indicator of the universe's development, but he was now able to reconcile entropy with local, system, and biological evolution. He theorized that while entropy must increase for the universe as a whole, there could be local variations in entropy. For a particular thermodynamic system, total entropy would be the sum of the entropy exchanged between the system and its environment and the internal entropy produced within the system, that is,  $dS = d_e S + d_i S$ .<sup>120</sup> This formulation allows the possibility of low or even zero entropy production,  $d_i S$ , in any particular locality as long as the entropy exchanged between a system and its environment,  $d_e S$ , is positive. Prigogine explained that

although  $d_i S$  is never negative, the flux term  $d_e S$  has no definite sign. As a result, during evolution a system may reach a state where [system] entropy is smaller than at the start... Thus, in principle at least, if we supply a system with sufficient negative entropy flow, we can maintain the system in an ordered state.<sup>121</sup>

Despite the requirement of the second law for increasing universal entropy, a locality could sustain order by maintaining an energy exchange with its environment.

Entropy for Prigogine, then, became the price of order in a system rather than merely a measure of its cascade into disorder.<sup>122</sup> In a situation similar to that of the quantum theory, the classical concept of entropy was a negative statement of the inability of science to gain complete knowledge and therefore complete control of thermodynamic systems. In contrast, as the price paid to maintain order, a signal of energy spent constructively, entropy within Prigogine's science became a positive indicator of the universe's irreversible evolution.

Working with this concept of entropy, Prigogine continued to examine non-equilibrium thermodynamic flows. He found that far from equilibrium, random fluctuations played a much different role than they did near or at equilibrium. Classical thermodynamics had shown that systems near equilibrium were dynamically stable, that is, random fluctuations were dampened as the system's steady-state conditions were maintained or remembered. For these systems, any oscillation was about the steady-state, and the initial conditions which created the system became unimportant; they were "forgotten."<sup>123</sup> As a system was driven far from equilibrium, however, fluctuations began to drive system behavior.<sup>124</sup> "At some critical distance from equilibrium," as the system developed along the "thermodynamic branch" that

remains stable into the "non-equilibrium range," the system reached a bifurcation point.<sup>125</sup> This point was a moment of stochastic change in the system from development along the stable thermodynamic branch to development along one of several other possible new branches of stable non-equilibrium order. At such a bifurcation, only the random fluctuations were responsible for the "choice" between possible new ordered states.<sup>126</sup> As Prigogine explained,

the system obeys deterministic laws, such as the laws of classical kinetics, between two bifurcation points, but in the neighborhood of the bifurcation points fluctuations play an essential role and determine the 'branch' that the system will follow.<sup>127</sup>

Because the mechanism of "choice" at a bifurcation point was a random fluctuation, a stochastic event, it would be impossible to return to, or determine, the original thermodynamic branch from the post-bifurcation system characteristics. The fluctuation, then, was *creative and irreversibly recorded by the system* in the new state of non-equilibrium order. It was this non-equilibrium order that Prigogine termed "dissipative structures."

Fully defined as the spatial and temporal organizations that irreversibly record random fluctuations at bifurcation points and survive due to their exchange of entropy with the surrounding flow,<sup>128</sup> dissipative structures are radically different from equilibrium states. As noted, equilibrium states maximized internal entropy in the *destruction of spontaneous fluctuations and the "forgetting" of initial conditions*. In contrast, the non-equilibrium dissipative structures minimized internal entropy production creating internal order that "remembers" the initial conditions that caused its creation at the expense of high rates of entropy exchange with the environment.

Prigogine wrote that

in addition to the coherent character exhibited by such states, one can show that the final configuration depends to some extent on the type of initial perturbation. This primitive memory effect makes these structures capable of storing information accumulated in a remote past.<sup>129</sup>

With its resulting creation of a dissipative structure, Prigogine noted, "the bifurcation introduces history into physics and chemistry, an element that formerly seemed to be reserved for sciences dealing with biological, social, and cultural phenomena [original emphasis]."<sup>130</sup>

## CHAPTER 8

### THE CONTEMPORARY CLAIM TO REVOLUTION

Particularly clear in his book Order Out of Chaos, co-authored with Isabelle Stengers, Prigogine has articulated his scientific findings and philosophy in such a way as to make a claim of paradigmatic scientific revolution based on his theory and work. In order to historically judge this claim, Prigogine's paradigm must be subjected to a similar examination that earlier revealed the inadequacies of the Newtonian paradigm. Historically, Prigogine's theories must not only be self-consistent, they must be able to resolve or philosophically have the potential to resolve the anomalies of Newtonian science.

Founded on a world-view that is fundamentally different from that of Newton and the classical paradigm, Prigogine attempted to successfully meet these requirements. His world of process and irreversible qualitative change contrasts sharply to Newton's "clockwork universe," in which reality was found in "changeless substances such as atoms, molecules or elementary particles," and "their locomotion."<sup>131</sup> Because nature was classically thought to be composed of these particles and their behavior, Newtonian reality lay in the microscopic realm, and complete knowledge of nature would lie in complete knowledge of her constituent, fundamental particles. The search for such reality led classical science to what has been termed the "myth of complete knowledge."<sup>132</sup> The truth of nature was slowly

but surely revealed by means of Newton's laws and their derivatives. With enough work and enlightened theory, science would achieve perfect knowledge of the universe as theorized by Pierre Simon de Laplace. In his work, A Philosophical Essay on Probabilities, he wrote that,

an intelligence which, at any given instant would know all the forces by which Nature is animated, and the respective situation of all the elements of which it is composed, if furthermore it were vast enough to submit all these data to analysis, would in the same formula encompass the motions of the largest bodies of the universe, and those of the most minute atom: nothing for it would be uncertain, and the future as well as the past would be present to its eyes.<sup>133</sup>

To be sure, nineteenth century scientists had not achieved the "Laplacean illusion," but to the extent that parts of nature had been reduced to mathematically described mechanical models, scientific knowledge was, as Galileo said, equal to God's. For classical science, then, the world was fundamentally, philosophically deterministic. It would take time to complete the scientific description of nature, but eventually, perfect knowledge of a particle would reveal perfect, *timeless* knowledge of nature.

