‘The Renaissance of Physics’: Karl K. Darrow (1891–1982) and the Dissemination of Quantum Theory at the Bell Telephone Laboratories

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Abstract Karl K. Darrow was a central actor in the reception of quantum theory in the Bell Telephone Laboratories. He was the first industrial physicist to dedicate his entire working time to the dissemination of novel concepts and theoretical tools by means of long review papers. The present paper analyzes the evolution of Darrow’s narratives of quantum theory and shows that Darrow’s reviews aimed at substantiating the view that physics was an evolutionary process. The paper argues that this view was connected to Darrow’s peculiar activity at the Bell Labs as well as to the contemporaneous attempts of leading American scientists to build an ideology of national science.

Keywords American ideology · Bell Telephone Laboratories · Quantum mechanics · Subcultures of physics · Erwin Schrödinger · Wave mechanics

1 Introduction

The evolution and establishment of quantum mechanics posed unprecedented challenges to those industrial laboratories that relied on physical research to develop innovative and competitive artifacts. Industrial laboratories had to implement novel intra-organizational communication strategies in order to acquire the new knowledge. They also had to reconfigure their organizational structure in order to apply the latest conceived theoretical tools to practical research problems. The introduction of quantum theory at the AT&T Bell Telephone Laboratories was one of the most interesting cases of this disruptive transformation in the application of fundamental physics. The acquisition of the concepts and theoretical tools of quantum theory, and their application to materials was a complex historical process, which involved at least two phases. The first was to retrain the research staff by communicating new theoretical developments to them—a process that lasted from the early 1920s to late 1930s. The second phase saw the hiring of young PhD physicists

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well-trained in quantum mechanics; this began in 1936, when the economic growth following a slight easing in the Great Depression allowed Bell Labs' director of research, Mervin J. Kelly (1894–1971), to appoint new members to the research staff (Hoddeson et al. 1992; Gertner 2012)[1].

Historian of science Lillian Hoddeson (1980) argued that the first step was unsuccessful. The lack of an adequate scientific training in modern physics made it impossible to apply the concepts and tools of quantum mechanics to the research needs of the Bell System. Nevertheless, it is just the first step that is of great historical value to understand how scientists tried to reconfigure their systems of beliefs in order to employ the new theoretical methods. This stage, indeed, shows the main cognitive struggles and interpretative difficulties. This process also reveals how communication schemes shaped the transmission of knowledge. Bell Labs' administrators adopted various strategies in order to disseminate the new physics, including maintaining an up-to-date library, organizing visits by leading theoretical physicists, encouraging researchers to attend courses and seminars in various universities, and publishing papers in the Bell System journals intended to explain the new physics in semi-popular fashion. Thanks to his stylistic ability in the exposition of scientific issues, the industrial physicist Karl K. Darrow became the central actor in the Bell Labs' efforts to retrain its researchers. Darrow published a number of long critical reviews in the *Bell System Technical Journal* (*BSTJ*) from 1923 to 1939, attended several symposia and courses, reported what he had learned to the scientific staff, and organized scientific conferences on quantum theory at the Bell Labs. Scientific dissemination shortly became Darrow's exclusive occupation at the Bell Labs, which made him the first industrial physicist to devote his whole working time to such an activity.

Various accounts suggest that beyond Bell Labs Darrow had a significant role in the reception of quantum theory in the United States, and several physicists recognized their debt to Darrow's efforts to disseminate a wide-ranging view of new theories through his critical review articles (Van Vleck 1967, p. 25; Weiner 1973, p. 27; Hoddeson 1980; Sopka 1988, pp. 87–88; Gertner 2012, pp. 41–42). Between the early 1920s and the late 1930s, Darrow occupied an exceptional position within the American scientific community as a synthesizer and interpreter of quantum theory at the juncture between university theoretical research and the American industrial environment. However, historians have so far given scant attention to Darrow's activity as a mediator between different subcultures of physics. The only scholarly study of Darrow's writings appears within philosopher of science Nancy Cartwright's analysis of the reception of quantum theory in the United States. Cartwright (1987) claimed that Darrow is a very fine example of the influence that the operationalist-pragmatist tradition had in the way in which American

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[1] The present paper covers a period from the late 1910s to late 1930s. The AT&T Bell Telephone Laboratories were created only in 1925. Before that date, the personnel that would merge into the Bell Telephone Laboratories worked in the Engineering Department of the Western Electric Co., which was one of the member companies of the Bell System. For the sake of brevity, I will use the term *Bell Labs* to refer to all the laboratories of the Bell System during the period under consideration.

physicists dealt with the philosophical problems of quantum theory. The present paper aims at extending and historicizing Cartwright's analysis.

Darrow's beliefs did not remain fixed while sudden theoretical developments were altering the face of physics. He had to actively reconfigure his worldview in order to engage with new concepts and new theoretical tools. By following the chronological order of Darrow's reviews of topics related to quantum theory, one discovers that Darrow's views evolved differently from those of leading American theoretical physicists. I will show that Darrow's interpretations and translations of the developments of quantum theory were strongly shaped by his peculiar role within the American physics community as well as his ideological view of physics as a continuous evolutionary process, from measurement to knowing, and from knowing to invention. I suggest that the relationship between Darrow's ideological cast and his expositions of quantum theory might reveal deep interconnections between the changing social-epistemic context embodied by the Bell Labs milieu and Darrow's interpretative endeavors. In conclusion, I argue that the evolutionary technoscientific views held by Darrow were embedded in the American ideology of national science, which dominated the scientific landscape in the period 1919–1930 (Tobey 1971).

2 Creating a New Profession in the Bell Labs: Darrow's Unique Role in the Life of American Physics

Born in 1891 in Chicago, Karl Kelchner Darrow exhibited from an early age an impressive interest in several different disciplines. A local newspaper documented Darrow's talent in both humanities and mathematics, dedicating to the 7-year-old boy a long article, in which the journalist stated that the young Darrow was already "an indisputable authority in history, geography and mythology, an unparalleled mathematician, a poet and author, and an expert at operating the typewriter" ("Karl Darrow's Genius"). The article provided an extremely vivid image of the personal capacities that would make Darrow a unique interpreter of physics from the early 1920s onward. The boy showed a striking memory coupled with a broad interest in various branches of knowledge from literature to mathematics, from art to natural science. Such a vast range of interests would become the mark of Darrow's approach to physics writing. As John H. Van Vleck (1899–1980) described it, Darrow's "unique role in the life of American physics" depended on his particular style, which in turn stemmed from "his wide literary and cultural background" (Van Vleck 1967, p. 25) (Fig. 1).

Among his various intellectual interests, Darrow chose to pursue the professional study of physics, while preserving his passion toward arts and literature. The University of Chicago provided an ideal environment for Darrow to complete his undergraduate and doctoral studies. There, Darrow received his Bachelor's degree in physics in 1911 and his PhD in 1917 with an experimental dissertation concerning the measurement of the ratio of the specific heats of hydrogen under the supervision of Robert Andrews Millikan (1868–1953).

