Animating the EPR-Experiment:
Reasoning from error in the search for Bell violations

Anubav Vasudevan

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Deborah G. Mayo, Chair
Laura Perini
Aris Spanos

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(ABSTRACT)

When faced with Duhemian problems of underdetermination, scientific method suggests neither a circumvention of such difficulties *via* the uncritical acceptance of background assumptions, nor the employment of epistemically unsatisfying subjectivist models of rational retainment. Instead, scientists are challenged to attack problems of underdetermination 'head-on', through a careful analysis of the severity of the testing procedures responsible for the production and modeling of their anomalous data.

Researchers faced with the task of explaining empirical anomalies, employ a number of diverse and clever *experimental* techniques designed to cut through the Duhemian mists, and account for potential sources of error that might weaken an otherwise warranted inference. In lieu of such progressive experimental procedures, scientists try to identify the *actual* inferential work that an existing experiment is capable of providing so as to avoid ascribing to its output more discriminative power than it is rightfully due.

We argue that the various strategies adopted by researchers involved in the testing of Bell's inequality, are well represented by Mayo's error-statistical notion of scientific evidence. In particular, an acceptance of her stringent demand for the output of severe tests to stand at the basis of rational inference, helps to explain the methodological reactions expressed by scientists in response to the loopholes that plagued the early Bell experiments performed by Alain Aspect *et al.*. At the same time, we argue as a counterpoint, that these very reactions present a challenge for 'top-down' approaches to Duhem's problem.

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Chapter 1: Introduction

The implications of Bell's theorem for our understanding of how quantum-scale systems interact, is a topic that has recently received a great deal of attention from philosophers concerned with the foundations of the physical sciences. There is little doubt that the theorem's popularity amongst this group stems from the fact that its subject matter – the non-local interactions of so-called 'entangled' composite systems – represents one of the more perplexing and counter-intuitive features of our modern scientific image of the world. Indeed, the idea of entanglement lies so close to the source of the many well-known paradoxes of quantum mechanics that Erwin Schrödinger, one of the founders of quantum theory, felt it apt to describe the sort of composition it represents as not *one*, but rather '*the* characteristic trait of quantum mechanics… that enforces its departure from classical lines of thought.'[1] In the light of Schrödinger's remark, it is not difficult to see why Bell's Theorem, which amounts to the formal expression of quantum mechanics' commitment to the 'spooky'[2] behaviors of entangled systems, plays a serious role in the debate of those concerned to develop a scientifically sound metaphysics.

Yet despite its potentially lofty theoretical implications, the story of Bell's theorem is, in large part, a story set in the laboratory. Its characters include not only theoreticians, but also a host of resourceful experimentalists whose principal charge was to 'bring to life' Bell's idealized thought experiments within the far-from-ideal milieu of

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[1] Schrödinger E., (1935) *Proceedings of the Cambridge Philosophical Society*, vol. 31, p. 555. It was in this article that Schrödinger coined the term 'entanglement.'
[2] Albert Einstein famously derided the troubling interactions between entangled pairs as 'spooky action-at-a-distance.'

the laboratory. In its entirety, the story of Bell's theorem represents a narrative of remarkable scope, countenancing the heady polemics pitting Einstein's local realism against Bohr's framework of complementarity[3], as well as more earthly developments in random number generation and the technology of photo-detectors. Historically, it extends across most of the twentieth century and into the future, with origins in the famous 1935 paper of EPR[4] and a continued relevance ensured by its fundamental contributions to the still-developing fields of quantum computation and quantum cryptography.

But perhaps the true magnitude of a full accounting of Bell's theorem is best appreciated with the recognition that, all told, it bears the burden of explaining how scientists managed to navigate the numerous inferential gaps that separate a simple sequence of pairs of '1's' and '0's' from a theoretical conclusion occupying the upper most levels of scientific abstraction. Put this way, it is easy to appreciate the difficulty of telling an unabridged history of Bell's Theorem, and that such a story even exists to be told seems a rather remarkable prospect. As R.P. Feynman writes, "It seems almost ridiculous that you can squeeze [the difficulties of quantum mechanics] into a numerical question that one thing is bigger than another. But there you are..."[5]

Certainly, the complete telling of this story is a project too large for a single paper; it is perhaps better suited for a book. Nevertheless, thanks to developments in our philosophical understanding of scientific models and their role in methodology, there are organizing techniques that permit the deconstruction of this narrative into chapters that

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[3] For an interesting discussion of how Bohr's criticism of EPR fits into the general Bell polemics, see Henry Folse's article, *Bohr on Bell*, published in *Philosophical Consequences of Quantum Theory* (Notre Dame Press: 1989).

[4] Einstein A., Podolsky B., Rosen N., (1935) *Phys. Rev.* vol. 47, p. 777.

[5] Feynman R.P., (1982) *International Journal of Theoretical Physics*, vol. 21., p. 467.

can be identified as distinct and self-contained epistemological episodes in the more general, overarching inquiry.

Deborah Mayo, in her 1996 book *Error and the Growth of Experimental Knowledge*, proposes a construal of scientific inquiry 'in terms of a series of representations or models ranging from the primary scientific…questions that are being addressed…to the nitty-gritty details of the generation and analysis of data.'[6] The objective of such a construal is to 'have at our disposal a framework that permits us to delineate the relatively complex steps from raw data to scientific hypotheses, and to systematically pose the questions that arise at each step.'[7] In the spirit of Mayo's suggestion, the remainder of this introduction will attempt to motivate a framework depicting the various models of inquiry employed in the general investigation into the non-local nature of entangled systems. Such a framework will serve two purposes: first, it will facilitate a careful demarcation of the intended scope of this paper; and second, it will help to establish precisely where my analysis differs from more conventional philosophical treatments of the subject.

It is necessary before introducing this framework, however, to make a few preliminary remarks concerning the general structure of Bell's Theorem and the specific role it plays in our understanding of non-locality. While many of the details will either be left out or left for later, this introduction should help to distinguish between the various levels at which Bell's Theorem can be scrutinized, and ultimately move us towards a precise specification of just how the analysis attempted in this paper fits into the larger landscape of the philosophical study of quantum mechanics.

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[6] Mayo D., (1996) *Error and the Growth of Experimental Knowledge* (Chicago Press), p. 128.
[7] Ibid., p. 129.

Bell's theorem, in its most general form, asserts that the statistical predictions of quantum mechanics are incompatible with those of the broad class of theories that posit 'local' hidden variables to fix the measurement outcomes performed on certain carefully prepared, composite physical systems. The theorem's proof is expressed in the language of the Bohm variation of the famous EPR *gedankenexperiment*[8] introduced in the paper by Einstein *et al.* entitled *Can Quantum Mechanical Description of Physical Reality be Considered Complete?*. The proof itself is a work in two stages, the first of which culminates in the articulation of a mathematical constraint – referred to, in the contemporary vernacular, as Bell's inequality – on the statistical predictions of any local hidden-variable (LHV) model of the EPR experiment. The second stage of the proof, then, demonstrates that the predictions of quantum theory stand in violation of this constraint. From these two conclusions it is inferred that the statistical output of quantum mechanics cannot be ascribed to an incomplete characterization of a set of local hidden-variables.

While this statement of the impossibility of an LHV construal of quantum mechanics is often labeled as 'Bell's Theorem,' it is important to realize that the contributions of Bell's work to our understanding of non-locality extend well beyond the establishment of one peculiar feature of the quantum mechanical formalism. By introducing Bell's inequality as a general constraint on the experimental predictions of the whole class of LHV models, Bell's work motivates a partitioning of the space of theories along empirically decidable lines, a partitioning that in no way depends upon the adequacy or correctness of quantum mechanics. A violation of Bell's inequality thus refutes a whole category of potential representations of the EPR phenomenon, and this

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[8] Bohm D., (1935) *Quantum Theory*, (Prentice Hall Publishing).

refutation persists even if the particular violation turns out not to match that predicted by quantum mechanics. As Jon Jarrett puts it:

…[T]he claim here is *not* that our best theoretical account of these phenomena, namely that of quantum mechanics, is not a local realistic account. That quantum mechanics is not a local realistic theory is, of course, true; but the claim being made here goes considerably beyond this. The claim is that we can have strong empirical evidence (I repeat – strong *empirical* evidence) that *no* local realistic theory is true of our world.[9]

Now, the criterion by which local realistic theories are delimited in the context of Bell's theorem is expressed in strictly formal terms.[10] Because of the formality of Bell's proposed 'locality criterion', the derivation of Bell's inequality as a necessary restriction on the predictions of LHV theories is simply a matter of mathematical proof. Of course, the *metaphysical* bite of Bell's theorem comes from the fact that this formal characterization of LHV theories is intended to map onto the *in*formal notion of local realism, an idea captured, roughly, by the following passage from Einstein's 1948 paper, *Quantum Mechanics and Reality*:

The concepts of physics refer to a real external world, i.e., ideas are posited of things that claim a "real existence" independent of the perceiving subject… Moreover, it is characteristic of these physical things that they are conceived of as being arranged in a space-time continuum. Further, it is essential for this

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[9] Jarrett J., *Bell's Theorem: A Guide to the Implications*, published in *Philosophical Consequences of Quantum Theory* (Notre Dame Press: 1989, Author's Italics).
[10] LHV theories are those theories which satisfy Bell's 'locality criterion', a criterion expressed in terms of the factorizability of the joint probability distribution describing the possible outcomes of spatially separated measurements performed on the two elements of an entangled pair

arrangement…that, at a specific time, these things claim an existence independent of one another, insofar as they "lie in different parts of space"[11]

An immediate question that arises at this stage of the discussion asks just how well Bell's 'locality criterion' captures the spirit of the framework of local realism, as described in the above passage. Are all and only LHV theories those that fit within Einstein's conception of physical reality? This sort of question, directed at the adequacy of the mathematical rendering of an informally expressed notion will, on my schematization, occupy the space between what I call a theoretical representation of a phenomenon – or, simply, a theory – and a theoretically *modeled* representation of that phenomenon.

In the context of our discussion of Bell's theorem, the important point to note about questions of this sort is that they are *not* concerned to ask whether Bell's inequality is, in fact, violated in certain EPR experiments, nor whether such violations speak against the class of LHV theories (as picked out by Bell's locality criterion). Instead, investigations of this sort *begin* with the refutation of LHV theories, and ask what such a refutation means for our general theoretical understanding of the EPR phenomenon. They are attempts to assimilate a formally expressed physical principle into an informal phenomenological description, and beyond that, into a metaphysical worldview.

I would suggest that the majority of philosophical treatments of Bell's theorem are concerned to address precisely these sorts of higher-level, interpretive issues. In Don Howard's paper *Holism, Separability and the Metaphysical Implications of the Bell experiments*, his perceived relationship between the practice and philosophy of physics is described in a manner consistent with my suggestion:

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[11] Einstein A., (1948) *Quantenmechanik und Wirklichkeit, Dialectica* 2, p. 320.

I regard physics as aiming, first, to establish formal principles… that function as constraints upon constructive models of the world. Developing the latter is the more properly metaphysical task; it is by the construction of [these] models that we learn in what kind of world the physical principles can be realized. The two types of investigation are complementary, with the elaboration of new principles further constraining and thus guiding the search for metaphysical models, and the development of new models helping to probe the limits of validity of the formal principles.[12]

Howard's idea in this passage is that it is the task of physics to provide the formal constraints on the informal models provided by philosophers. Physics provides a formalism in which to make sense of the empirical world, and philosophers of physics – or philosophically minded physicists – tell us just what sort of world those principles reveal.

I will not say anything more about Howard's characterization of the relationship between physics and metaphysics, except to note that I find much of what he says to be compelling. My point of introducing his distinction between the practice and philosophy of physics is simply to suggest that if we adopt his terminology, the analysis performed in this paper is *not* an exercise in the metaphysics of non-locality. No claims will be made about the proper theoretical construal of Bell's formal criterion of locality[13], nor will I discuss the implication of Bell's Theorem for scientific realism, or probabilistic models of causality. Instead, I intend to discuss the lower-level experimental challenges that scientists faced in the design and execution of an experiment capable of demonstrating a genuine violation of Bell's inequality.

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[12] Howard D., *Holism, Separability and the Metaphysical Implications of the Bell experiments* published in *Philosophical Consequences of Quantum Theory* (Notre Dame Press: 1989)

As suggested above, the significance of Bell's Theorem resides not only in its proof of the inconsistency of an LHV construal of quantum mechanics, but also in the connection which it establishes between a theoretically modeled parameter *viz.*, a theory's violation of Bell's locality criterion, and an estimable measure that could, at least in principle, be made the subject of a realizable experimental inquiry *viz.*, a violation of Bell's inequality. The establishment of this connection grants a theoretical relevance to the project aimed at designing and executing an actual experiment of the sort depicted in the idealized EPR *gedanken*, a test capable of providing evidence of a genuine Bell violation. The story of how scientists grappled with and ultimately overcame the many challenges that opposed the execution of such a test is the chapter in the history of Bell's Theorem that I will be concerned to investigate.

The framework depicted in figure 1.1 is a graphical summary of the discussion so far. Again, the point of such a framework is to provide an organizing structure for understanding a particular scientific inquiry in terms of the various ways in which the phenomenon under study can be modeled. In its most raw representational form, the output of a test designed to detect Bell violations can be understood as a simple series of '1's and '0's; beyond that it can be represented as a statistically modeled observation[14], and beyond that as a genuine Bell violation. Bell's theorem suggests that any phenomenon that can be modeled as a Bell violation can also be represented as a non-LHV statistical phenomenon, and more abstract theoretical thinkers take this representation to warrant the disconfirmation of Einstein's informally expressed framework of local realism. The very same phenomena, then, can be represented, one the

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[14] The task of articulating and evaluating a statistical model within which to embed the raw data, is perhaps the most basic and fundamental task facing scientists engaged in the testing of Bell's inequality. I will not, however, discuss here, these 'lowest-level' challenges.

one hand, as the raw data output from a complicated experimental apparatus, and, on the other, as the '…deathblow for one of the… fundamental elements of our classical view of the world.'

The difficult task facing scientists is to supply the inferential bridges that connect these various models of a phenomenon, and the numerous stages of this task occur at varying levels of theoretical abstraction. As indicated in figure 1.1, most philosophical treatments of Bell's theorem begin with the discounting of LHV models of the EPR phenomenon and extract from that refutation metaphysical lessons. My analysis, on the other hand, has as its *conclusion* the demonstration of a violation of Bell's inequality and aims to extract what *methodological* insight can be had from an examination of the scientific work required to achieve that end. In an important sense, then, the principal subject of this paper is not Bell's theorem at all. It is instead the series of experiments designed to live up to the various idealizations characterizing the stylized experimental setting of the EPR *gedanken*. The particular challenges facing the scientists engaged in the design of these experiments amount to criticisms directed at the adequacy of particular testing protocols to reveal a genuine violation of Bell's inequality, and consequently, rule out the whole class of LHV theories from the scientific running.