The Copenhagen interpretation of the quantum theory was a critical turning point for both the Newtonian and Prigoginian paradigms. Historically, the quantum theory made such an impact on modern science because at the same time it made great applicative advances, it struck at the logical, philosophical foundation of the Newtonian paradigm. Bohr's complementarity, Heisenberg's uncertainty and Born's waves of quantum probability revealed that the Laplacean illusion was in fact, fundamentally impossible. While the quantum theory left the foundation of the paradigm intact, it changed the scientist's perception of the science practiced. Science

was for the first time fully exposed to its practitioners, no longer transparent, complete or deterministic in its mathematical modeling of nature. When science could no longer deliver perfect, timeless, ordered knowledge of nature, the unchallenged intellectual security that it had provided its practitioners was lost.<sup>134</sup>

The quantum theory, a self-revelation for classical science, becomes an important catalyst in Prigogine's revolution. Because the Copenhagen scientists substituted a description of the science they were practicing for the description of nature, the quantum theory left the Newtonian belief in a mechanical force/particle world intact. Accepting this change in focus and lacking a viable, alternate world-view, the classical paradigm approached philosophical bankruptcy. Instead of accepting a bankrupt science which could no longer explain nature, Prigogine turned to look again at nature, adopting a new world-view qualitatively different from that of the classical mechanical one. Because it was a qualitative change, classical roles and assumptions were radically changed or even abandoned. For Prigogine, time was a reality of nature not a scientific illusion or construct which, moreover, recorded the transformation of nature as complexity increased. Reality could be found in process and interaction, within and among systems, in a world that was fundamentally irreducible, random and historically evolving.

Spontaneous, self-organizing Bénard convection cells and other dissipative structures gave Prigogine the first experimental, physical evidence of a completely natural process of qualitative change in matter. If the world were, as the Newtonian paradigm presupposed, fully deterministic, then such qualitative change would be

inexplicable. The great intelligence imagined by Laplace would be able to determine the exact location and momentum of all the fundamental particles of the universe, but in its mechanical world, would be unable to describe, or recognize as real, the form and organization of that those particles. Laplace's demon would be able to recognize only large quantities of particles in close proximity to each other, but would fail to provide any explanation as to the system created by those particles. If, however, as the theory of evolving dissipative structures suggested, the matter of the world were subject to real, qualitative change, the reality of nature would lie in the time directed, evolving processes shaping and organizing a system of matter, not in the matter itself. The system and its structure define the reality of the matter found within. For Prigogine, there is no "dead" or inanimate matter. The world is full of interacting systems which process flows of energy and matter.

With his claim that the reality of nature lies in processes and qualitative change instead of changeless fundamental particles of matter, Prigogine created the world-view necessary for a new, non-Newtonian paradigm. While the science of dissipative structures and far-from-equilibrium thermodynamics provides scientific support to this claim, the new science's reconciliation of the anomalies of the Newtonian paradigm provides historical validity. As outlined earlier, the mechanistic determinism of the Newtonian paradigm could not explain the irreducible processes of thermodynamics and evolution. Both the universal increase of entropy dictated by the second law and the increase of order in evolution were processes which required a real, directed time contrary to the reversible time of Newton. Furthermore, the two processes stood in

conflict with each other in seemingly irreconcilable contrast. Dissipative structures showed Prigogine, however, that entropy was not an indicator of disorder, but in fact, was the indicator of an evolving ordered system. The maintenance of a dissipative structure required external entropy production, and its evolution depended on its reorganizing to produce external entropy at a higher rate. Incredibly then, increased evolution required increased entropy.

Prigogine's claim is also strengthened from the historical point of view because it incorporates Newtonian science into the new paradigm and makes logical, self-consistent sense of the quantum theory. Prigogine recognizes that Newtonian mechanics is very accurate in describing certain areas of nature. Specifically, Newtonian science applies to idealized situations in which irreversible processes are ignored. Recognizing the limited applications for Newtonian science particularly highlighted by the quantum theory, Prigogine's paradigm does not exclude or destroy classical work. Instead, Newton's idealizations are accepted into a more encompassing theory. Prigogine wrote that "the usual formulation of classical (or quantum) mechanics has become 'embedded,' in a larger theoretical structure, which also allows the description of irreversible processes."<sup>135</sup> According to Prigogine, this larger theoretical structure allows for the fusion of two visions, the unification of dynamics and thermodynamics.<sup>136</sup> For simple systems such as a pendulum, or for an idealized approximation of certain natural systems, one need look no further than Newtonian dynamics. But if dynamics is the only reality of nature, organization, structure and certainly biological systems become inexplicable. If, however, dynamics fits into a

larger framework, different descriptions of nature's many levels are possible.

From the perspective of his new paradigm, Prigogine was able to explain consistently the conclusions of the Copenhagen interpretation of the quantum theory. As mentioned earlier, Prigogine recognized that the negative limitations that Copenhagen placed on the practice of science in the Newtonian paradigm were the positive attributes of nature itself. The laboratory scientist, in making an observation of the system (nature) to which he or she belongs created information in the recorded "phenomenon" of measurement. For the Copenhagen scientists, this meant a loss of information and an inaccessibility to the reality of undisturbed nature. However, the actions of the atomic scientist searching for the fundamental particle were, for Prigogine, no different from any other natural process. In dissipative structures Prigogine had demonstrated how a similar self-observation (random fluctuation or collision) within a thermodynamic flow could create, irreversibly, a record of its occurrence. In both cases an interaction, an observation, occurred and the price of the information created by the process was an increase of entropy, that is, the irreversible dissipation of some energy.

For Prigogine, then, science is a process which exemplifies the reality of nature. As the Copenhagen scientists correctly recognized, scientific measurement is a dependent rather than independent activity and this activity creates reality (an observation, a pointer reading) out of random possibilities. Again, the information gained by this interaction is gained at the expense of energy dissipated irreversibly. Where Bohr and Heisenberg stopped short of applying these findings of the quantum

theory to nature, Prigogine continued. Within his new paradigm, not only is science quantum theoretical, nature is quantum theoretical. Nothing in nature is completely independent of its environment. Nature, in fact, is the continuous interaction and transformation of the energy and matter of the universe. The price of this constant and irreversible evolution is energy dissipation and the increase of universal entropy. The Copenhagen uncertainties which limit deterministic measurement are understandable only if humans are part of this natural evolution of the universe. If human life is natural then as members of the system of interactive, evolving processes called nature, scientists cannot have perfect knowledge of the whole system. From within a system, total knowledge of the system is by definition impossible. Prigogine has quoted Paul Valéry writing that "determinism is only possible for an observer outside his world while we describe the world from within."<sup>137</sup>