Fig. 1 Photograph of Karl K. Darrow. (AIP Emilio Segre Visual Archives, Darrow Collection)

Although he spent almost two years of study in Paris and Berlin between 1911 and 1913, Darrow's approach to physics was shaped almost exclusively by Millikan's teachings (Darrow 1964)[2]. Darrow's diaries of this formative period highlight Millikan's impact on Darrow's view of physics. Experiments were the centerpiece of the academic courses. The subordination of theoretical advancements to novel experiments shows that Millikan taught physics as an experimentally-driven discipline. Darrow's diaries also reveal that quantum theory was not part of the normal physics curriculum at that time. Darrow acquired some knowledge of the developments of quantum theory only *after* he completed his dissertation by attending a summer course taught by Millikan himself. The reading assignments of this course focused on experimental problems and instrumental methodologies confirming that Millikan's teaching agenda was built on the belief that experiments had primacy over theory (Darrow 1917a).

Not only did Millikan shape Darrow's views on physics; Millikan also had an active role in the continuation of Darrow's professional career. Soon after Darrow earned his PhD, Millikan helped him to obtain a research position at the Engineering Department of the Western Electric Company, which would become the AT&T Bell Telephone Laboratories in 1925 (Millikan 1917). When Darrow joined the research staff of the Bell System in 1917, the multidisciplinary research environment was in ferment. The 1917 entry of the United States into the war requested major efforts by U.S. industrial companies to serve the military needs of their country. The involvement of physicists in the military research agenda of the

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[2] Unless otherwise reported, the biographical information contained in this section is taken from this interview.

American government during World War I was deeply transforming the relationship physicists had with their discipline. While before the war physicists conceived themselves as lone researchers, the coordinated and product-focused military efforts led several leading American scientists to appreciate the value of team-organized and interdisciplinary environments for pursuing pure research. Since the United States began organizing their industrial structures for the entry into the war, the research teams of the Bell System actively worked on military projects, and the industrial multidisciplinary environment became a model of research organization for several universities (Kevles 1971, pp. 102–138; Tobey 1971, pp. 20–61). Darrow was hired to increase the scientific manpower of the Bell System working on military projects.

The successes of Bell Labs' researchers in pure physics led several historians to study the essential elements of the Bell Labs environment. The various accounts provide a complex landscape of contradictory images. In particular, the role of pure research within the organizational strategies of the research directors is controversial. On the one hand, historian of science Steven Shapin convincingly argues that industrial laboratories were not morally inferior to academic environments in their commitment to pure research, providing several examples concerning the freedom enjoyed by Bell Labs' industrial physicists (Shapin 2008). On the other hand, certain Bell Labs' research directors pointed out that scientists' research freedom was rigorously subordinated to the commercial needs of the firm (Millman 1983, pp. xiii-xxi, 1–17). By epitomizing the various historical accounts, it is possible to deduce that the balance between pure and applied research within the Bell Labs milieu was historically contingent and depended on specific negotiations between research directors and the research staff.

An essential historical element that favored the Bell System involvement in pure research was Millikan's direct influence in shaping the views and actions of various research directors of the firm. Several of Millikan's students found jobs within Bell Labs and some reached eminent positions, including Frank B. Jewett (1879–1949)—who became Vice-President of the AT&T in 1921 and President of the Bell Labs in 1925—and Harold D. Arnold (1883–1933)—who became the Director of the Research Branch of the Engineering Department in 1921 and the first director of the AT&T Bell Telephone Laboratories in 1925 (Gertner 2012, pp. 9–40). Darrow, then, was following a route common to many experimental physicists who graduated under Millikan in the first decades of the twentieth century.

Darrow appreciated the lively environment and the spirit of research, and began helping with the Bell System's war efforts (Darrow 1917b). Soon after the war, however, a physical problem jeopardized his career at the Bell Labs: His trembling hands made him unsuitable to continue experimental research (White 1976). Nevertheless, thanks to Arnold and Jewett's managerial decisions, instead of losing his job, Darrow was asked to organize the unpublished literature of scientific and engineering memoranda. Later, Darrow became a sort of "intelligencer to the community at the laboratory" (Darrow 1964)[3], occupying a void in the organization

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[3] This expression was used by the interviewer W. J. King.

of the industrial firm with a series of activities aimed at acquiring new knowledge within the Bell System research environment.

Such an activity was multifaceted and evolved with time. The deep changes due to the development of quantum physics highlighted the need for Bell Labs' researchers to maintain an updated knowledge of physics. To accomplish this task, 23 members of the Bell System research staff, mostly of the Physical Research Department, organized a society called Colloquium. This society organized meetings that enabled members "to keep in touch with recent thought and experiment in physics and allied sciences" (Darrow 1920a)[4]. In 1919, the "little republic of serious thinkers," as the society was later called, began gathering two evenings a month in which one of the members introduced a topic to be discussed by the participants (Darrow 1920b; "Modern Physical Theories"). Darrow's lack of involvement in active research allowed him a central role in the Colloquium, becoming its perpetual secretary ("First meeting").

The informal and voluntary character of the Colloquium demonstrates that this dissemination was more a need of individual researchers than a strategy developed by research directors. The beginning of Darrow's activities in disseminating quantum theory did not depend, then, on well-organized research strategies. They were an outcome of the interplay of individual decisions of research directors trained by Millikan and personal interests of Bell Labs' physicists. Only in 1923, when Darrow began publishing a series of papers in the *Bell System Technical Journal* (*BSTJ*), did Darrow's role within the Bell System research organization assume a more stable form.

While continuing his work on the organization of the unpublished literature, Darrow began using his literary talent to write typed reports about the meetings of the American Physical Society. Starting as a spontaneous activity, Darrow's role as a synthesizer and interpreter of new ideas became a real job. In 1923, the *BSTJ* editor Robert W. King asked him to write reports of the recent developments of physics that could be of interest for the Bell System community of researchers. The quarterly *BSTJ* had been created in 1922 with the intent to publish articles by the staff concerning scientific and engineering aspects of electrical communication. During the first year, the publishing policy maintained a strong link between the production needs of the Bell System and the issued topics. Darrow's papers were the first and unique exception to such a policy. Following King's request, Darrow began publishing a permanent section called "Contemporary Advances in Physics." The foreword of Darrow's first paper clearly cast the aim of the overall series: to make available to the Bell Labs' research staff and the broader readership of the journal reviews of recent researches in physics that Darrow considered of special interest. As the foreword pointed out, the publication was a way to institutionalize a work that Darrow was already doing in a more informal manner (Darrow 1923).