Like all good stories, the experimental history of the search for Bell violations offers us insight into matters that extend beyond its own, limited domain. In particular, the methodological reactions engendered by criticisms of the early Bell experiments, provide a clear illustration of the commitment of scientific workers to the development of
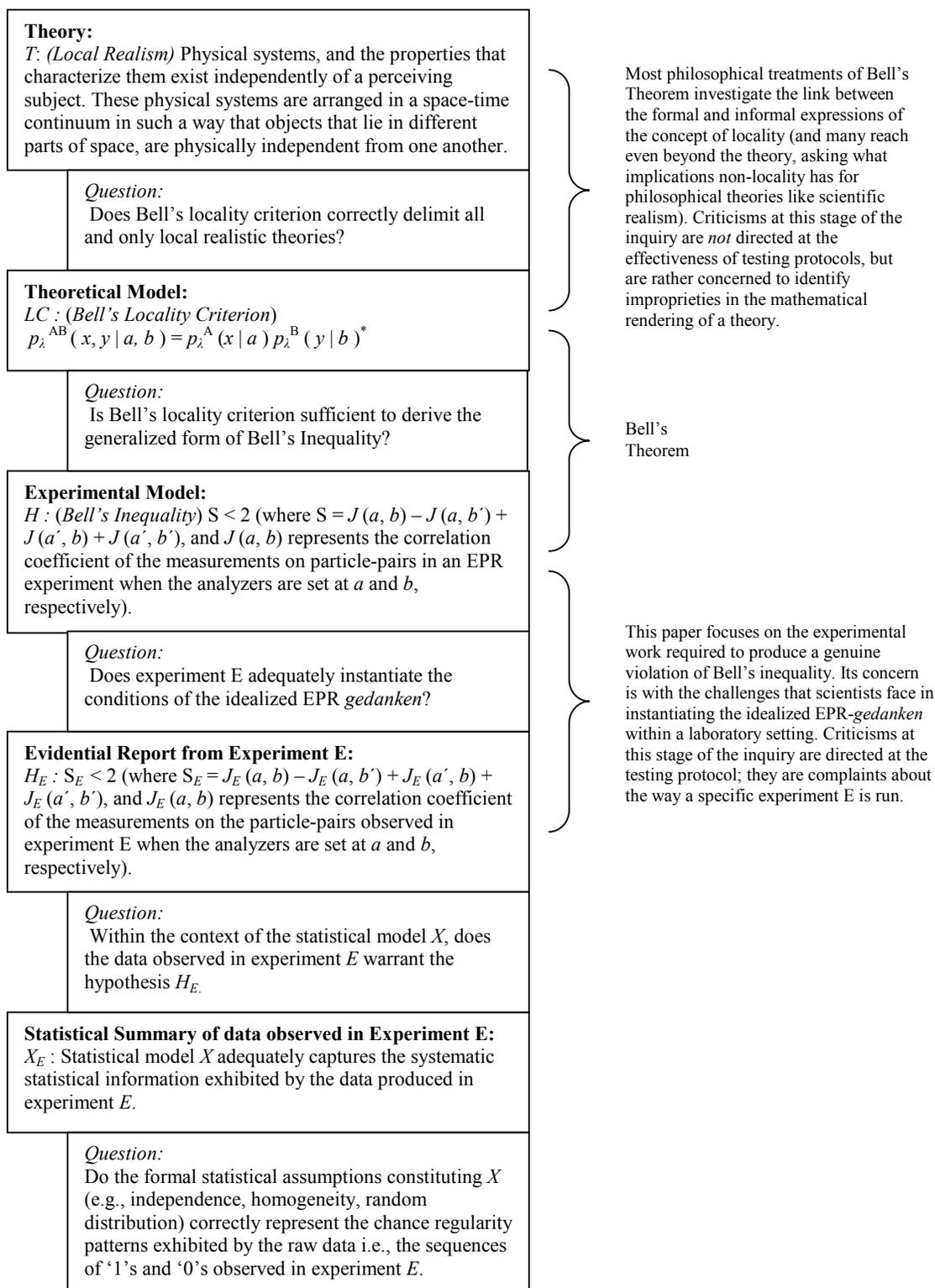
severe tests[15] capable of accounting for all the various errors that might infect an otherwise warranted inference.

In support of this claim, it will be argued that even the most *prima facie* implausible attempts to 'save' LHV models from empirical disconfirmation were given due consideration, and they often played the role of catalysts in the development of new and better experimental settings. When tests capable of ruling out such attempts to rescue locality were impracticable due to technological limitations or a simple lack of experimental creativity, rather than describe the existing results as conferring a certain 'likelihood' upon the possibility of an LHV construal of the phenomenon, scientists worked to delimit the precise theoretical scope of the available experimental evidence: If a particular experiment was incapable of discounting the whole class of LHV models of the EPR phenomenon, then, it was asked, what subset of LHV theories could it successfully rule out?

In the following chapters I will attempt to articulate a more careful defense of these claims. The structure of my discussion will take as its focus the visible photon correlation experiments performed by Alain Aspect and colleagues in the early eighties, considered by many to be the first tests to provide conclusive evidence of the fundamental non-locality of certain natural processes *via* a demonstration of a violation of the generalized form of Bell's inequality. In Chapter 2, I will present an introduction to this experimental program by way of a careful depiction of the conceptual loopholes that challenged the optimistic interpretation of the Aspect group's results as indicative of a genuine Bell violation. In Chapter 3, I will attempt to articulate the methodological

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[15] Later this notion of 'severity' will be identified with that developed in Deborah Mayo's error-statistical approach to scientific methodology. See Section 3.2.

responses of scientific workers to these 'Duhemian' challenges, and argue that their reactions betray a fundamental commitment to the development of severe testing schemes within which the various errors that might weaken an otherwise warranted inference are accounted for.

Theory:
T: *(Local Realism)* Physical systems, and the properties that characterize them exist independently of a perceiving subject. These physical systems are arranged in a space-time continuum in such a way that objects that lie in different parts of space, are physically independent from one another.

Question:
 Does Bell's locality criterion correctly delimit all and only local realistic theories?

Theoretical Model:
LC : (*Bell's Locality Criterion*)
$p_\lambda^{AB}(x, y \mid a, b) = p_\lambda^A(x \mid a)\, p_\lambda^B(y \mid b)$ *

Question:
 Is Bell's locality criterion sufficient to derive the generalized form of Bell's Inequality?

Experimental Model:
H : (*Bell's Inequality*) S < 2 (where S = *J* (*a*, *b*) − *J* (*a*, *b′*) + *J* (*a′*, *b*) + *J* (*a′*, *b′*), and *J* (*a*, *b*) represents the correlation coefficient of the measurements on particle-pairs in an EPR experiment when the analyzers are set at *a* and *b*, respectively).

Question:
 Does experiment E adequately instantiate the conditions of the idealized EPR *gedanken*?

Evidential Report from Experiment E:
H_E : S_E < 2 (where S_E = J_E (*a*, *b*) − J_E (*a*, *b′*) + J_E (*a′*, *b*) + J_E (*a′*, *b′*), and J_E (*a*, *b*) represents the correlation coefficient of the measurements on the particle-pairs observed in experiment E when the analyzers are set at *a* and *b*, respectively).

Question:
 Within the context of the statistical model *X*, does the data observed in experiment *E* warrant the hypothesis H_E.

Statistical Summary of data observed in Experiment E:
X_E : Statistical model *X* adequately captures the systematic statistical information exhibited by the data produced in experiment *E*.

Question:
Do the formal statistical assumptions constituting *X* (e.g., independence, homogeneity, random distribution) correctly represent the chance regularity patterns exhibited by the raw data i.e., the sequences of '1's and '0's observed in experiment *E*.

Most philosophical treatments of Bell's Theorem investigate the link between the formal and informal expressions of the concept of locality (and many reach even beyond the theory, asking what implications non-locality has for philosophical theories like scientific realism). Criticisms at this stage of the inquiry are *not* directed at the effectiveness of testing protocols, but are rather concerned to identify improprieties in the mathematical rendering of a theory.

Bell's Theorem

This paper focuses on the experimental work required to produce a genuine violation of Bell's inequality. Its concern is with the challenges that scientists face in instantiating the idealized EPR-*gedanken* within a laboratory setting. Criticisms at this stage of the inquiry are directed at the testing protocol; they are complaints about the way a specific experiment E is run.

* The notation used here is that devised by Jon Jarret in his (1989). $p_\lambda^{AB}(x, y \mid a, b)$ refers to the probability with which a joint measurement of a particle-pair in a locally realizable state λ yields an output of *x* at analyzer A (set to *a*) *and* an output of *y* at analyzer B (set to *b*). $p_\lambda^A(x \mid a)$ is the probability with which a measurement of one element of a particle-pair in a locally realizable state λ yields an output of *x* at analyzer A (set to *a*) when no measurement is performed at analyzer B ($p_\lambda^B(y \mid b)$ is similarly defined).

Figure 1.1 : Models of Inquiry employed in the evaluation and interpretation of Bell violations.

Chapter 2: Case Study – The Aspect Experiments

2.1: Introduction

In a 1981 article published in the *Physical Review Letters* – co-authored by Alain Aspect, Philippe Grangier and Gérard Roger – the findings of the then most recent of a series of experiments designed to detect Bell violations were summarized in a triumphant decree: "[The] results, in excellent agreement with the quantum mechanical predictions, strongly violate the generalized Bell's inequalities, and rule out the whole class of realistic local theories."[16] More than ten years later, in a 1994 edition of the *Physical Review A*, Paul Kwiat and colleagues from the University of California, Berkeley, preferring a less optimistic rendition of the situation, presented the following contra-dictum: "…to date, *no incontrovertible violation of Bell's inequalities has been observed.*"[17]

The fact that such disparate opinions punctuate the professional discourse associated with a *single* scientific hypothesis should stand both as evidence for the complexity of the theoretical and technical considerations bound up with its evaluation, and as a signal for philosophers concerned with the methodology of the physical sciences to stop and take notice.

In the following chapters, I will attempt to extract what methodological insight can be had from an analysis of the experimental program within modern quantum physics

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[16] Aspect A., Grangier P., and Roger G., (1981) *Phys. Rev. Lett.*, vol. 47, p. 460. The Aspect group was certainly not alone in attributing to their results a noteworthy theoretical significance. Bas van Fraassen, in his (1991) writes: "The recent experiments by Aspect and others leave no hope for local co-ordination to explain… quantum mysteries," (although he is careful to qualify this aplomb by noting that the findings are not 'logically watertight'). And Tim Maudlin in his (1994) writes, "Aspect's experiments…have produced observable data which cannot be predicted by any theory which disallows influence of the career of one particle [in an EPR setup] on the behavior of the other once they separate."