## CHAPTER 9

## CONCLUSION

With his formulation of universal mathematical laws describing a materialistic world-reality and the experimental method for investigating that world, Sir Isaac Newton created a paradigm of science, in 1687, that dominated for over two centuries. As theorized by Thomas Kuhn in his 1962 treatise on scientific revolution, Newton's paradigm gave its scientists all the "conceptual boxes" into which they attempted, for the three centuries following the publication of the Principia Mathematica, to fit their experimentally gained experience of the world. Against the expectations that they derived from the paradigm, the scientists of the eighteenth, nineteenth and twentieth centuries weighed experimental anomalies in the process of applying the paradigm's principle foundations to all areas of scientific pursuit. For the majority of the time, this "normal science" proceeded without crisis, even with the extension of the paradigm to areas of experience almost completely foreign to Newton's mechanics, as with James Clerk Maxwell's formulation of electromagnetic theory. In the early twentieth century, however, the paradigm received its most legitimate and defining challenge with the development of the quantum theory. The crisis surrounding this challenge, however, has laid the foundation for a new paradigm, based on the revolutionary work of contemporary scientists of the Brussels school of physical chemistry and thermodynamics.

With their formulation of what became known as the Copenhagen interpretation of the quantum theory in 1927, Niels Bohr and Werner Heisenberg shook the foundations of the Newtonian paradigm to such an extent that many believed that paradigm to be obsolete. Bohr's complementarity and Heisenberg's uncertainty principle combined to challenge the classical scientists' fundamental views of the science they were practicing. The paradigm they inherited, through the philosophical filter of Ernst Mach, placed a premium on the absolute independence of the observer for objective measurement and the fundamental determinism of Newton's materialistic force-particle world. While the reality of the observer-observed interdependence that the quantum theory recognized was generally accepted, when combined with the apparent loss of determinism and the fundamental limit on man's progress towards complete knowledge, the quantum theory created a great feeling of loss and uncertainty in the scientific community. Considered by many to be a revolution which demonstrated the obsolescence of the Newtonian paradigm, the quantum theory instead represented the ultimate self-recognition by the scientific community of the limits of that paradigm.

Access to whatever, ultimately existed in reality was lost, in principle and forever. What scientists described in the sub-atomic realm was not nature but the result of their own probing. Objective instrument readings in laboratories depended on the effects of selected pieces of macroscopic apparatus from the scientists' world of experience interacting with microscopic nature. These results could never be thought of as existing "naturally." So far as anyone would know, by experimental observation,

results only existed when scientists precipitated them. Thus laboratory observations were artifacts of scientific inquiry that stood between scientists and nature. Science now became an obstacle to actual knowledge of nature, which could never be accessed directly. This meant that the Copenhagen interpretation of the quantum theory left the world as either dependent on the scientists observations for its existence or as only existing because of events or realities of which scientists were forbidden to ever have complete knowledge. The world had become either a dream or a measure of our ignorance.

Thus, the loss of determinism in the Copenhagen interpretation was seen to be a loss in the determinism of the scientific description of a Newtonian world that could still be fundamentally determined. The quantum accuracy and the inescapable link between the observer and the observed became recognized as the definitional limits of the practice of this non-deterministic method. Yet the world was still implicitly full of materialistic particles ruled by universal mathematical laws, as Newton established. Bohr explained, "there is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature."<sup>138</sup> With the quantum theory, then, the language of the paradigm's laws changed, and the hope of the unlimited potential of the paradigm to describe the world was dashed against the limitation of the quantum.

There is little doubt that the quantum theory exposed the ultimate limitation of the Newtonian paradigm for explaining and describing the world-view in which its

practitioners believed. There is little doubt as well that the recognition of this limitation caused great uncertainty and emotion in the scientific community. For the scientists who participated in the development and articulation of the quantum theory, Heisenberg noted that

this violent reaction on the recent development of modern physics can only be understood when one realizes that here the foundations of physics have started moving; and that this motion has caused the feeling that the ground would be cut from science. At the same time it probably means that one has not yet found the correct language with which to speak about the new situation.<sup>139</sup>

As Kuhn defined in his theory, it is the lack of this new language to describe experience that kept the quantum theory from achieving a revolution in science. According to Kuhn, a revolution requires the existence of at least two paradigms between which a faith level choice is made.<sup>140</sup> While the scientists of the Copenhagen interpretation recognized the inability of their paradigm to fully and completely describe the world, they failed to offer any alternative. The shock of the revelation created part of the blockage that stopped a new paradigm from developing, and the continued belief in the fundamental tenets of Newton's paradigm furnished the remainder.<sup>141</sup> Heisenberg's attempt to explain the impact of the theory reveals the strains of Mach's influence on these scientists which helps to explain their final reaction to the anomalies that the quantum revealed. He wrote that

we have had to forego the description of nature which for centuries was considered the obvious aim of all exact sciences. All we can say at present is that in the realm of modern atomic physics we have accepted this state of affairs because it describes our experience adequately.<sup>142</sup>

Because they could no longer consider their instrumental measurements to be realistic,

these scientists described their experience in a logical, non-contradictory manner as Mach had prescribed. The result was that their paradigm became self-aware of its interaction with, instead of independence from, the rest of the world. With this awareness, the scientist was no longer explaining nature, but man's relationship with nature. Heisenberg summarized, writing that

the objective reality of the elementary particles has been strangely dispersed. not in the fog of some new ill-defined or still unexplained conception of reality, but into the transparent clarity of a mathematics that no longer describes the behavior of the elementary particle but only our knowledge of this behavior. The atomic physicist has had to resign himself to the fact that his science is but a link in the infinite chain of man's argument with nature, *and that it cannot simply speak of nature 'in itself.'*<sup>143</sup>

If taken into consideration with the nineteenth century anomalies of thermodynamics and Darwinian evolution, the "quantum revelation" signals the failure of the universal claims made for the Newtonian paradigm. Because the lack of an alternative paradigm forced the practitioners of science to accept their now limited science,<sup>144</sup> the scientific community entered a period of philosophical crisis in which new, extra-paradigmatic science could flourish. The Belgian chemist Ilya Prigogine has been a leader in research and theory in such non-traditional domains. Prigogine's work departed from the classical paradigm by establishing its basis in the "anomalies" of thermodynamics and evolution. Study of non-equilibrium thermodynamics has lead Prigogine to make a claim to a new world-view and with it a new scientific paradigm.