Some of the directors of research of the Bell System showed an uncommon intuition in allowing Darrow to use his literary talents in the behalf of the entire community of physicists. As Darrow and other physicists stressed, such an activity was

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[4] The list of the topics of the first season clearly shows that the principal aim of the Colloquium was to engage with the development of quantum theory ("Meeting of the Colloquium").

essential for two reasons. First, Darrow was creating a bibliography in which novel research endeavours were epitomized in order to make them intelligible to researchers specialized in different areas of physics; second, in a more implicit way, Darrow's papers were an attempt to slow down the centrifugal forces of specializations within the growing American community of physicists (Van Vleck 1967; White 1976; Wooldridge 1976; Gertner 2012, pp. 41–42). In 1929, the American Physical Society (APS) recognized the vital importance of this kind of literature by creating the *Reviews of Modern Physics*, which shared the same targets of Darrow's "Contemporary Advances in Physics" (Lalli 2014).

Before the APS began publishing *Reviews of Modern Physics*, Darrow's reviews were almost unique in the American physics literature. Even after the APS institutionalized the need for long critical reviews, Darrow's writings maintained exceptional features. For these reasons, they represent fundamental documents for investigating the transmission of knowledge between different cultural and institutional settings. Darrow's interpretation of quantum theory, his choices of topics, his rhetorical style, his philosophical background are all elements that improve our knowledge of how the new physics was transmitted from European theoretical physics departments to an American industrial environment. To analyze Darrow's writings, it is necessary to consider both the two spatial features of the environment in which Darrow acted; namely, the specific fluctuating subculture of the industrial laboratory of the Bell System, and the broader philosophical underpinning of the American reception of quantum mechanics (Coben 1971; Schweber 1986; Holton 1988; Schweber 1990; Assmus 1992a, 1992b). This kind of approach will allow me to draw the strong connection between Darrow's views and the technoscientific ideology held by several exponents of the American physical community in the period in which American theoretical physics "came of age" (Sopka 1988, pp. xvii-xxiii).

3 Darrow's Interpretation of Old Quantum Theory: Waves, Corpuscles, and the Art of Model Building

Old quantum theory was the main topic to which Darrow dedicated his quarterly reviews in the period 1923–1926. In this period, Darrow's papers dealt almost exclusively with the atomic structure and spectral phenomena. Although Darrow preferred focusing on experimental issues, he did not elude conceptual problems and provided his personal judgments. In particular, the relationship between the corpuscular and undulatory pictures of light puzzled Darrow. The complex and perplexing features of this relationship led him to reveal his underlying philosophical beliefs when he first discussed the topic in 1925.

Darrow built his paper concerning the corpuscular and wave phenomena of light on the opinion that experiments had primacy over theory. Such a view is evident in Darrow's assessment of Planck's theory of the blackbody radiation. Darrow (1925) declared that Planck's theory "might practically be confined to the pages of the more profound treatises on the philosophical aspects of physics, if certain experiments had not been guided to seek and to discover phenomena so simple that none could fail to apprehend them, so extraordinary that none could fail to be amazed" (p. 286). Here, not only did Darrow maintain that experiments should guide theoretical research; he also extrapolated two features that experiments must have to be significant. The experiments should lead to the discovery of phenomena that are both simple and unforeseen. These kinds of phenomena were the best suited for stimulating the growth of reliable physical theories—a view that was deeply related to Darrow's overall perspective about what theoretical physics should be.

Darrow considered model building as the fundamental practice of the theoretical branch of physics. This belief became explicit in Darrow's discussion of the photon concept that Albert Einstein (1879–1955) had introduced in 1905. To demonstrate that the apparent lack of physical reality of theoretical models should not prevent one to formulate bold hypotheses, Darrow argued that the "absurdity" of the photon concept faded gradually out of view since Einstein's heuristic hypotheses led to explain more and more experimental phenomena (p. 287). Darrow used the expression "as if" to epitomize the relationship between observations and theoretical models. In the photoelectric effect, the emissions of electrons occurred *as if* the energy of light was concentrated in packets of amount $h\nu$. After having illustrated a variety of experiments bearing on the photon concept, Darrow admitted that they forced one to accept that radiation travels by means of corpuscles of specific energy and momentum. This view, Darrow stressed, was irreconcilable with the wave phenomena characterizing light behavior in different experimental settings. Moreover, the definition itself of the energy and momentum of the photon depended on wave concepts such as frequencies and wavelengths. To reconcile these two seemingly incompatible views, Darrow called for what he defined "a *revolutionary* extension of the art of thinking" (p. 326 my emphasis). Only such a revolutionary transformation could allow physicists to cope with the copresence of such different phenomena; but, unfortunately, Darrow did not try to define the factors that should characterize the modification in the way of thinking he was demanding.

In order to understand Darrow's view of revolutionary change one has to rely on the prolegomena to the first edition of his book *Introduction to Contemporary Physics*, in which Darrow (1926) provided a more clear assessment of both his philosophical views and methodological prescriptions. Cartwright (1987) has recognized the explanatory clarity and philosophical outlook of this text describing it as a "fine piece of philosophy" (p. 426). Darrow's prolegomena was one of the main sources of Cartwright's analysis of the American response to the philosophical queries posed by quantum theory. In Darrow's words, Cartwright argues, one can uncover the conceptual roots of the apparent lack of philosophical anxiety of the American physicists. According to Cartwright, the apparent disinterest of American physicists toward philosophical questions was related to the influence of Bridgman's operationalism as a prescriptive rule for ensuing reliable scientific research. In Darrow's prolegomena, however, Cartwright found the manifestation of a philosophical perspective wider than operationalism, which she epitomized in two methodological prescriptions:

> (1) The task of physics is to describe what it can as accurately as it can, at the same time striving for simplicity and economy of presentation. In particular, the task of physics is not to explain. (2) Physics should not postulate hypotheses, but should accept only what is experimentally verifiable[5].

These two philosophical theses, Cartwright maintained, shaped the American reception of quantum theory and Darrow was an intellectually clear example of a national philosophical tradition.

Cartwright is right when she affirms that Darrow exposed quite explicitly the first thesis. The second thesis, instead, seems to me not to adequately capture Darrow's thoughts. Moreover, the view Darrow articulated was not simply a mirror of the broader cultural milieu, neither can one say that it represented a coherent philosophical doctrine. Darrow's normative prescriptions came out of the historically contingent intellectual conflict between his views of physics as an evolutionary process and the specific status of theoretical physics in that period. When Darrow wrote the book, quantum theory was "a lamentable hodgepodge of hypotheses, principles, theorems, and computational recipes rather than a consistent theory", as Jammer (1966, p. 196) defined it. Darrow's response to such a hodgepodge was to stress the relevance of model-building activity in the advancement of knowledge. The criterion physicists should follow to build physical models was that the models be as simple as possible and describe the greatest number of phenomena—features well summarized by Cartwright's first prescription rule. For Darrow (1926), the belief that simple models governed also complex phenomena was an "act of faith" (p. xix). Such an act of faith had induced theorists to apply the models built on simple experimental phenomena to more complex ones. Darrow contended that the theory of quanta had revealed the limits of this procedure by leading to the coexistence of mutually irreconcilable models such as the corpuscular and wave theories of light, used to explain different phenomena related to the same physical entities.