[17] Kwiat P., Eberhard P., Steinberg A., and Chiao R., (1994) *Phys. Rev. A*, vol. 49 no. 5 p. 3209. [authors' emphasis]

that has aimed to provide evidence of a genuine Bell violation. More specifically, I will argue that the image best suited to characterize the development and evolution of this program is *not* one in which experimental failures are circumvented through an appeal to the beliefs of scientific workers, but is rather one in which such failures prompt the design of new and better testing schemes, and motivate a careful investigation into the true theoretical scope of the existing experimental findings.

2.2 : Preliminaries - Bell's Theorem and the Einstein-Podolsky-Rosen (EPR) *Gedankenexperiment.*

Bell's Theorem, in its most general form, asserts that the statistical predictions of quantum mechanics are incompatible with those of the broad class of theories that posit 'local' hidden variables to fix certain measurement outcomes performed on carefully prepared, composite physical systems. Though I will not, in this paper, reproduce a proof of Bell's theorem, it will be necessary to describe, briefly, the experimental context within which it is derived. The loopholes which constitute the framework for the program's polemics can then be seen as originating out of particular difficulties involved with the 'bringing to life' of this idealized thought experiment within an actual laboratory setting.

The basic structure of the EPR setup consists of three components: 1) a source of 'particle-pairs' from which the members of the pair are projected along oppositely directed paths[18]; 2) A pair of measuring devices (or analyzers), each of which is placed

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[18] I place the term "particle-pairs" in quotation marks, because the 'particles' employed in the Aspect instantiation of the EPR setup are actually *photonic* cascade emissions from doubly-excited Ca atoms. Of course, the use of the term 'particle' to characterize light quanta requires substantive qualification, and as

along the trajectory of one of the emitted particles and each possessing a single setting

(labeled *a* or *b* respectively) that can be independently assigned some value

corresponding to an angular orientation in the plane orthogonal to the paths of the

particles[19]; and 3) a pair of detectors (A and B) coupled to the measuring devices that

map the outputs of their measurements onto the bivalent set $\{1, 0\}$[20] (a schematic of the

setup is presented in Figure 2.1[21]).

An "EPR-type experiment" is an experiment wherein a sample of 'identical'

particle-pairs[22] is scrutinized – using the setup outlined above – and information

describing the statistical correlations between the outputs of the detectors are recorded for various combinations of analyzer settings. So, for example, one EPR-type experiment might align *a* and *b* along a particular axis and evaluate the probability of 'agreement' between the source emissions (i.e., a (1,1) result or a (0,0) result) based on the data
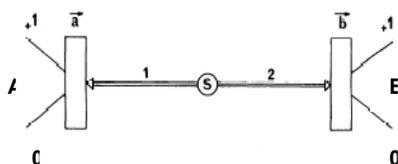
Figure 2.1: Einstein-Podolsky-Rosen *Gedankenexperiment*
Particle-pairs separate from the source S, and impinge upon measuring devices, set to *a* and *b* respectively, whose output registers either a '1' or a '0' at detectors A and B. Quantum mechanics predicts strong correlations between these measurements for certain well-specified source emissions.

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we shall see, the infelicities associated with this description will play a crucial role in attacks against the 'fair-sampling' hypotheses that were employed in many early experiments.
[19] The analyzer settings can simply be thought of as orientations in the plane normal to the flight of the particles (e.g., in Bohr's original version of the thought experiment, analyzer settings corresponded to the *directions* of the magnetic field gradients in a pair of Stern-Gerlach magnet). An analyzer's setting is independent of both the setting of the other analyzer and of the setting assigned to it during the examination of a previous particle-pair.
[20] This 'bare-bones' description of an EPR setup, is essentially a description of what Jon Jarrett terms a 'Mermin Contraption', after physicist and philosopher N. David Mermin. The few differences between my description and Mermin's are entirely superficial (e.g., where my detectors map measurements onto the set $\{1, 0\}$, Mermin Contraptions have outputs that take values from the set {"R", "G"} – corresponding to the lighting of red/green lamps) and are made so as to make the transition to a discussion of the Aspect experiments as fluid as possible.
[21] Image taken from Aspect A., Grangier P., Roger G., (1982) *Phys. Rev. Letters*, 49, no. 2., p. 91.
[22] The relation of 'identity' here used is simply meant to apply to those particle pairs produced from *ostensibly* identical sources in an *ostensibly* identical fashion. The question which asks of the legitimacy of describing the particle-pairs thus produced as being *physically identical* is precisely the question of whether or not there are 'hidden-variables.'

obtained from a million independent trials.

Now suppose we assume that the statistical correlations observed in an EPR-type experiment are due to information *localized* within the examined particle pairs. In other words, suppose that a *complete* description of the physical state of a pair of source emissions – labeled hereafter as λ – would be information sufficient to determine the probabilities with which the various outcomes of an EPR-measurement[23] might occur. Furthermore, suppose that this state description is such that its evolution and development can be informed only by 'local' physical processes i.e., those that obey the finite signal exchange limits suggested by relativistic conceptions of the world. Any explanation of the EPR-correlations that satisfy these *prima facie* plausible conditions, will be referred to as a *local hidden-variable* (LHV) theory. In the context of the idealized EPR experiment, the measurement events on the two particles constituting the emitted pair are free to be separated by great distances, so that an LHV theory's commitment to only subluminal physical interaction, implies that a measurement occurring in one hemisphere of the apparatus can have no direct effect on the outcome of a measurement at the other. In other words, the probability with which one of the detectors, say A, yields a particular outcome, say '1', is a function of only λ and the *correspondent* analyzer's setting – in this case *a* (likewise, the probability of a particular outcome occurring at B is a function of only λ and *b*). It was a crucial insight on the part of Bell to realize that this *separability condition* applies to all LHV interpretations of the idealized EPR-*gedanken*.

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[23] This explanation of the EPR-correlations is *not* inconsistent with a *fundamentally stochastic* physical theory. Even if the best prediction of a single measurement outcome amounts to the provision of a probability distribution over the space of possible outcomes, the account here described of the EPR-correlations would simply require that the *distribution be fixed* by a complete state description of each particle-pair.

The second major insight at work in the derivation of Bell's Theorem, is the recognition that for EPR experiments which employ *multiple* detector settings, the strength of the correlations predictable by an LHV theory is mathematically constrained. To understand why this is the case, it will be useful to envision the behavior of the particles as a sort of game between two conspiring teammates. The formal mathematical constraints imposed on the correlations detected in an EPR-type experiment – referred to in the contemporary vernacular as Bell's inequalities – can then be analogized as informal *epistemological* constraints imposed on the team's coordinative efforts by the various rules of the game. This game-theoretic rendition of the experimental setting is nicely articulated by Tim Maudlin in his book *Quantum Non-locality & Relativity*:

> These are the rules of the game: you and your friend start out together in a room [the source in an EPR setup]. You know that each of you will leave the room by a different door and after some period of time will each be asked a question. The question consists of a number between 0 and 180 written on a piece of paper. Your answer must be either the word ["one" or the word "zero"]. Before you leave the room you have no idea which question either of you will be asked. However while in the room you and your friend are permitted to devise any strategy you please in order to coordinate your answers… [and] you are permitted to adopt an entirely new strategy each time [the game is played].[24]

The strategy devised by the partners represents the state specification of the composite two-particle system (in other words, λ); the questions that they are asked correspond to the analyzer settings employed in the experiment; and the rule that forbids any communication between teammates once they have left the room, represents the

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[24] Maudlin T., (1994) *Quantum Non-locality & Relativity* (Blackwell Publishers), p. 14.

separability condition which states that a measurement on one of the particles can have no *direct* effect on the outcome of a measurement on the other. In sum, we can say that an LHV theory of the EPR-correlations is one in which all of the particle-pairs employed in the analysis *follow the rules of the above-defined game*.

Now, it is important to notice that there are, in these rules, no explicit limitations on the sort of strategy that the teammates can adopt[25]. If they like, they could even incorporate an element of stochasticity into their plans, perhaps deciding to flip a coin when asked a particular question, and answering according to the result of the flip. Still, despite this strategic freedom, there remain coordinative limitations that arise from certain of the game's rules. For instance, the fact that each player is allowed no prior knowledge of what question she will be asked, suggests that for maximal control, she must plan in advance how to respond to each of the 181 possible questions. In addition, the rule prohibiting one player from communicating with her partner once they have both exited the room, suggests that a precise coordination *between* the teammates will require a joint-strategy that accounts for the added contingencies that arise from one player's not being privy to the specifics of the other's inquisition.