Based on the science of dissipative structures, Prigogine's paradigm holds process, time and qualitative change as the realities of nature. In direct opposition to the determined mechanistic world of Newton, Prigogine's world is fundamentally

random and irreversible, allowing for the creation of new structure and new information. In Prigogine's non-deterministic world, such creation in nature is an ongoing process and the foundation of reality.

Because process is the foundation of reality and time is essentially real, much of human experience that lay outside of the Newtonian paradigm is brought within that of Prigogine. Thermodynamic processes and Darwinian evolution are not only explicable for Prigogine, they are necessary attributes of an evolving, thermodynamic universe. In such a universe, the spontaneous, self-organization of matter into a living system ceases to be a statistical miracle and becomes a natural probability. Life and mankind no longer stand in opposition to an alien nature, but become embedded in it.<sup>145</sup>

If, then, there is a valid historical claim to scientific revolution, it lies not with the Copenhagen interpretation of the quantum theory and its self-revelatory limitation on the Newtonian paradigm, but with the contemporary work of Ilya Prigogine. Prigogine's claim passes the Kuhnian requirement for revolution by creating a fundamentally different world view. Based on process and a real time, Prigogine's paradigm finds a place for the science that has preceded it as well as for those realms of experience that Newtonian science could not explain. Born of the crisis surrounding the quantum theory, Prigogine's paradigm claims to provide the new language with which humankind can express its complete experience in nature. Prigogine concludes that

it has to be recognized that this role of time, of evolution, the concept of an historical world, has become more and more prevalent on all

levels of science, from elementary particles up to the cosmological scale. This is indeed a deep change, so deep that I believe that we are living through one of the greatest revolutions in Western science since its very foundation by Newton.<sup>146</sup>

The open claim Prigogine has made to revolution has caused many to criticize the man and his work. He has been accused of plagiarism by the disciples of the British scientist Alan M. Turing, who consider the substance of the dissipative structures theory to be rooted in Turing's work on biological organization, "The Chemical Basis of Morphogenesis."<sup>147</sup> René Thom has further termed Prigogine a "traitor to science" for his introduction of fundamental randomness into nature.<sup>148</sup> Recognizing that Prigogine has thus far promised more in the potential of his theories than he has delivered in application, N. Katherine Hayles wrote that Prigogine's work was less practically useful in research than that of the chaoticians.<sup>149</sup> Called a mystic by some and a poor scientist by others,<sup>150</sup> Mitchell Waldrop wrote in his 1992 book on the contemporary science of complexity that "Prigogine...was considered by many other physicists to be an insufferable self-promoter who often exaggerated the significance of what he had accomplished."<sup>151</sup>

There is little question, however, as Prigogine noted above, that contemporary science is undergoing a radical change from that which preceded it. There is a feeling within the scientific community that classical assumptions are not longer valid or tenable. A contemporary scientist J. Lighthill said in a lecture titled "The Recently Recognized Failure of Predictability in Newtonian Dynamics,"

I have to speak on behalf of the broad global fraternity of practitioners of mechanics. We collectively wish to apologize for having mislead the general educated public by spreading ideas about the determinism of

systems satisfying Newton's laws of motion that, after 1960, were proved incorrect.<sup>152</sup>

Despite the criticism he has received Prigogine is supported by several prominent scientists, including Paul Davies, Alistair Rae and Victor Wiesskopf<sup>153</sup> and is recognized as a leader in the contemporary science of complexity, self-organization and emergence.<sup>154</sup> While the actuality of a scientific revolution in the twentieth century can only be decided by the eventual acceptance of a new paradigm by the scientific community, Prigogine's claim to the development of a new paradigm of science is at the very least conceptually valid.

## NOTES

<sup>1</sup>Niels Bohr, Atomic Theory and the Description of Nature (Cambridge: The University Press, 1961), 92.

<sup>2</sup>Ilya Prigogine and Isabelle Stengers, Order Out of Chaos (New York: Bantam Books, 1984), 291-313.

<sup>3</sup>Ilya Prigogine, From Being to Becoming (San Francisco: W.H. Freeman, 1980), xvi.

<sup>4</sup>Ilya Prigogine and Isabelle Stengers, Order Out of Chaos.

<sup>5</sup>Thomas Kuhn, The Essential Tension (Chicago: The University of Chicago Press, 1977), 152.

<sup>6</sup>I. Bernard Cohen, Revolution in Science (Cambridge: The Belknap Press of Harvard University Press, 1985), 170.

<sup>7</sup>Ibid., 173.

<sup>8</sup>Alistair Rae, Quantum Physics: Illusion or Reality? (Cambridge: Cambridge University, 1986), 2; Barbara Lovett Cline, Men Who Made a New Physics (Chicago: The University of Chicago Press, 1987), 34.

<sup>9</sup>Cline, 98; Louis de Broglie, The Revolution in Physics (New York: Noonday Press, 1953), 14; Victor Guillemin, The Story of Quantum Mechanics (New York: Charles Scribner's Sons, 1968), vii; Banesh Hoffman, The Strange Story of the Quantum (New York: Harper & Brothers, 1947), ix; Kurt Gottfried, Quantum Mechanics (New York: W.A. Benjamin, Inc., 1966), 1; George Gamow, Thirty Years That Shook Physics (New York: Anchor Books, 1966), xiii.

<sup>10</sup>J.W.N. Sullivan, The Limitations of Science (New York: Mentor, 1933).

<sup>11</sup>Stephen Toulmin, ed., Physical Reality (New York: Harper, 1970), 35; Werner Heisenberg, Philosophic Problems of Nuclear Science (New York: Fawcett, 1952), 29.

<sup>12</sup>Toulmin, 35; Heisenberg, Philosophic Problems of Nuclear Science, 29.

<sup>13</sup>Thomas S. Kuhn, The Structure of Scientific Revolution (Chicago: The University of Chicago Press, 1970), 2.

<sup>14</sup>Frederick Suppe, ed., The Structure of Scientific Theories (Urbana: The University of Chicago Press, 1977), 461.

<sup>15</sup>Imre Lakatos and Alan Musgrave, eds., Criticism and the Growth of Knowledge, Proceedings of the International Colloquium in the Philosophy of Science, Bedford College, 1965, (Cambridge: The University Press, 1970), 253.