Darrow's activity as a synthesizer and interpreter of new ideas helped him to find various examples to demonstrate the scientific value of accepting different, and often incompatible, theoretical models of the same supposed entity. To show that this methodology had been useful in the advancement of knowledge, Darrow contended that scientists had been drawing different atom models to describe different phenomena. The nineteenth-century chemists' atom model was different from the rigid elastic sphere early twentieth-century physicists conceived to describe gas features such as elasticity, pressure and specific heat. The latter model, in turn, was completely different from the Rutherford-Bohr atom model, which dealt with the radiation emitted by luminous gases. Each of the three models had its irreplaceable function explaining a particular range of phenomena, but they were barely compatible and did not lead to a coherent vision of the ultimate atom, interpreted as a real entity. Darrow advised the students to "adopt the practice of regarding atom-models as creations of the imagination, as the building stones of mental models designed to copy chosen phenomena of the environing world" (p. xxii), and maintained that this was the practice actually adopted by most physicists. In other

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[5] Cartwright 1987, p. 425.

words, each model had its own validity only within the range of phenomena that it was designed to imitate. The issue that Darrow problematized seems to be, then, more the reality content of theoretical hypotheses than the indisputable role of hypothesizing in the practice of theoretical physics.

Philosopher of science Ian Hacking (1983, pp. 27–28) argued that it is fundamental to differentiate between two kinds of realism: realism about theories—according to which theories are either true or false and science aims at discovering how the world really is—and realism about entities, according to which several entities described by scientific theories exist objectively. Hacking made the point that experimentalists usually believe in physical entities because they can use them (p. 262). One is tempted to ask whether and how Darrow's philosophical perspective fits Hacking's criteria. Certainly, Darrow's view of theoretical physics as a model-building activity demonstrates that, for him, theories were not true and could not aspire to grasp the world as it is. But what about entities? In the prolegomena, Darrow implied that entities such as atoms and electrons existed independently of the theories built to describe their experimental features, but did not explain the reasons underlying this conviction. Darrow just took their existence for granted.

Darrow's main target was to give precise normative rules that theoretical physicists should follow to advance the knowledge of nature. Usually, Darrow argued, only a limited number of features of invisible entities were to be considered as experimentally verified. In order to explain broader phenomena, it was necessary to build models whose properties included and yet exceeded the ones empirically detected. Darrow prescribed a sort of freedom of stipulation about these exceeding properties. The only requirement was that these hypothesized properties should describe an ample range of phenomena. Darrow's advice was not to consider such surplus properties as physical realities and to use different models depicting the same entity in different situations.

In order to extend Cartwright's analysis, it is necessary to emphasize that the issue at stance in Darrow's reflections was the unity of physics as a discipline. Darrow was trying to find some criteria to counterbalance the conceptual and social forces that were undermining the coherence of the theoretical apparatus as well as the compactness of the physics community. In the prolegomena, not only did Darrow explicitly reject that theories might catch the real world; more fundamentally, Darrow was implying that physicists had to renounce to what Hacking (1996, p. 50) calls *local reductionism*; namely, the possibility that physics could be reduced to a set of fundamental principles, from which all the scientific laws might be deduced. In the history of physics, this practical precept has been playing a strong role in the self-perception of unity by practitioners of physics (Cat 1998). In order to articulate a different criterion on which to base a unitary view of physics, Darrow replied to the challenge posed by the conceptual incongruences of the wave-particle duality, by stressing the methodological unity of the model-building practice[6].

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[6] My interpretation of Darrow's writings as a quest for the methodological unity of physics is analogous to the analysis philosopher of science Jordi Cat (1998) made of the debate between emergence and reductionism in physics as implicitly referring to two different models of unification.

Darrow’s book (1926) was a recasting of those articles he had been publishing in the *BSTJ* that assessed the structure of the atoms and related phenomena in the framework of the old quantum theory. One might consider Darrow’s prescription about the net separation between theoretical models and the underlying reality as a response to the “revolutionary extension of the art of thinking” he was asking for to cope with quantum inconsistencies. In Darrow’s opinion, quantum dominion had definitely ruled out the local reductionist program of physics. To reconfigure their theoretical work, physicists had to consider different ways in which to define their activity. Darrow, then, linked the revolutionary change to the re-definition of theoretical work as a research practice limited to the building of models. Of course, Darrow’s thoughts show several elements of the pragmatist perspective that had a great relevance in the philosophical attitude of several American physicists. However, they show more than that. Darrow’s peculiar role makes it evident the tension between the theoretical evolution of quantum physics and his underlying ideological conviction. As I will show in the next sections, Darrow’s subsequent reviews of the advancement of quantum mechanics demonstrate that Darrow continued to reconfigure his philosophical beliefs in order to intellectually engage with novel theoretical developments.

4 Wave Mechanics and the Heuristic Value of Visualizability in Physics

Darrow could not imagine that while his book was being printed, Max Born (1882–1970), Werner Heisenberg (1901–1976), Pascual Jordan (1902–1980), and Erwin Schrödinger (1887–1961) were discovering the basis of quantum mechanics. To assess the novelties produced in the other side of the Atlantic Ocean, Darrow followed a path quite common in the early reception of both matrix and wave mechanics. He read with anxiety the publications of Heisenberg, Born and Jordan, while embracing with relief Schrödinger’s elaboration of De Broglie’s wave interpretation of particles’ behaviour. In his *BSTJ* reviews, Darrow completely bypassed the publications concerning matrix formalism. Darrow (1927) dedicated, instead, the entire first review of the new physics to wave mechanics. He spoke as a representative of the enthusiasm rose in the world of physics about Schrödinger’s theory, which seemed “to promise a fulfilment of th[e] long-baffled and insuppressible desire” of those physicists who “yearn[ed] for *continuity* in their images of science” (p. 653 my emphasis). In July 1926, he had got the impression that Schrödinger’s theory was widely regarded as superior to the concurrent approach pursued by the theoretical physicists in Copenhagen and Gottingen. Canadian-American spectroscopist Arthur Jeffrey Dempster (1886–1950), had offered him a vivid image of the reception of Schrödinger’s papers in Munich:

> Schrödinger's recent developments seem to have put Born and Heisenberg's papers into eclipse (to everyone's apparent satisfaction). At Munich there seems to be the hope that we would possible formally get a satisfactory formulation of the quantum theory in the way[7].

Although Darrow tried to maintain his role of impartial observer of what was going on in physics, he did not hide his preference for Schrödinger's approach. Darrow's personal predisposition is unsurprising because a great number of physicists favorably received wave mechanics[8]. Not only did wave mechanics provide theoretical tools more practicable to resolve specific problems than those of matrix mechanics, it also seemed promising for the possibilities to expand its range of applicability. Moreover, Schrödinger's return to a quasi-classical conception based on the continuity of nature entailed a reinstatement of the visualizability of nature, which the abstractness of matrix mechanics seemed having ruled out permanently. The wave formalism allowed for a descriptive link between microphysical phenomena and more familiar ones, which physicists could use as examples and inspiration (Jammer 1966, pp. 274–84; MacKinnon 1980; Wessels 1983; Beller 1983, 1997; Mehra and Rechenberg 1987, pp. 577–868).