As it turns out, the rules of this simple game, and the epistemological barriers that they support, preclude the possibility of any two players devising a long-term strategy whose application could successfully reproduce the sort of statistical correlations that quantum mechanics predicts for certain carefully contrived EPR-type experiments[26]. So –

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[25] Indeed, it is this non-specificity that allows Bell's Theorem to speak against the *whole category of LHV theories of EPR-correlations.*

[26] To be only slightly more specific, quantum theory dictates that for experiments in which the particle-pairs under scrutiny are formed in a coupled 'singlet-state' (with respect to some observable), the weighted average (or expectation value) of the product of the measurement outcomes at A and B is proportional to the cosine of the angle between a and b, a function that cannot be expressed as the composite of two functions, one depending only on a, and the other only on b.

to continue within our game-theoretic metaphor – for these peculiar settings, if we assume the validity of the quantum mechanical correlation functions, it seems we must admit that the players somehow manage to cheat the rules![27]

Considered alone, one might be apt to think that the recognition of deception on the part of the examined pairs does not constitute an intractable difficulty for strictly local interpretations of quantum theory; after all, there are perhaps processes unbeknownst to classical physics, though nevertheless consistent with its principles, that might permit a rapport between the particles even *after* they have left the room – inexplicabilities do not always give rise to paradox. However, the peculiar difficulty about the quantum theoretic account of the particles' behavior is not a *de facto* consequence of their mendacity. It instead results from the observation that they manage such deception in spite of the fact that both the distance separating their interrogations, and the time at which their inquisitions are detailed, are left unspecified in the generic description of the game. The players, upon reaching their respective destinations, could, in principle, be separated by hundreds of light-years and face questions whose exact content was formulated just instants before their arrival! If the predictions of quantum mechanics are assumed correct, then the coordinative efforts of certain carefully prepared physical systems somehow allow for an exchange that can overcome the radical spatial isolation effected by the

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[27] Of course one might suggest that the incompatibility between Quantum Mechanics and LHV theories is best resolved not by an acceptance of duplicity on the part of the players, but rather by a wholesale abandonment of the game analogy. I take Bohr's shift towards 'quantum monism' to be an instance of this sort of suggestion. The paradoxes of EPR, for Bohr, are resolved by considering the entire experimental setup as a single quantum system. In this case, it is not that the teammates are managing to subvert the rules, but rather, that there is only ever a single player! On the other hand, Bohm's *non-local* hidden variable interpretation of Quantum Mechanics is an example of an attempt to relax the rules of the game, while maintaining that EPR-correlations are still correctly modeled as resulting from a sort of 'strategic coordination.' For details, see *Phys. Rev.*(1952) vol. 85, pp. 169-93.

structure of the EPR setup. They must, it would seem, interact in such a way as to violate

the *finite* limitations on the magnitude of signal velocities that are mandated by strictly

local conceptions of the world. This observation – that quantum mechanics predicts

certain observable effects that cannot be explained within any local description of the

EPR-phenomenon – is just an informal statement of Bell's theorem.

In an article entitled *Bertlmann's socks and the nature of reality*, J.S. Bell

attempts to elucidate the paradoxical nature of the non-local interactions that quantum

theory describes as informing the EPR-correlations, by contrasting the quantum casting

of the EPR scenario with the tale of Dr. Bertlmann and his piebald socks:

> Dr. Bertlmann likes to wear two socks of different colors. Which color he will have on a
> given foot on a given day is quite unpredictable, but when you see that the first sock is
> pink you can already be sure that the second sock will not be pink. Observation of the
> first, and experience of Bertlmann, gives immediate information about the second. There
> is no accounting for tastes, but apart from that there is no mystery here.[28]

The point of the story is that it is not unusual to encounter strong statistical correlations

between the properties of two systems that are non-interacting at the time of their

observation. In this particular case, the systems are Dr. Bertlmann's socks. The type of

explanation that we offer for such correlations is common fare: At some point in their

history, the two systems were allowed to interact (either directly or indirectly) and, as a

result of this interaction, they were 'stamped' with the properties that are later observed

to be correlated. In the case of Dr. Bertlmann's socks, the causal interaction was

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[28] Bell J.S., (1987) *Speakable and Unspeakable in Quantum Mechanics* (Cambridge Press), p. 139.

mediated by Bertlmann's choice of colors when his socks were first put on. The socks then 'carried' these colors through their separation, at which time the reported correlation was observed. If the quantum-mechanical EPR-correlations could be made the subject of an analogous explication, then we would have no cause to label them as paradoxical at all: the correlations that relate the members of an EPR-pair would, in this case, straightforwardly result from properties stamped on the particles at the time of their interaction – presumably, the time during which they cohabitated the source[29]. But, as it has been suggested, such an analysis is simply incapable of describing the statistical behavior of certain carefully contrived, quantum systems. If Bertlmann's socks were to follow the example of these curious non-local exhibitionists, then we would have to admit not only that an observation of his leading sock's color provides *information* about his second sock's color, but also that the observation of the former, at the moment it takes place, somehow *effects* the latter's character: "It is as if we had come to deny the reality of Bertlmann's socks, or at least of their colors, when not looked at. And as if a child had asked: How come they always choose different colors when they *are* looked at? How does the second sock know what the first has done?"[30]

Of course, without genuine empirical corroboration of a Bell violation, what curiosity might be said to attach to the essential '*non*-locality' of quantum mechanics amounts to nothing more than a puzzling idiosyncrasy of a particular theoretical formalism; a curious implication of an abstract, mathematical system. For Bell's theorem

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[29] It is clear that Einstein was in favor of just such a non-paradoxical interpretation of the probabilistic output of quantum mechanics. He writes: "I am, in fact, firmly convinced that the essentially statistical character of contemporary quantum theory is solely to be ascribed to the fact that this theory operates with an incomplete description of physical systems." (Schilpp P.A., (1988) *Albert Einstein: Philosopher-Scientist vol. 1*, p. 66.)

[30] Ibid., p. 143.

to be of *physical* significance – and for the paradoxes of quantum entanglement to amount to more than just puzzles – an *actual* EPR-experiment has to be performed, and a violation of Bell's inequality observed. In 1981, a group of physicists led by Alain Aspect, then engaged at the *Institut d'Optique Théorique et Appliquée* in Orsay, France, attempted to take up this charge.

2.3 : The Aspect Experiments

The experimental apparatus employed by the Aspect group was a modified version of the proposed extension to the Kocher-Commins design first described by Clauser, Horne, Shimony and Holt in 1969[31] which involved the measurement of the polarization correlations between the photons emitted from an atomic cascade. The basic conceit supporting the design of their apparatus was this: if an atom can be doubly excited with no consequent change in its overall angular momentum, the two photons fluoresced from the atom in a decay to its ground state – a decay which can be very rapid in the case of certain excitations – must exhibit a net angular momentum of zero so as to conform to general conservation strictures[32]. The polarizations of these emissions then, being a direct measure of their angular momenta, are, according to quantum theory, strongly correlated in what is known as a coupled-singlet state. This state, as it turns out, cannot be represented within any LHV model of the photon-pair; thus, a verified measurement of the polarization correlations predicted by the quantum-mechanical description of the phenomenon, would count as direct evidence for a Bell violation, and so stand against the whole class of theories that posit a strictly local explanation of the EPR-correlations.

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[31] Clauser J., Horne M., Shimony A., Holt R., (1969) *Physical Review Letters,* vol. 23, no. 15, pp. 880-4.
[32] For a more careful account of the cascade effect, and for details regarding the specific transitions induced in the Aspect experiments, see Jim Baggott's book *Beyond Measure* (2004), pp. 164-5.

To more fully articulate the technical details of the apparatus employed in the Aspect tests, it will perhaps be useful to return to the generic model of the EPR *gedanken* described in the previous section of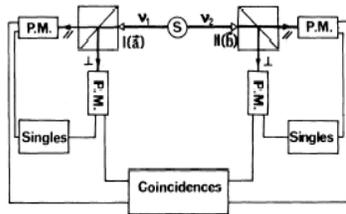 this chapter, and associate each of its three elements with their counterpart components from the setup employed by the Aspect group.

Figure 2.2 : Aspect Group's Experimental Setup
Two polarizers, in orientations *a* and *b*, coupled to pairs of orthogonally oriented photoelectric tubes, perform measurements of the linear polarization on photons v_1 and v_2, emitted from source S. The counting electronics are used to monitor coincidences.