<sup>16</sup>Kuhn, The Structure of Scientific Revolutions, 5.

<sup>17</sup>Kuhn, The Structure of Scientific Revolutions, 23.

<sup>18</sup>Kuhn, The Structure of Scientific Revolutions, 24.

<sup>19</sup>Kuhn, The Structure of Scientific Revolutions, 36.

<sup>20</sup>Kuhn, The Structure of Scientific Revolutions, 65.

<sup>21</sup>Lakatos, 250.

<sup>22</sup>Kuhn, The Structure of Scientific Revolutions, 77.

<sup>23</sup>Kuhn, The Structure of Scientific Revolutions, 79.

<sup>24</sup>Kuhn, The Structure of Scientific Revolutions, 115.

<sup>25</sup>Kuhn, The Structure of Scientific Revolutions, 150.

<sup>26</sup>Lakatos, 234.

<sup>27</sup>Lakatos; Suppe; Cohen.

<sup>28</sup>G. Holton, Thematic Origins of Scientific Thought (Cambridge: Harvard, 1973), 118.

<sup>29</sup>Holton, 120-138; Toulmin, 46; Cline, 81; Niels Bohr, Essays 1958 - 1962: On Atomic Physics and Human Knowledge (London: Interscience, 1963), 3; Werner Heisenberg, Physics and Philosophy (New York: Harper, 1958), 94.

<sup>30</sup>Ernst Mach, The Science of Mechanics (LaSalle: Open Court Publishers, 1960), 345.

<sup>31</sup>Mach, 226.

<sup>32</sup>Kuhn, The Structure of Scientific Revolutions, 24.

<sup>33</sup>Holton, 221; Toulmin, 46.

<sup>34</sup>Cline, 34.

<sup>35</sup>Heisenberg, Physics and Philosophy, 30.

<sup>36</sup>Cline, 53.

<sup>37</sup>Cline, 55.

<sup>38</sup>Heisenberg, Physics and Philosophy, 32.

<sup>39</sup>Cline, 98.

<sup>40</sup>Cline, 99.

<sup>41</sup>Cline, 100.

<sup>42</sup>Heisenberg, Physics and Philosophy, 34.

<sup>43</sup>Abraham Pais, Niels Bohr's Times, In Physics, Philosophy, and Polity (Oxford: Clarendon Press, 1991), 128.

<sup>44</sup>Cline, 207.

<sup>45</sup>Pais, 308.

<sup>46</sup>Pais, 240.

<sup>47</sup>Cline, 198.

<sup>48</sup>Pais, 286.

<sup>49</sup>David Cassidy, Uncertainty: The Life and Science of Werner Heisenberg (New York: W.H. Freedman & Co., 1992), 223, 9th plate.

<sup>50</sup>Max Born, The Born - Einstein Letters (New York: Walker, 1971), 23, 82, 88, 91.

<sup>51</sup>Born, 91.

<sup>52</sup>Pais, 431.

<sup>53</sup>Rae, 14; J.M. Jauch, Are Quanta Real? (Bloomington: Indiana University Press, 1973), ix; Bohr, Atomic Theory and the Description of Nature, 88; Heisenberg, Physics and Philosophy, 167.

<sup>54</sup>Bohr, Atomic Theory and the Description of Nature, 92.

- <sup>55</sup>Bohr, Atomic Theory and the Description of Nature, 91; Holton, 149-150.
- <sup>56</sup>Bohr, Atomic Theory and the Description of Nature, 101; Cline, 98; de Broglie, 14; Guillemin, vii; Hoffman, ix; Gottfried, 1; Gamow, xiii.
- <sup>57</sup> Ibid.
- <sup>58</sup>Niels Bohr, Atomic Physics and Human Knowledge, 64.
- <sup>59</sup>Bohr, Atomic Theory and the Description of Nature, 96.
- <sup>60</sup>Heisenberg, Physics and Philosophy, 80.
- <sup>61</sup>Werner Heisenberg, The Physicist's Conception of Nature, trans. Arnold Pomerans (New York: Harcourt, Brace & Co., 1958), 9.
- <sup>62</sup>Bohr, Atomic Theory and the Description of Nature, 54.
- <sup>63</sup>Holton, 119.
- <sup>64</sup>Bohr, Atomic Theory and the Description of Nature, 84, 92, 53, 33, 54; Heisenberg, The Physicist's Conception of Nature, 39; Born, 23.
- <sup>65</sup>Heisenberg, The Physicist's Conception of Nature, 14.
- <sup>66</sup>Born, 82.
- <sup>67</sup>Bohr, Atomic Theory and the Description of Nature, 92.
- <sup>68</sup>Bohr, Atomic Theory and the Description of Nature, 53.
- <sup>69</sup>Heisenberg, The Physicist's Conception of Nature, 49.
- <sup>70</sup>Heisenberg, The Physicist's Conception of Nature, 37.
- <sup>71</sup>Heisenberg, Physics and Philosophy, 49.
- <sup>72</sup>Kuhn, The Structure of Scientific Revolutions, 77.
- <sup>73</sup>Bohr, Atomic Theory and the Description of Nature, 53, 56, 60, 103, 115; 9 Bohr 5; Heisenberg, The Physicists' Conception of Nature, 29, 30; Werner Heisenberg, Physical Principles of the Quantum Theory, trans. Carl Eckart and Frank C. Hoyt (Chicago: Dover, 1930), 10; Heisenberg, Philosophic Problems of Nuclear Science, 16, 22, 46.
- <sup>74</sup>Bohr, Atomic Theory and the Description of Nature, 115.
- <sup>75</sup>Heisenberg, Philosophic Problems of Nuclear Science, 46.

<sup>76</sup>Bohr, Atomic Theory and the Description of Nature, 60.

<sup>77</sup>Heisenberg, The Physicists's Conception of Nature, 29.

<sup>78</sup>Ibid., 30.

<sup>79</sup>Ibid., 29.

<sup>80</sup>Robert Artigiani, "From Epistemology to Cosmology," in The Evolution of Cognitive Maps, ed. E. Lazlo et al. (New York: Gordon & Breach, 1993), 29-60.

<sup>81</sup>Heisenberg, The Physicist's Conception of Nature, 29.

<sup>82</sup> Werner Heisenberg, "The Representation of Nature in Contemporary Physics," in Symbolism in Religion and Literature, ed. Rollo May (New York: Braziller, 1961), 228.