It was precisely the possibility to build a visualizable account of Schrödinger's theory that shaped Darrow's method of exposition. Darrow pointed out that wave mechanics allowed a multiplicity of approaches and that the one he chose was substantially different by those followed by both Schrödinger and Louis De Broglie (1892–1987). His method of exposition, Darrow (1927) believed, was "the one which Schrödinger meant when he wrote 'I had originally the intention of establishing the new formulation of the quantum conditions in this more visualizable (*anschaulich*) way, but preferred a neutral mathematical form, because it makes the essence clearer'" (p. 655).

With his focus on the visualizability of the new description, Darrow was touching one of the most controversial topics in the developments of quantum physics. The notion of *anschaulichkeit* and its relation to the quantum world has led to deep philosophical disagreements between the main actors of the theoretical development of quantum mechanics (Miller 1984, pp. 125–183; Camilleri 2009, pp. 48–53; Jähnert and Lehner 2015). In these controversies, Schrödinger maintained that a visualizable account of the quantum phenomena was essential. However, it is controversial the exact role that this concept played in Schrödinger's development of wave mechanics as well as the connection of such a concept with his broader philosophical position. While some physicists and philosophers claim that Schrödinger's quest for visualization stemmed from his ontological realist position (see, e.g., Harré 1992), philosopher of science Henk de Regt (1997) has convincingly argued that Schrödinger was a methodological realist. For Schrödinger, so De Regt's argument goes, *anschaulichkeit* meant both visualizability and intelligibility because understanding was equivalent to forming space-time pictures. However, De Regt concludes, Schrödinger did not believe that these space-time pictures reproduced

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[7] Dempster 1926.

[8] Historian of science Mara Beller has convincingly argued that the success of Schrödinger's approach was widespread and not limited to "the conservative quarterlies of the physics community" (Beller 1983, p. 470).

reality; Schrödinger thought that scientists should work as if they did (for the complexity of Schrödinger's philosophy, see also Wessels 1983; Bitbol 1996; Beller 1997).

Darrow's own approach to such a controversial issue led him to expose his personal interpretation of what visualization meant. While he seemed to follow what De Regt interprets as the Schrödinger's program for visualization, Darrow's account is curiously different from Schrödinger's. The differences between them gave a clue to Darrow's understanding of Schrodinger's theory as well as his personal program based on the conviction that physics was an evolutionary and continuous process. Darrow did not find it helpful to address wave mechanics from the point of view of the Hamilton analogy between mechanics and optics, which constituted a fundamental part in the evolution of Schrödinger's approach to wave mechanics (Schrödinger 1928, pp. ix, 13–40; for recent in-depth historical analyses see Joas and Lehner 2009; Renn 2013). He insisted, instead, that physical common vibratory processes were essential in order to understand the theory. For him, the word visualization was connected to the possibility of relating the most recent theoretical advancements to mechanical processes well known by a broad section of the scientific community, including the applied physicists and engineers of the Bell Labs.

In order to provide a visualizable account of wave mechanics, Darrow relied on the theory of acoustics whose characteristic problems, Darrow argued, corresponded to the characteristic problems of wave mechanics. From the theory of acoustics, Darrow selected three vibratory phenomena that could be used as models to visualize the atomic stationary states as stationary wave patterns whose natural frequencies corresponded to the quotient between the stationary states' energies and the Planck constant h. The three "familiar examples of stationary wave-patterns," as Darrow (1927, p. 664) called them, were the stretched string, the tensed membrane, and the ball of fluid confined in a spherical shell. The first phenomenon represented the simplest instance of a vibratory phenomenon in one spatial dimension and two variables x and t. The tensed membrane corresponded to the case of a physical system with two spatial dimensions and three variables; while the third, and more complex, example represented a physical vibratory system in three spatial coordinates and four variables x, y, z, and t. The latter, Darrow contended, "present[ed] the closest analogy to the atom-model for the hydrogen atom in wave-mechanics" (p. 673).

Darrow showed that the imposition of boundary conditions and the correlated choice of the coordinate system rigorously determined the frequencies of the permitted vibrations in all the three cases. The mathematical treatment of the three processes allowed Darrow to calculate the formulas of the eigenvalues and eigenfunctions in term of the boundary conditions. The reader might build, then, a clear image of wave mechanics solutions by relating the wave-mechanical formalism to familiar phenomena. Of course, the phenomenon most difficult to visualize was the three-dimensional case of the fluid in a spherical shell. Contrary to the other two acoustic models, the term ψ appearing in the associated wave equation of the three-dimensional fluid could not be interpreted as a perpendicular displacement of the medium with respect to its static position. Darrow, however, did not renounce to the possibility to visualize the wave motion and suggested the reader to consider ψ "as a condensation or a rarefaction, after the fashion of sound-waves" (p. 675).

Once Darrow had completed the discussion of the three examples of wave patterns, his aim turned into relating the mathematical formalism and its associated physical pictures to the cases to which Schrödinger had applied wave mechanics, including the one-dimensional harmonic oscillator and the hydrogen atom. To accomplish this correlation Darrow asked the reader for an imaginative effort: “It would suffice to imagine strings and fluids not uniform like those of the simple theory of vibrating systems and sound but varying from point to point in a curious and artificial way” (p. 655). Darrow was thus seeking to describe through images of physical processes those mathematical terms that made wave mechanics different from ordinary acoustic models. The general differential equation of wave motion was:

$$u^2\nabla^2\Psi = d^2\Psi / dt^2 \tag{1}$$

where ∇^2 was the Laplacian differential operator, and ψ stood for the quantity transmitted by the wave, which in acoustic models was the displacement of the medium from its equilibrium position. In acoustic models, u was the velocity of propagation of the wave front, and u^2 was, of course, always a positive constant. In wave mechanics, the same did not hold. There were cases in which the wave-mechanical correspondent to u^2 varied in function of the coordinates, and cases in which it could take negative values. This meant that one should imagine a string or a fluid whose deformation traveled with an imaginary wave speed. Although Darrow recognized the danger in attaching to mathematical terms words “devoid of any physical meaning,” he did not renounce to use visualizable analogies. For him, the acceptable solutions of Schrödinger’s wave equations of the harmonic oscillator and the hydrogen atom represented respectively “imaginary strings” and “imaginary fluids.” More specifically, Darrow pointed out that any stationary states of the hydrogen atom might be represented by an imaginary fluid, each pervading the whole space.