Recall that in a generic EPR-type experiment, 'particle-pairs' emitted from a source, impinge upon two analyzers placed along their oppositely directed paths, and register either a '1' or a '0' at detectors coupled with the analyzers. In the Aspect experiments, the source of entangled pairs was a 'beam of calcium [atoms]…irradiated at 90° by two lasers focused on the interaction region, roughly a cylinder 1 mm long, and 60 μm in diameter.'[33] The photon emissions from the atomic cascade, now correlated with respect to their polarization orientations, were then collimated by various optical lenses in the direction of 'polarizing cubes made of two prisms with suitable dielectric thin films on the sides stuck together.'[34] These polarizers were the instantiations of the generic analyzers described in the 'bare-bones' description of the EPR setup, with *a* and *b* representing the directions of their respective optical axes. Mounted on each of the rotatable mechanisms that housed the polarizing cubes, were two photomultipliers, followed further by the electronics necessary to monitor coincidence detections between the separated hemispheres of the apparatus[35]. One of the photomultipliers was oriented so

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[33] Aspect A., Grangier P., and Roger G., (1981) *Phys. Rev. Lett.*, vol. 47 p. 461.
[34] Aspect A., Grangier P., and Roger G., (1982) *Phys. Rev. Lett.*, vol. 49, no. 2, p. 92.
[35] The cascade process by which the photon pairs are produced takes a finite time to occur (~5 ns). Consequently, the members of each pair are not emitted from the source at exactly the same time. This

as to detect photons *transmitted* through its correspondent polarizer, and the other was placed along the path of the photons *reflected* from the device. A detection at the former would count as an output of '1' and a detection at the latter, an output of '0' (a schematic of the setup is pictured in Figure 2.2[36]).

The statistics that were employed in the calculation of the Aspect groups' reported results were based upon five runs lasting 100-seconds apiece, during each of which approximately 8000 particle-pairs were examined. The experiment was repeated for a series of polarizer orientations, and, as predicted by quantum mechanics, the correlation coefficients thus determined indicated a strong violation of the generalized form of Bell's inequality – a violation of approximately 40 standard deviations[37]:

> In conclusion, our experiment yields the strongest violation of Bell's inequality ever achieved and excellent agreement with quantum mechanics. Since it is a straightforward transposition of the ideal Einstein-Podolsky-Rosen… scheme, the experimental procedure is very simple, and needs no auxiliary measurements…[38]

Though confident in tone, this report is quickly qualified with the following addendum:

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forced the Aspect group to invoke a detection 'window' of approximately 20 ns during which serial detections in the two hemispheres of the apparatus would register as a detection of a particle pair. In order to correct for the 'accidental coincidences' thus registered (i.e., those coincidences that reflected detections of two distinct emission events), Aspect *et al*. developed a method from which the accidental coincidence rates could be inferred from the measured rates of single detections. Though it will not be further discussed in this paper, this 'subtraction of accidentals' has been a source of unease for some critics of the Aspect experiments. See, for example, Caroline Thompson's (2004) entitled *Subtraction of "accidentals" and the validity of the Bell tests.*

[36] Image taken from Aspect A., Grangier P., Roger G., (1982) *Phys. Rev. Letters*, 49, no. 2., p. 92.

[37] The particular formulation of Bell's inequality that was scrutinized in the Aspect experiments, was $-2 \leq S \leq 2$, where $S = E\,(a,b) - E\,(a,b') + E\,(a',b) + E\,(a',b')$, and $E\,(a,b)$ represents the correlation coefficient of the measurements when the polarizers are set at a and b, respectively. The reported results of the Aspect experiments, $S_{expt} = 2.697 \pm 0.015$, stand in clear violation of the above inequality.

[38] Aspect A., Grangier P., Roger G., (1982) *Phys. Rev. Letters,* 49, no. 2., pp. 93-4. (italics added)

> Two loopholes do remain open for advocates of realistic theories without action at a distance [LHV theories]. The first one, exploits the low-efficiencies of the detectors…The second one, exploits the static character of all previous experiments.[39]

The remainder of this chapter will be devoted to describing these two loopholes in the Aspect group's experimental design: the detection-efficiency loophole and the lightcone loophole.

2.4 : The Detection-Efficiency Loophole

Within the idealized experimental setting of the EPR *gedankenexperiment*, each and every one of the particle-pairs emitted from the source is presumed to impinge upon the analyzer-detector apparatuses and so yield an output that contributes to the correlational data that occupies one side of a Bell inequality. It is simply assumed, that for each particle-pair leaving the source, a representative combination of 1's and 0's will stand as residue from that pair's analysis. Of course, within the context of Bell's Theorem, such an assumption is altogether reasonable, for when one is simply concerned to articulate a distinction in the predictions of two physical theories, it makes good sense to operate within the *simplest* theoretical context capable of supporting such a discrepancy. However, when one's task involves not merely establishing a theoretical divergence but actually *identifying* which side of the division best represents the real world, then the acceptance of simplifying assumptions for simplicity's sake is no longer an available luxury.

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[39] Ibid., p.94.

Real-world instantiations of the EPR-*gedanken* suffer from all the various imperfections that characterize the far-from-ideal milieu of the laboratory, and the scientists who invoke these models in the service of loftier, theoretical aims are forced to grapple with such infelicities head-on. In particular, their statistical analyses must take account of (and correct for) those source emissions that *fail* to register outputs at their inevitably imperfect detector apparatuses. Improprieties in the correlational data resulting from an excess of such undetected emissions, represent errors that enter through a 'detection-efficiency loophole'.

Recall, that the detectors employed in the Aspect experiments were photomultiplier tubes aligned with the parallel and transverse axes of a linear polarizer. The quantum efficiency of these tubes – roughly, the ratio of electrons liberated from a photoelectric surface to the number of photons incident on that surface – was surprisingly low, on the order of 10%. This means that if 1,000,000 photons were to enter the detectors during the course of a run, only 100,000 or so would be detected, and so included in the statistics of the test. Worst still, of all the correlated pairs leaving the source, only a very small fraction manage to enter the photoelectric tubes, so that all told, in photon experiments employing atomic cascades, *only one in every million source emissions contributes to the final measurement*.

If this limited sample is not representative of the whole ensemble of source emissions – in other words, if it is somehow the case that the strength of the EPR-correlations is a function of the efficiency with which pairs are detected – then a violation of Bell's inequality, if derived from an analysis of this sample, would not be sufficient cause to reject the possibility of a strictly local interpretation of the EPR-correlations.

To better illustrate this point, consider the following simple experiment: One is asked to determine the probability with which a marble, when selected at random from a collection of black and white marbles (in unknown proportion), will turn out to be black, and proceeds by selecting one hundred marbles *each from the top of a bag containing the entire collection* and associates with the desired probability the ratio of the number of black marbles in the sample to the total number of marbles pulled from the bag – in this case, one hundred. It should be clear that if an answer provided by this method is to be regarded as even an approximate solution to the problem, the procedure by which the sample was obtained *viz.*, selection from the top of the bag, must be shown to yield an unbiased sample. If, for example, the marbles are such as to require that all the white marbles settle to the bottom of the bag, then the analysis described above of a sample obtained by selection from the top will say nothing about the composition of the entire population. Thus, if there is no knowledge regarding the distribution of black and white marbles in the bag, a test of the above sort producing a sample of 99 black marbles and one white marble cannot discriminate between the following two interpretations of its results: 1) (Approximately) 99% of the marbles in the collection are black, and the density of black marbles in the bag is uniform throughout; and 2) Less than 99% of the marbles in the collection are black, and the density of black marbles in the bag decreases with depth.

Similarly, if the statistical output obtained from the Aspect group's experimental apparatus was not reinforced by some independently verified assessment of the scrutinized sample's adequacy, then the correlational data extracted from an analysis of this sample could not be said to lend favor to either of the following of its possible

implications: 1) The examined correlations, having been derived from a fair sample of the entire ensemble of source emissions, demonstrate a violation of a Bell inequality, and so rule out the possibility of a strictly local analysis of the ERP phenomenon; and 2) the examined correlations, having occurred within an *inadequate* statistical sample, fail to demonstrate a genuine Bell violation as the strength of the correlations detected in an EPR experiment decreases with increasing detector efficiencies.