<sup>83</sup>Heisenberg, The Physicist's Conception of Nature, 25.

<sup>84</sup>Prigogine and Stengers, Order out of Chaos, 41.

<sup>85</sup>A. Lee McAlister, The History of Life, (Englewood Cliffs, New Jersey: Prentice Hall Inc., 1968), 23; Michael Ruse, The Darwinian Evolution, (Chicago: The University of Chicago Press, 1979), 161; William D. Stansfield, The Science of Evolution, (New York: Macmillan Publishing Co., 1977), 31.

<sup>86</sup>Peter J. Vorzimer, Charles Darwin: The Years of Controversy, (Philadelphia: Temple University Pres, 1970), 3.

<sup>87</sup>McAlister, 26.

<sup>88</sup>McAlister, 27; Ruse, 228.

<sup>89</sup>Alfred S. Romer, The Procession of Life, (Cleveland: World Publishing Co., 1968), 6; A.W. Sturtevant, A History of Genetics, (New York: Harper & Row, 1965), 17.

<sup>90</sup>McAlister, 27-34; Romer, 7.

<sup>91</sup>C. Truesdell, The Tragicomical History of Thermodynamics, 1822-1854, (New York: Springer-Verlag, 1980), 204.

<sup>92</sup>Ibid.

<sup>93</sup>Truesdell, 204; George Hatsopoulos and Joseph Keenan, Principles of General Thermodynamics, (New York: Wiley & Sons Inc., 1965), xviii.

<sup>94</sup>Kurt C. Rolle, Introduction to Thermodynamics, (Columbus: Charles E. Merrill Publishing, 1973), 8.

<sup>95</sup>J. Serrin, ed., New Perspectives in Thermodynamics, (New York: Springer-Verlag, 1986), vii; P.W. Bridgman, The Nature of Thermodynamics, (Cambridge: Harvard University Press, 1943), 3,6.

<sup>96</sup>F.C. Andrews, Thermodynamics: Principles and Applications, (New York: Wiley-Interscience, 1971), 4; Bridgman, 4.

<sup>97</sup>Rolle, 8,174.

<sup>98</sup>Ibid, 175.

<sup>99</sup>Peter Fong, Foundations of Thermodynamics, (New York: Oxford University Press, 1963), 18.

<sup>100</sup>Peter Atkins, The Second Law, (New York: W.H. Freeman & Co., 1984), 7.

<sup>101</sup>Atkins, 5.

<sup>102</sup>Bridgman, 4.

<sup>103</sup>Bridgman, 3.

<sup>104</sup>Aage Petersen, "The Philosophy of Niels Bohr" Bulletin of Atomic Scientists 19 (7): 8-14.

<sup>105</sup>Heisenberg, "The Representation of Nature in Contemporary Physics," 227.

<sup>106</sup>Andrews, 5.

<sup>107</sup>Ibid, 4.

<sup>108</sup>Ilya Prigogine and Peter Glansdorff, "L'écart à l'équilibre interprété comme une source d'ordre Structures dissipatives," Academie Royale de Belgique, Bulletin Classe Scientific 59 (1971): 672.

<sup>109</sup>Ilya Prigogine, "Entropy Revisited," lecture (Bruxelles, F.S., 1990): 1.

<sup>110</sup>William Lepkowski, "The Social Thermodynamics of Ilya Prigogine," C&EN (April 16, 1979): 30.

<sup>111</sup>Prigogine, "Entropy Revisited," 4.

<sup>112</sup>Ilya Prigogine, "The Meaning of Entropy," lecture given at International Circle for Research in Philosophy conference at Rice University, Houston, Texas, 22 March 1984: 11; Prigogine, "Entropy Revisited," 4.

<sup>113</sup>"A Chemist Told How Life Could Defy Physics Laws," The New York Times, 12 October 1977, IV, 19:4.

<sup>114</sup>Prigogine, From Being to Becoming, 203.

<sup>115</sup>Prigogine, "The Meaning of Entropy," 2.

<sup>116</sup>Prigogine and Stengers, Order Out of Chaos, xxviii.

<sup>117</sup>Ilya Prigogine, "The Microscopic Theory of Irreversible Processes," in Self-Organization: Autowaves and Structures Far from Equilibrium: Proceedings of an International Symposium, Pushchine, USSR July 18-23, 1983, ed. V.I. Krinsky (New York: Springer-Verlag, 1984), 23.

<sup>118</sup>Prigogine, From Being to Becoming, 2.

<sup>119</sup>Prigogine and Stengers, Order Out of Chaos, 278.

<sup>120</sup>Prigogine, From Being to Becoming, 6; Prigogine and Stengers, Order Out of Chaos, 118; Ilya Prigogine, Gregoire Nicolis and Agnes Babloyantz, "Thermodynamics of Evolution," in Physics Today vol. 25, no. 11 (November 1972): 24.

<sup>121</sup>Ibid.

<sup>122</sup>Ilya Prigogine, "What is Entropy," Naturwissenschaften 76 (1989): 7.

<sup>123</sup>Prigogine and Stengers, Order Out of Chaos, 129.

<sup>124</sup>Prigogine, From Being to Becoming, 132.

<sup>125</sup>Ibid, 93-94.

<sup>126</sup>Prigogine and Stengers, Order Out of Chaos, 177; Ilya Prigogine, "Nonequilibrium Thermodynamics and Chemical Evolution: An Overview," Aspects of Chemical Evolution, ed. Dr. G. Nicolis (New York: John Wiley & Sons, 1984), 58; Prigogine, From Being to Becoming, 106,132; Prigogine, Nicolis and Babloyantz, 27.

<sup>127</sup>Prigogine, From Being to Becoming, 106.

<sup>128</sup>Ilya Prigogine, "Can thermodynamics explain biological order?" Impact of Science on Society vol. 23, no. 3 (July-September 1973): 163.

<sup>129</sup>Prigogine, Nicolis and Babloyantz, 26.

<sup>130</sup>Prigogine, From Being to Becoming, 106.

<sup>131</sup>Ilya Prigogine, "Only An Illusion," Tanner Lecture on Human Values, Jawaharlal Nehru University, New Dehli, 18 December 1982, 4; Ilya Prigogine, "Man's New Dialogue With Nature," unpublished lecture, 1.