Darrow’s efforts to build an analogy between wave mechanics and more visualizable phenomena led him to believe that “the vibrating imaginary fluid [would] furnish the customary symbolism for expressing the data of experiment,” for many years to come (p. 685). Darrow’s confidence derived from his belief in the heuristic power of visualizable models in the advancement of knowledge. Although still incomplete, Schrödinger’s theory represented a model very close to Darrow’s own ideal of physical theory. Not only did the theory capture in a single picture a number of different phenomena, including the Davisson-Germer experiment on the diffraction of electrons recently performed at the Bell Labs; it also provided a visualizable scheme to relate invisible phenomena to more familiar ones. For Darrow, the physical models should be as simple as possible, and his discussion of wave mechanics demonstrates that visualizability was a fundamental element in Darrow’s conception of simplicity in physics.

That his discussion of wave mechanics was immersed in Darrow’s view of theoretical physics as a model-building activity is demonstrated by his discussion of the physical meaning of the wavefunction ψ. At the end of the paper, Darrow distanced himself from Schrödinger’s tentative electromagnetic interpretation of ψ as a measure of the density of the electric charge. In the four part of his paper “Quantization as a Problem of Proper Values,” Schrödinger had suggested that the term

$$\rho = e\,\psi\psi^* \tag{2}$$

was the electron charge density; where e was the charge of the electron, ψ was the wavefunction, and ψ^* was its complex conjugate. Even recognizing the heuristic value of considering Eq. (2) as a measure of the electric density, Darrow exposed the difficulties to regard it as a realistic picture of what was going on inside the atom. How could one accept the dissolution of the electron in space and, at the same time, use in the wave equation the Coulomb potential that described the force between two localized particles? Darrow used this striking contradiction to confirm his own view that physical theories did not aim at the truth, while he seemingly considered Schrödinger’s interpretation as a step in the direction of an ontological explanation. Darrow wanted to make it clear that the success of Schrödinger’s model depended only on the fact that it was “unrivalled [as] a *device* for *picturing* the radiation-process” (p. 700 my emphasis). The relationship between Schrödinger’s model and the reality of microscopic phenomena was, in Darrow’s views, out of reach of theoretical analysis. This perspective led Darrow to distance himself from Schrödinger’s views in the following years by embracing the statistical interpretation of the wave function, while retaining his preference for Schrödinger’s formalism.

5 Ensemble-Statistical Interpretation of the Wavefunction

After 1927, Darrow faced the task to deal with the developments and the wide acceptance of a more abstract quantum mechanics. Darrow went along a very personal route by continuing to believe that the wave picture had an epistemic and physical priority over the particle picture, while at the same time embracing the statistical interpretation of the wave function. The first of Darrow’s attempt to cope with the new formulation of quantum mechanics concerned Heisenberg’s indeterminacy principle, which Darrow (1930) called the “principle of indefiniteness.” Darrow disagreed with the usual translation of Heisenberg’s word *Unbestimmtheit*. As Darrow saw it, both uncertainty and indeterminacy did not represent the very idea underlying the mathematical formulation of the principle. Although Darrow did not explain the reason of his semantic choice, one might relate it to his understanding of the principle. Darrow stressed that Heisenberg’s principle was a successful attempt of “harmonizing contradictory ideas,” by fusing together the corpuscular and the wave pictures (p. 188). Seemingly, Darrow followed those physicists who, like Niels Bohr (1885–1962), saw in the Heisenberg’s principle a partial solution to the problem of the wave-particle duality (Jammer 1966, pp. 66–79). However, Darrow held a very personal interpretation by stressing that the fusion of the two apparently irreconcilable pictures was made at the expense of the corpuscular picture.

The way in which Darrow illustrated the principle adhered to this general perspective, by challenging Heisenberg's exposition of the principle. Darrow criticized the use of the γ-rays *Gedankenexperiment* to prove the principle because *thought* and *experiment* were, for him, two contradictory words. Darrow preferred to review actual experiments in which the relationship between the "indefiniteness" principle and the observations was factually evident. The banning of thought experiments from the methodology of physics was an important indication of Darrow's beliefs concerning the prescriptive rules that should have governed reliable scientific research. Methodology and theories were indissolubly linked in a general view of physics in which experiments and visualizability continued to have a privileged epistemic value. Darrow called *illustrations* the actual applications of the principle he discussed in his paper. Illustrating and visualizing were the actions that allowed Darrow to maintain a contact between a tangible and visible world, and the new physical theories, which presented a high degree of abstractness. This attempt underlay Darrow's interpretation of Heisenberg's principle. For him, the principle was "a startling way to save the waves, affirming in substance that what they cannot describe cannot exist" (Darrow 1930, p. 189).

In a subsequent paper on quantum mechanics, the merging of epistemological perspectives and theoretical descriptions became even more explicit. Four years later, Darrow (1934) published a long review of various aspects of quantum mechanics, including wave mechanics, matrix algebra and quantum operators. In this account, Darrow clarified what was the epistemological perspective guiding his assessment of the new advancements in physics. The contradictory copresence of corpuscular and wave conceptions of microphysical phenomena had been Darrow's main concern about quantum physics. Darrow could not figure out how to link such contradictory images of the physical world and he interpreted all the theoretical advancements as a response to this concern. In 1934, after quantum mechanics had reached a level of completeness unpredictable ten years earlier, Darrow evaluated what had been accomplished. The result of this evaluation was to distance his exposition from the way in which quantum mechanics was usually discussed and taught.

Darrow (1934) expressed his distaste for "[t]he trend toward perfect abstraction, which for several years ha[d] been dominant in quantum mechanics" (p. 44). As Darrow explicitly stated, he belonged to the group of scientists who "crave[d] to retain, for as long as possible, as many as possible of the links with the past" (p. 44). This attempt to maintain a clear connection with past achievements in physics led Darrow to restate his preference for Schrödinger's approach. For Darrow, corpuscular and wave pictures had not the same epistemic place in quantum mechanics, but "corpuscles must be subordinated to the waves" (p. 44).

In this paper, Darrow seemed even more inclined to follow Schrödinger's exposition than he had been in his previous paper on wave mechanics. Here, indeed, Darrow accepted Schrödinger's optical-mechanical analogy, which he had dismissed in "Introduction of Wave Mechanics" (Darrow 1927). However, this propensity toward Schrödinger's approach remained embedded in the strong conviction that theoretical physics was a model-building practice as Darrow's interpretation of the wavefunction demonstrates. Darrow accepted what is usually called the ensemble-statistical interpretation of quantum mechanics, according to which wavefunctions do not apply to an individual system (Jammer 1974, pp. 38–44, 440–443; Beller 1990). Darrow (1926) believed it to be a strength of the theory that it did not deal with individual atoms "for no statement about the individual behavior of an atom [could] ever be subject to an experimental test" (p. 319).

In order to understand the singularity of Darrow's approach, it is useful to evaluate it against the views held by American theoretical physicists at the time. As Cartwright showed, the statistical interpretation, which Darrow accepted, was widely accepted by the American community of theoretical physicists between the late 1920s and the early 1930s (Cartwright 1987, p. 419). Cartwright used the widespread acceptance of the ensemble-statistical interpretation to confirm that the operationalist-pragmatist philosophical perspective had shaped the American reception of quantum theory. However, the nuanced differences between the various approaches were even more revealing than their similarities. To make these distinctions emerge, one can compare Darrow's views with those of Van Vleck, who was to become a champion of the statistical interpretation of quantum mechanics in the United States.