The possibility of this latter interpretation of the Aspect results was substantiated by Emilio Santos in a 1992 paper published in the *Physical Review A*, in which a 'natural'[40] local hidden variable model of the EPR-correlations was formulated that 'agrees with quantum mechanics in the low-efficiency region but departs from it at high efficiencies [so that] genuine…Bell inequalities are never violated.'[41] It is important to note that the existence of such a model does *not* address the validity of Bell's theorem, which, again, expresses a fundamental inconsistency between the statistical predictions of LHV theories and those of quantum mechanics when applied to a *highly stylized experimental setting*. Instead, Santos' work brings into question the ability of the Aspect tests to properly replicate the idealized context of the EPR-*gedanken*. Indeed, Santos readily admits that were one to assume that the efficiency with which correlated pairs are detected had no intrinsic effect on the strength of the EPR-correlations, then the Aspect groups' findings would amount to a genuine Bell violation:

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[40] Whereas Santos describes the LHV model that he develops as 'natural', I think a more appropriate adjective would be the weaker 'plausible', or perhaps the still weaker 'conceivable', for no hidden variable theory will be 'natural' given that the very nature of LHV theories requires that they extend beyond the bounds of even our most advanced understanding of physical processes. The 'naturalness' attributed to the model by its author comes from his observation that 'at the core of a hidden-variable theory is the assumption that the systems that are identical according to quantum theory are actually not identical… and this includes the whole process of crossing the polarizer and being detected.' So a model which portrays the correlations that obtain between the members of a composite system as depending on the efficiency of the devices used in their analysis, is not, *de facto*, discouraged by the framework of local realism.

[41] Santos E., (1992) *Phys. Rev. A*, vol. 46, no. 7. p. 3646.

…[A]lthough a linear extrapolation of the measured polarization correlations to higher [detection] efficiencies would violate the Bell inequality, this fact does not imply that a violation will be produced if the experiments are actually performed with more efficient [detection schemes]…Consequently I can safely claim that the problem of whether a local realistic picture of the physical world is possible remains open.[42]

2.5 : The Lightcone Loophole

Experiments designed to detect violations of Bell's inequalities are engineered so as to instantiate the experimental setting which houses the EPR-*gedanken*. Loopholes in the architecture of these experiments, can thus be associated with those features of the EPR-setup which obscure its straightforward translation into the inherently imperfect environment of the laboratory. In the last section, one of these features – the assumed one-to-one correspondence between emission and detection events – was shown to give rise to a 'detection-efficiency' loophole. In this section, we will see how another feature of the idealized EPR-setting – the space-like separation of joint measurement events – renders still more problematic the optimistic interpretation of the Aspect group's findings as conclusive evidence of a genuine Bell violation.

The abnormality of quantum theory's construal of the EPR-*gedanken* can be attributed to the stubborn defiance of the correlation functions described therein to fit within a strictly local construction of the phenomenon i.e., a construction positing only physical processes that satisfy the speed-of-light velocity limit mandated by modern, relativistic conceptions of the world. In section 2.2, this 'queerness' was articulated

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[42] Ibid., p. 3655.

within a game-theoretic rendition of the experimental setup, where the members of an examined pair were analogized as partners playing a statistical game. The purpose of that discussion was to suggest that the quantum mechanical predictions for the correlation functions that obtain between the members of certain carefully prepared composite physical systems, *cannot* be construed as the outcome of strictly 'local' coordinative efforts on the part of two collusive teammates. Instead, such 'entangled' physical systems must manage to transgress the stipulated rules of the game by either obtaining preemptive information about the questions that they will face, or by managing to communicate to each other the specifics of their inquisitions once they have exited from the source. In the language of the EPR-*gedanken*, such duplicity would amount to a communication across the hemispheres of the apparatus that might influence the production of the strong correlations observed in an EPR-type experiment. But why was it assumed that such quantum transgressions are inconsistent with the ideals of locality? In other words, what made reasonable the assumption that an LHV model of the physical world *requires* that the two hemispheres of the measurement apparatus employed in an EPR-type experiment be unqualifiedly *closed-mouth*?

Within the idealized experimental context of the EPR-*gedanken*, a defense of this separability assumption was based upon the combination of an arbitrarily *large* distance separating the hemispheres of the detection apparatuses, and an arbitrarily *small* time difference between the fixing of the analyzer settings and the occurrence of the measurement events: If the analyzer/detector apparatuses are separated by hundreds of light years, and the details of the analyzers' setup are specified just instants before the particles arrive, it would take a *super*luminal mode of communication – equally troubling

from the standpoint of locality – for a measurement outcome at one of the hemispheres to inform a subsequent measurement at the other. Thus, within the context of the EPR-model, Bell's separability condition – that is, the assertion that the results of a measurement at detector B do not depend on the outcome of a measurement at detector A – is a direct consequence of an LHV construal of the idealized experimental setup.[43]

Difficulties arise, however, when this setup is realized not in the infinitely pliant imagination of a theoretician, but instead in the environment of a laboratory whose dimensions are *not* free to extend light-years and whose instruments *lack* the acute 'reflexes' of their idealized concomitants. The analyzers employed in the most prominent of the early Aspect tests were separated by a modest thirteen meters, and were set *prior* to, and held fixed throughout, the time periods during which data were being collected. Thus, within these non-ideal experimental settings, the satisfaction of Bell's separability condition was *not* a necessary consequence of an LHV construal of the experimental setting, for one could, as an example, imagine a signal communicated from one hemisphere to the other, *at a speed less than or equal to the speed of light*, which would allow the measurement outcome at one side of the apparatus to be directly influenced by the orientation of its partner device. This possibility was recognized by the Aspect group, and in a 1982 paper published in the *Physical Review Letters* the difficulty is summarized as follows:

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[43] More will be said about this in the next chapter, where I will discuss the modified Aspect tests employing dynamic polarizer devices. I will construe the technique of designing an experiment so that a supplementary assumption is made a deductive consequence of the primary hypothesis under test (and the details of the experimental architecture) as a particular 'blocker strategy' for removing Duhemian obscurities.

> As pointed out by Bell, it is possible, in [experiments that employ static setups] to reconcile supplementary-parameter [LHV] theories and the experimentally verified predictions of quantum mechanics: 'The settings of the instruments… [may be] made sufficiently in advance to allow them to reach some mutual rapport by exchange of signal with velocity less than or equal to that of light.'…"[44]

To defuse the possibility of such a reconciliation, Bell proposed the performance of an experiment in which the orientations of the analyzers were to be randomly fixed *during* the flight of the particles, so that the possibility of communication between the hemispheres of the apparatus, at speeds equal to or slower than that of light, could be discounted as a potential explanation of the observed correlations. Such 'dynamic' experiments would enforce the physical separation necessary for Bell's separability condition to follow deductively from the finite signal velocity limit imposed by the idea of locality. In the terminology of relativity theory, this separation requires a measurement which occurs in one hemisphere of the apparatus to lie outside of the forward *lightcone* of the measurement event at the other; this is where the loophole gets its name.

It is important to note, in closing, that the sort of 'signal' ruled out by the shift to dynamic experiments is a signal unaccounted for in modern physical theory. Indeed, it might seem that such a coordination of measurement outcomes would represent some kind of conspiracy: Why, after all, should one posit a physical process foreign to the established principles of physics, simply to foil the non-local interpretation of the EPR phenomenon? Isn't the necessity of an *ad-hoc* addition to any local construction of the EPR-scenario, itself a mark against the plausibility of an LHV construal of the

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[44] Aspect A., Grangier P., Roger G., (1982) *Phys. Rev. Letters*, 49, no. 25., p. 1805.

phenomenon? One of the goals of the following chapter will be to provide at least a partial answer to questions of this sort.

2.6 : Conclusion

The objective of this chapter was to provide a brief introduction to the experimental program in modern quantum physics that has aimed to evaluate the empirical adequacy of LHV models of the EPR-phenomenon. My discussion has focused on the experiments performed by Alain Aspect and his colleagues in the early 1980's, considered by many to be the first tests to provide conclusive evidence of the fundamental non-locality of certain natural processes *via* a demonstration of a violation of the generalized form of Bell's inequality. These ingenious tests marked the commencement of a careful and exacting scientific discourse investigating the extent to which the data of experience require a shift away from the classical renderings of such physical concepts as independence and causality; a discourse, so potentially far reaching in its implications, and abstract in its subject matter that it has been labeled by some as a study in 'experimental metaphysics' – an example of 'putting philosophy to [the] test'[45].

Still, despite the groundbreaking character of these early experiments, they are, of course, only the beginnings of a much longer and more involved story. Over the last twenty years, the Aspect tests have been made the subject of a set of probing and carefully formulated criticisms aimed at discrediting their results as inconclusive demonstrations of a genuine Bell violation. Though expressed at different times, in different ways, by a number of different scientists, the large majority of these criticisms can be identified as exploiting one of two loopholes in the architecture of their

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[45] Bell J.S., (1987) *Speakable and Unspeakable in Quantum Mechanics* (Cambridge Press), p. 81.

experiments' design: the detection-efficiency loophole and the lightcone loophole. In the two previous sections of this chapter, I associated each of these potential sources of error with particular features of the idealized EPR-*gedanken* that present challenges to its instantiation in the material realm of the laboratory.