<sup>132</sup>Ilya Prigogine, "The Origins of Complexity," unpublished lecture, 1; Ilya Prigogine, "Time and Human Knowledge," Environment and Planning, B: Planning and Design 12 (1985): 5.

<sup>133</sup>Simon Pierre de Laplace, A Philosophical Essay on Probabilities, trans. Frederick W. Truscott and Frederick L. Emory (New York: Dover Publications, 1952).

<sup>134</sup>Prigogine, "Time and Human Knowledge," 5.

<sup>135</sup>Prigogine, From Being to Becoming, 159.

<sup>136</sup>Prigogine, "The Meaning of Entropy," 12; Prigogine, "Only An Illusion," 32.

<sup>137</sup>Prigogine, "Only An Illusion," 6.

<sup>138</sup>French and Kennedy, 302.

<sup>139</sup>Heisenberg, Physics and Philosophy, 167.

<sup>140</sup>Kuhn, The Structure of Scientific Revolutions, 77.

<sup>141</sup>Bohr, Atomic Physics and Human Knowledge, 88.

<sup>142</sup>Heisenberg, The Physicist's Conception of Nature, 25.

<sup>143</sup>Ibid., 15.

<sup>144</sup>Heisenberg, Physics and Philosophy, 167; Heisenberg, The Physicist's Conception of Nature, 25.

<sup>145</sup>Prigogine, "The Meaning of Entropy," 3.

<sup>146</sup>Prigogine, "Time and Human Knowledge," 7.

<sup>147</sup>Andrew Hodges, Alan Turing (New York: Simon & Schuster, 1983): 466; Alan M. Turing, "The Chemical Basis of Morphogenesis" Philosophical Transactions of the Royal Society of London, series B, vol 237 (1952-1954), 37-72.

<sup>148</sup>René Thom, "Halte au hasard, silence au bruit," Le Débat (1980): 119-32.

<sup>149</sup>N. Katherine Hayles, Chaos Bound (Ithaca: Cornell University Press, 1992).

<sup>150</sup>John Briggs and David Peat, Turbulent Mirror (New York: Harper and Row, 1989): 151,208.

<sup>151</sup>M. Mitchell Waldrop, Complexity: The Emerging Science at the Edge of Order and Chaos (New York: Simon & Schuster, 1992): 32.

<sup>152</sup>J. Lighthill, "The Recently Recognized Failure of Predictability in Newtonian Dynamics," in Proceedings of the Royal Society A407 (1986).

<sup>153</sup>Paul Davies, Cosmic Blueprint; Rae, Quantum Physics: Illusion or Reality?; Victor Wiesskopf, "The Frontiers and Limits of Science," Daedalus, vol 113, no 3 (1984): 186.

<sup>154</sup>Waldrop, Complexity.

## SELECTED BIBLIOGRAPHY

- Andrews, F.C. Thermodynamics: Principles and Applications. New York: Wiley-Interscience, 1971.
- Artigiani, Robert. "From Epistemology to Cosmology." in The Evolution of Cognitive Maps, ed. E. Lazlo et al., 29-60. New York: Gordon & Breach, 1993.
- Atkins, Peter. The Second Law. New York: W.H. Freeman & Co., 1984.
- Bell, J.S. Speakable and Unspeakable in Quantum Mechanics. Cambridge: Cambridge University Press, 1987.
- Bohr, Niels. Atomic Physics and Human Knowledge. New York: Wiley, 1958.
- \_\_\_\_\_. Atomic Theory and the Description of Nature. Cambridge: The University Press, 1961.
- \_\_\_\_\_. Essays 1958-1962: On Atomic Physics and Human Knowledge. London: Interscience, 1963.
- Born, Max. The Born - Einstein Letters. New York: Walker, 1971.
- Bridgman, P.W. The Nature of Thermodynamics. Cambridge: Harvard University Press, 1943.
- Briggs, John and David Peat. Turbulent Mirror. New York: Harper & Row, 1989.
- Cassidy, David C. Uncertainty: The Life and Science of Werner Heisenberg. New York: W.H. Freeman and Co., 1992.
- Cline, Barbara Lovett. Men Who Made a New Physics. Chicago: The University of Chicago Press, 1987.
- Cohen, I. Bernard. Revolution in Science. Cambridge: The University Press, 1985.
- Davies, Paul and John Gribbin. The Matter Myth. New York: Simon & Schuster, 1992.

- De Broglie, Louis. The Revolution in Physics. New York: Noonday Press, 1953.
- Ferris, Timothy. Coming of Age In The Milky Way. New York: Doubleday, 1988.
- Fong, Peter. Foundations of Thermodynamics. New York: Oxford University Press, 1963.
- French, A.P. and P.J. Kennedy. Niels Bohr: A Centenary Volume. Cambridge: Harvard, 1985.
- Gamow, George. Thirty Years That Shook Physics. New York: Anchor Books, 1966.
- Gottfried, Kurt. Quantum Mechanics. New York: W.A. Benjamin, Inc., 1966.
- Gribbin, John. In Search of Schrödinger's Cat. New York: Bantam Books, 1984.
- Guillemin, Victor. The Story of Quantum Mechanics. New York: Charles Scribner's Sons, 1968.
- Hatsopoulos, George and Joseph Keenan. Principles of General Thermodynamics. New York: John Wiley & Sons, 1965.
- Hayles, N. Katherine. Chaos Bound. Ithaca: Cornell University Press, 1992.
- Heisenberg, Werner. Physical Principles of the Quantum Theory. Translated by Carl Eckart and Frank C. Hoyt. Chicago: Dover, 1930.
- \_\_\_\_\_. Philosophical Problems of Nuclear Science. New York: Fawcett, 1952.
- \_\_\_\_\_. Physics and Philosophy. New York: Harper, 1958.
- \_\_\_\_\_. The Physicist's Conception of Nature. Translated by Arnold J. Pomerans. New York: Harcourt, Brace & Co., 1958.
- \_\_\_\_\_. "The Representation of Nature in Contemporary Physics." in Symbolism in Religion and Literature, ed. Rollo May. New York: Braziller, 1961.
- Hodges, Andrew. Alan Turing. New York: Simon & Schuster, 1983.
- Hoffman, Banesh. The Strange Story of the Quantum. New York: Harper and Brothers, 1947.
- Holton, G. Thematic Origins of Scientific Thought. Cambridge: Harvard, 1973.