In 1929, Van Vleck declared that the choice among the various formulations of quantum mechanics depended on the mathematical training:

> [T]he wave formulation of the new mechanics is apt to appeal most strongly to mathematical physicists who have been trained primarily along the line of classical nineteenth century mathematical physics, whereas the matrix formulation appeals more strongly to those who have been trained in the mathematics of the old quantum theory, especially the correspondence principle[9].

Van Vleck was describing a generation gap depending on the different mathematical training of younger American theoretical physicists with respect to the older generation. Like many theorists of his generation, Van Vleck stood for the more abstract formalism of the transformation theory of Paul Dirac (1902–1984) and Jordan, interpreted as a statistical description of the behavior of several particles. The transformation theory pleased him because it was the most comprehensive formulation of quantum mechanics and included all the other formulations as special cases. In Van Vleck's views, the statistical interpretation became the physical viewpoint that allowed for the unification of all the various mathematical approaches. As for Schrödinger's theory, Van Vleck (1929b) contended that it was strongly related to what he called its "extreme hydrodynamical interpretation" (p. 480); namely, the view that the electron was a fluid-like substance whose actual motion was described by the wave equation. According to Van Vleck, this interpretation appealed only to those physicists who were "rather loath to accept the revolutionary philosophy of Heisenberg's indeterminism principle" (p. 479).

Historical studies corroborated Van Vleck's opinion that different interpretations of quantum mechanics depended on different mathematical trainings (Sopka 1988; Servos 1986). However, I have shown that Darrow accepted the statistical interpretation of the wave equation and discarded what Van Vleck called its "extreme

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[9] Van Vleck 1929a, p. 485.

hydrodynamical interpretation." Darrow preferred Schrödinger's theory because it was more visualizable than the alternative approaches. More deeply, Schrödinger's formalism allowed Darrow to maintain "the links with the past." The particular role of wave mechanics in Darrow's view of the progress of physics suggests that the choice between different formalisms touched a more profound level than the generation gap Van Vleck emphasized. The divergence between Darrow and Van Vleck's attitudes stemmed from different opinions about how physics evolved, which in turn depended on their daily activities. Van Vleck was a theorist who actively engaged with the physical problems of quantum mechanics, while Darrow had a completely different role. He tried to make sense of these fast theoretical changes for a broader community of physicists. These changes were undermining the unity of physics because conceptual problems were distancing the assumptions held by quantum theorists from those used, for example, by the experimenters who provided the experimental basis of quantum mechanics (see, e.g., Chang 1995). In a period of theoretical instability, Darrow chose to explore and highlight the coherence of the scientific tradition. The different activities of Van Vleck and Darrow led to conflicting descriptions of quantum mechanics even though the proponents shared the same broad philosophical position and accepted the same physical interpretation. As I will show shortly, Darrow's choice depended, in fact, on precise ideological views on the progress of physics.

6 The Evolutionary Character of Physics

Schrödinger's equation was the mathematical tool that allowed Darrow to bridge novel theoretical developments with classical physics, and to demonstrate the evolutionary character of physics. When Darrow (1925) first tried to review the wave-corpuscle duality, he concluded his paper asking for a revolutionary change of mind in order to deal with the contradictory results of different experiments. Ten years later, he challenged the revolutionary perspective by pointing out, instead, that "what [was] happening in modern physics [was] a tremendously rapid evolution" (Darrow 1936, p. 16). The program of unifying the wave and corpuscular pictures of both radiation and matter accomplished by quantum mechanics was only apparently revolutionary. This appearance was fueled by "many among the workers in quantum mechanics [who] have helped to confirm that impression, by writing or speaking of the downfall, the overthrow, or the repudiation of classical theories" (Darrow 1934, p. 24). But, Darrow stressed, there had never been a revolution "more gradual, more cautious, more tenacious of all the virtues of the old regime" (p. 24). The radicalism of single new ideas did not touch the "immense conservatism of the scientific mind," which continued to drive the progress of physics (p. 24). Although physicists were making "strange things" with the Hamilton equation, the very equation and, above all, the relationship between mathematical computations and observations showed a clear continuity with classical physics (p. 24). In Darrow's views, Maxwell and Lorentz were not superseded. Quite the contrary, they provided the unmodified bases of the new advancements.

The clearest exposition of Darrow's belief in the evolutionary character of physics is in the collection of the lectures Darrow (1936) gave before the Lowell Institute in Boston, published with the revealing name of *The Renaissance of Physics*. The introduction of the book was an ode to the conservatism of physics. For Darrow, contemporary innovators moved in a very definite path whose borders had been solidly built by the works of their predecessors. Darrow's thesis of the evolutionary process of physics, of course, required that something remained constant in what might seem a twisting of the ordinary notions of physics, such as particles and waves, or space and time. When Darrow tried to define what he called the "royal line" of physics (p. 16), he contended that the "historic continuity of physics" depended on the permanence of the tools, theoretical as well as material (p. 78). Centuries of research have provided the physicists with all the "instruments for the hand" and the "instruments for the mind," which they used to do their daily work (p. 14). Without such instruments, Darrow implied, physicists could do nothing. And the tools did not change in an abrupt revolutionary way. On the contrary, they persisted and made possible novel combinations of the representation of nature.

While the gradual transformation of experimental tools seemed self-evident to Darrow, the development of quantum mechanics required an in-depth analysis of the evolutionary character of theories. To demonstrate that intellectual tools resisted revolutionary changes as much as measuring instruments did, Darrow again referred to the normative usefulness of the model-building activity. Darrow took as the most relevant example the copresence of corpuscle and wave theories in contemporary explanations of quantum phenomena. As Darrow saw it, physicists "ha[d] spent centuries trying to reject either the wave theory or the corpuscle theory; and [they] ha[d] ended by keeping them both, tacitly consenting to whatever violence must be done to our habits of thought" (p. 15). But, how should one interpret such a coexistence of apparently irreconcilable theories? In the chapter on the duality of waves and corpuscles, Darrow eventually gave up any hope of resolving the mystery in any definite manner. He expressed his scepticism about all the metaphysical explanations that had so far been proposed, and advised the reader not to blindly follow any particular school of thought.