- Jauch, J.M. Are Quanta Real? Bloomington: Indiana University Press, 1973.
- Kuhn, Thomas S. The Structure of Scientific Revolutions. Chicago: The University of Chicago Press, 1970.
- \_\_\_\_\_. The Essential Tension. Chicago: The University of Chicago Press, 1977.
- Lakatos, Imre and Alan Musgrave, eds. Criticism and the Growth of Knowledge. (Proceedings of the International Colloquium in the Philosophy of Science, Bedford College, 1965). Cambridge: The University Press, 1970.
- de Laplace, Simon Pierre. A Philosophical Essay on Probabilities. Translated by Frederick W. Truscott and Frederick L. Emory. New York: Dover Publications, 1952.
- Lepkowski, William. "The Social Thermodynamics of Ilya Prigogine." in C & EN (16 April 1979): 30-33.
- Mach, Ernst. The Science of Mechanics. LaSalle: Open Court Publishers, 1960.
- McAlister, A. Lee. The History of Life. Englewood Cliffs, NJ: Prentice Hall, 1968.
- Mehra, Jagdish and Helmut Rechenberg. The Historical Development of Quantum Theory. Vol. 1, Part 1. New York: Springer-Verlag, 1962.
- Monod, Jacques. Chance and Necessity. Translated by Austryn Wainhouse. New York: Alfred A. Knopf, 1971.
- Moore, Walter. Schrödinger: Life and Thought. Cambridge: Cambridge University Press, 1989.
- Pais, Abraham. Niels Bohr's Times, In Physics, Philosophy, and Polity. Oxford: Clarendon Press, 1991.
- Prigogine, Ilya. "Can thermodynamics explain biological order?" Impact of Science on Society vol 23, no 3 (July-September 1973): 159-79.
- \_\_\_\_\_. "Symmetry Breaking Chemical Instabilities." Irreversible Thermodynamics and the Origin of Life, ed. G.F. Oster, 11-24. New York: Gordon & Breach Science, 1974.
- \_\_\_\_\_. From Being to Becoming. San Francisco: W.H. Freeman, 1980.
- \_\_\_\_\_. "Only An Illusion." Tanner Lecture on Human Values, Jawaharlal Nehru

University, New Dehli, 18 December 1982.

\_\_\_\_\_. "Man's New Dialogue With Nature." Unpublished lecture, 1982.

\_\_\_\_\_. "The Meaning of Entropy." Lecture given at conference at Rice University, 22 March 1984 by the International Circle for Research in Philosophy, Houston, Texas.

\_\_\_\_\_. "The Microscopic Theory of Irreversible Processes." In Self-Organization: Autowaves and Structures Far from Equilibrium, Proceedings of an International Symposium, Pushchine, USSR July 18-23, 1983, ed. V.I. Krinsky. New York: Springer-Verlag, 1984.

\_\_\_\_\_. "Nonequilibrium Thermodynamics And Chemical Evolution: An Overview." in Aspects of Chemical Evolution, ed. Dr. G. Nicolis. New York: John-Wiley & Sons, 1984.

\_\_\_\_\_. "The Rediscovery of Time." Zygon vol 19, no 4 (December 1984): 433-47.

\_\_\_\_\_. "Time and Human Knowledge." Environment and Planning, B: Planning and Design 12 (1985): 5-20.

\_\_\_\_\_. "The Birth of Time." Foundations of Physics, vol 16, no 5 (1986): 437-43.

\_\_\_\_\_. "What is Entropy." Naturwissenschaften 76 (1989): 1-8.

\_\_\_\_\_. "Entropy Revisited." Unpublished lecture, Bruxelles, 1990.

\_\_\_\_\_. "The Origins of Complexity." Unpublished lecture.

Prigogine, Ilya and Peter Glansdorff. "L'écart à l'équilibre interprété comme une source d'ordre Structures dissipatives." Academie Royale de Belgique: Bulletin Classe Scientific 59 (1971): 672-702.

Prigogine, Ilya and G. Nicolis. "Fluctuations in Nonequilibrium Systems." Proceedings of the National Academy of Sciences vol 68, no 4 (September 1971): 2102-7.

Prigogine, Ilya, Gregoire Nicolis and Agnes Babloyantz. "Thermodynamics of Evolution." Physics Today vol 25, no 11 (November 1972): 23-28, part 2: vol 25, no 12, (December 1972): 38-44.

Prigogine, Ilya, G. Nicolis, R. Herman and T. Lan. "Stability, Fluctuations, and Complexity." Collective Phenomena, vol 2, no 2 (1975): 103-9.

- Prigogine, Ilya and Isabelle Stengers. Order Out of Chaos. New York: Bantam Books, 1984.
- Rae, Alistair. Quantum Physics: Illusion or Reality? Cambridge: Cambridge University, 1986.
- Rolle, Kurt C. Introduction to Thermodynamics. Columbus: Charles E. Merrill, 1973.
- Romer, Alfred S. The Procession of Life. Cleveland: World Publishing Co., 1968.
- Ruse, Michael. The Darwinian Revolution. Chicago: The University of Chicago Press, 1979.
- Schrödinger, Erwin. What is Life? and Mind and Matter. Cambridge: Cambridge University Press, 1969.
- Serrin, J, ed. New Perspectives in Thermodynamics. New York: Springer-Verlag, 1986.
- Spencer, Herbert. First Principles. New York: The DeWitt Revolving Fund, 1958.
- Stansfield, William D. The Science of Evolution. New York: Macmillan Publishing, 1977.
- Sullivan, J.W.N. The Limitations of Science. New York: Mentor, 1933.
- Sturtevant, A.W. A History of Genetics. New York: Harper & Row, 1965.
- Suppe, Frederick, ed. The Structure of Scientific Theories. Urbana: University of Illinois Press, 1977.
- Thom, René. "Halte au hasard, silence au bruit." Le Débat, 1980: 199-32.
- Toulmin, Stephen, ed. Physical Reality. New York: Harper and Row, 1970.
- Truesdell, C. The Tragicomical History of Thermodynamics, 1822-1854. New York: Springer-Verlag, 1980.
- Vorzimmer, Peter J. Charles Darwin: The Years of Controversy. Philadelphia: Temple University Press, 1970.
- Weisskopf, Victor F. "The Frontiers and Limits of Science." Daedalus, vol 113, no 3 (1984): 186ff.