With *The Renaissance of Physics*, Darrow's personal struggle with quantum mechanics, and, in particular, with the particle-wave duality, came to an end with a strong reaffirmation of his earlier philosophical position on the necessary copresence of different theoretical models. By the late 1930s, Darrow claimed, the intellectual war between the two conceptions had "died away without victory" (p. 168). All physicists had come to embrace, or at least, to tolerate the duality. All they needed to know were De Broglie's rules of correlation linking energy and momentum of the particles with the frequencies and wavelength of the associated waves. The experimental evidence for the different phenomena was overwhelming. While Darrow considered the various interpretations to be inconclusive, he claimed total confidence in the experimental verifications of both wave and corpuscular phenomena. In the conclusion of his ten-year personal conceptual fight with the wave-particle duality, Darrow reconfirmed his belief that experiments had priority over theories in the evolution of physics. He contended that physicists had to believe in waves because of the phenomena of diffraction, and had to believe in corpuscles because they had seen their splashes and tracks in the Wilson chamber. Darrow's apparent endorsement of the positivist motto that "seeing is believing" represented actually a view quite different from those held by the leading exponents of positivist and logical-positivist doctrines (Hacking 1983, p. 63). Darrow was perfectly aware that there were different ways of seeing. When he stated that his generation was the first to have seen the atom, he stressed that physicists had not seen it in the same way in which they saw macroscopic objects, such as balls and pebbles. Physicists had seen atomic tracks. For Darrow, there was no epistemic difference between seeing an object and seeing its tracks; both constituted conclusive evidence for the ultimate reality of the physical entities. Such a view was consistent with a strong tradition in experimental physics, which historian of science Peter Galison (1997, p. 22) called "image tradition"—an epistemic tradition that experimentalists upheld throughout the twentieth century. Although Darrow was not an experimental physicist, he was one of the most receptive exponents of this tradition and his focus on visualizable theoretical models seems to be in line with this tradition. In all of his writings on quantum mechanics, he consciously tried to build a hermeneutics of quantum mechanical problems that would allow the continuity of this tradition to emerge out of the changing world of theoretical physicists.

7 Conclusion. American Ideology of National Science and the "Renaissance of Physics"

Darrow was neither a theoretical nor an experimental physicist. He was a mediator between different subcultures of physics. Darrow believed in the need for synthetic reviews of complex developments in physics and dedicated his stylistic talent to this purpose. Nevertheless, he did not receive passively what was going on in theoretical physics. On the one hand, he had to reconfigure his set of beliefs in order to cope with the duality of the wave-corpuscle pictures of light and matter as well as with the theoretical responses to this problem. On the other hand, he interpreted and translated the new concepts and mathematical tools in a very personal way. Cartwright's interpretation of Darrow's words as embedded in the American operationalist-pragmatist approach to quantum theory is valuable, but it does not consider the several nuances of this case as well as its historical evolution. Darrow shared various common epistemological beliefs with other American physicists, but he questioned the inclination for abstractness of matrix algebra and transformation theory, which many American theoretical physicists showed (Van Vleck 1929a, 1929b; Sopka 1988, pp. 221–302). Darrow's personal accounts of quantum theory ultimately depended on the strong belief that physics was essentially an evolutionary discipline—a view deeply different from that maintained by those theoretical physicists who stressed the revolutionary character of the new theories.

Although Darrow gave equal relevance to the theoretical and material tools in the continuity of physics, his picture of how physicists acquire knowledge focused on the experimental side of physics. He affirmed his admiration for Kamerlingh Onnes's famous motto "through measuring to knowing" (Darrow 1936, p. 51). For Darrow, measurement was the only way through which conceptions of invisible entities acquire meaning. Since nature did not present herself in such a way that simple laws could be deciphered, so Darrow's argument went, physicists needed to arrange for situations that allowed them to observe the underlying simplicity. Thus Darrow demonstrated his full adherence to a Baconian view of experimental physics: Only by forcing nature into a specific artificial setting could she reveal a part of her secrets (Hacking1983, p. 246).

One is tempted to trace the connections between Darrow's full commitment to the Baconian view of experimentation and his working milieu. The Bell Labs were a multidisciplinary setting in which physicists and engineers worked closely together in a goal-oriented practice. Since the late nineteenth century, in such an environment the borders between pure and applied science were contingently shifting and, often, disappeared (Shapin 2008). Darrow argued that the engineer was nothing but an applied physicist. He also stated that the pure and the applied physicist made essentially the same thing. They both modified nature: the former to understand her; the latter to make her serve people. What Darrow was implicitly providing was a description of his own perception of how scientists acted and thought in a techno-scientific environment[10].

Experimentation, in Darrow's words, became a means for dividing the atom and using its constituent parts to create new elements. Even though Darrow was probably influenced by the recent discoveries of new particles, such as the neutron and the positron, the major factor influencing Darrow's explicit connection between pure and applied physics strongly depended on the ideological trend that American physicists were following in the 1920s. Historian of science Ronald Tobey (1971) argued that leading American scientists tried to popularize an ideology of national science in the post-World War I period. The conservative character of such an ideology implied that scientific progress was evolutionary, not revolutionary. Tobey maintained that this ideology considered experimental physics and goal-oriented industrial research groups as an alternative model of inquiry to the solitary and esoteric practices of theoretical physics. In their struggle for recognition and funds, certain American scientists were trying to build an image of pure sciences as the basis of applied sciences. Millikan, one of the principal actors in developing such an ideology, claimed that American industrial development would have suffered if pure research were not supported sufficiently. This ideological hierarchy served as an argument for the funding campaign for the National Research Council among American industrial firms, which started in 1926.

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[10] Darrow's description shares common elements with the idealized framework the historian of science John Pickstone (2000) has created about the ways in which scientists know nature and make artifacts.

AT&T was one of the few industrial firms that substantially contributed to the fund. The reciprocal influence between Millikan's views on physics and the research policies of the Bell Labs was enormous and complex (Kevles 1971; Gertner 2012). Millikan also had a strong influence in shaping Darrow's view of physics as well as his career. Darrow had been a student of Millikan and the latter strongly supported the appointing of the former within the research staff of the Bell System. Moreover, Darrow's position at the juncture between experimental and industrial physics was in line with the ideology professed by many American scientists. It is unsurprising that the politically conservative Darrow sincerely shared the set of values popularized by Millikan in the 1920s. *The Renaissance of Physics* was, indeed, the summa of this ideological view of physics. In the introduction, Darrow (1936) explicitly asked the reader to accept that engineering was "a province of physics" (p. 6). By subordinating applied physics and engineering to pure physics, Darrow was giving his contribution to the widespread endeavor to provide funding for the National Research Council.

Seen in this ideological perspective, the "historic continuity of physics" stood as the central argument on which Darrow tried to demonstrate the genetic role of physics with respect to related applied sciences. The diachronic continuity between classical physics and quantum theory corresponded to the synchronic continuity of methods between different disciplines. Darrow disliked specializations. For him, the unification of physics was to be social as well as epistemic. A community of pure and applied physicists should have continued to be able to discuss all the topics of the various subdisciplines of physics. His work to spread the new knowledge and the way in which he coped with various topics had just this aim: to preserve as long as possible the continuity of physics. While he thought of himself as a champion of the temporal continuity of physics, his implicit purpose was to challenge the impending fragmentation of the physics community (Weart 1992; Kaiser 2012). From this perspective, Darrow's reading of quantum theoretical developments and his commitment to Schrödinger's formalism were just some of the strategies through which he struggled for epistemic and social continuity within physics.

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