My hope has been to introduce the Aspect experiments as a background against which to identify and scrutinize the behavior of real scientists grappling with the challenges of Duhemian underdetermination. In this case, we have a real-to-life example of a theoretical hypothesis whose evaluation, if simply based upon the output of these early tests, depends upon a constellation of auxiliary assumptions about the mechanics of the experimental procedure. The relevant question, then, asks how scientists faced with such a tangle of interdependent hypotheses proceeded to disentangle the cluster, so that a particular theoretical claim might stand (or fall) according to its own evidential merit. In the next chapter, I will attempt to perform this analysis by examining the methodological responses to both of the loopholes described above. My objective will be to argue that the techniques employed by working scientists to overcome the challenges of underdetermination do *not* involve a 'Bayesian' escape into an evaluation of the relative 'confidences' that they feel towards the various hypotheses of a theoretical manifold. On the contrary, their methodological reactions support the notion that it is only after a careful probing of *all* the various errors that might infect an otherwise warranted inference, that scientists are willing to describe the output of a test as conferring support upon a theoretical claim.

Chapter 3: Responding to the Duhemian Challenge

3.1 : Introduction

In the last chapter, I depicted the Duhemian ambiguities surrounding the interpretation of the early Aspect experiments as prompting two general criticisms, each motivated by the recognition of a particular loophole in the structure of the experiments' design. These loopholes represented distinct 'avenues of escape' for those who wished to preserve a strictly local construction of the EPR-phenomenon in spite of the reported findings of the Aspect tests.

In this chapter, I will attempt to articulate some of the strategies employed in response to these Duhemian challenges. In particular, I will argue that in order to overcome the deficiencies of their tests, and learn from their imperfect experimental schemes, scientists employed the following general techniques:

(1) Where at all possible, new and improved experiments were designed, capable of 'blocking' attempts to explain away their findings as resulting from failures to properly instantiate the idealized setting of the EPR-*gedanken*.

(2) When such 'blocker strategies' were impracticable – due to a lack of either technological sophistication or experimental creativity – an investigation into the *true* theoretical scope of the available evidence was pursued.[46]

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[46] In the case of the Bell experiments, this investigation involved assimilating carefully specified assumptions into the experimental setting of the idealized EPR *gedanken*, allowing for the formulation of 'weaker' versions of Bell's inequality that *could* be severely scrutinized within existing experimental schemes. See section 3.4 below.

The general philosophical thesis which I hope will be supported by my analysis, is that scientific method, when faced with Duhemian problems of underdetermination, suggests neither a circumvention of such difficulties *via* the uncritical acceptance of background assumptions, nor the employment of epistemically unsatisfying subjectivist models of rational retainment. Instead, scientists are challenged to attack problems of underdetermination 'head-on', through a careful analysis of the severity of the testing procedures responsible for the production and modeling of their anomalous data.

The reaction provoked among scientific workers charged with the task of apportioning blame is not the uncalculated 'guesswork' endorsed by the Lakatosian mantra, 'blame anything, so long as you do so in a progressive fashion'; nor is it a retreat – as advocated by Bayesians – into an analysis of the relative confidences felt towards the various hypotheses that combine to predict an observable effect. Instead, researchers faced with the task of explaining empirical anomalies, are challenged to employ a number of diverse and clever *experimental* techniques designed to cut through the Duhemian mists, and account for potential sources of error that might weaken an otherwise warranted inference. In lieu of such progressive experimental procedures, scientists try to identify the *actual* inferential work that an existing experiment is capable of providing so as to avoid ascribing to its output more discriminative power than it is rightfully due.

In the next section, I will provide a brief philosophical review of Duhem's problem and outline two distinct and radically different responses to the challenges it presents. The first will be derived from the Bayesian account of theory confirmation, and the second, from Deborah Mayo's error-probabilistic approach to scientific methodology.

In the remainder of the chapter, I will argue that the various strategies adopted by researchers involved in the testing of Bell's inequality, are well represented by Mayo's error-statistical notion of scientific evidence. In particular, an acceptance of her stringent demand for the output of severe tests to stand at the basis of rational inference, helps to explain the methodological reactions expressed by scientists in response to the loopholes that plagued the early Aspect tests. At the same time, I will argue as a counterpoint, that these very reactions present a challenge for the Bayesian 'solution' to Duhem.

3.2 : Philosophical Background – Fallibilism in Falsification: Modern reactions to Duhem[47]

The simple hypothetico-deductive (HD) model of scientific inference, made famous by Karl Popper[48], operates through the application of deductive reasoning in the mode of *modus tollens* (or negating the consequent) to a statement describing a singular implication of a hypothesis and the assertion of the falsity of the implied singular claim. So, if a hypothesis, *H*, implies an evidential claim, *e*, the observation that *e* is false, implies the falsity of hypothesis *H*:

P1) $H \rightarrow e$

P2) $\sim e$

$\therefore \sim H$

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[47] Much of this discussion follows from Deborah Mayo's (1997) paper *Duhem's Problem, The Bayesian Way, and Error Statistics* (Philosophy of Science: vol. 64), p. 224.

[48] See Popper K., *The Logic of Scientific Discovery.*

At first blush, the inference from a violation of Bell's inequality to the rejection of Bell's locality criterion (*LC*), appears to represent a particular instantiation of this mode of reasoning: Here, the hypothesis under test is *LC* – the claim that all physical processes capable of influencing the state of a system, satisfy the finite signal velocity limit suggested by relativity theory. The evidential claim said to follow from this hypothesis is a statistical output from an EPR-type experiment that satisfies the generalized form of Bell's inequality (*e*). The discovery of a violation of Bell's inequality ($\sim e$), would thus provide disconfirming evidence for *LC*, and, thereby, illustrate the fundamentally *non-local* origins of the EPR-correlations.

There is, of course, a well-known difficulty with the application of this sort of reasoning to actual scientific testing scenarios, where not one but a number of hypotheses – including auxiliary assumptions about the mechanics of the experimental procedure – combine to yield testable results. If the *conjunction* of these theories is what yields testable conclusions, disconfirming evidence, on the simple HD model, can at most imply that at least one of the conjuncts is false:

P1) $(H \ \& \ (A_1 \ \& \ A_2 \ \& \ ... \ \& \ A_n)) \rightarrow e$

P2) $\sim e$

$\therefore \sim H \ \textbf{v} \sim (A_1 \ \& \ A_2 \ \& \ ... \ \& \ A_n)$

This, then, is Duhem's problem as it will be discussed in this paper: It appears that the process of implicating one of the constellation of theories whose combination is required to produce a testable claim can never be resolved by strictly formal considerations; there will always remain open loopholes through which any one of the theories, considered in isolation, might escape logical disproof.

In actual testing scenarios, Duhem's problem identifies an inferential *gap* between an experiment's results and the discrediting of any single theoretical hypothesis.[49] In an attempt to bridge this gap, philosophers have suggested extending the bounds of rational inference beyond the limits of the simple HD model, allowing *non-deductive* methods to assist in the evaluation of theories. One proposal for such an extension comes from the Bayesian School in the philosophy of science. These 'Bayesians' propose the use of formal probability theory to resolve Duhemian underdetermination, suggesting that *Bayes's Theorem* (a fundamental theorem of the probability calculus) serves as an accurate model for the rational preferencing of theories.

Bayes's Theorem asserts that

$$P(H \mid e) = [P(e \mid H)\, P(H)] \,/\, [P(e \mid H)\, P(H) + P(e \mid {\sim}H)\, P({\sim}H)]^{50},$$

where 'P(a | b)' is read 'the probability of a given b.' When interpreted as a mechanism for theory evaluation, the probabilities that enter into a Bayesian calculation refer to an

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[49] This phrase is borrowed from Imre Lakatos's article *Falsification and the Methodology of Scientific Research Programmes*, published in Lakatos I., Musgrave A., (ed.) (1970) *Criticism and the Growth of Knowledge* (Cambridge Press).

[50] The terms P(*H*) and P(~*H*) are referred to as prior probabilities, since they represent an agent's degree of belief *prior* to the acquisition of evidence *e*; P(*e* | ~*H*) is commonly referred to as the Bayesian 'catch-all' factor; and P(*H* | *e*) is referred to as the posterior probability of *H*.

agent's *degrees of belief*, and conditional probabilities measure her beliefs on the assumed acceptance of certain specified background claims.

The basic principle underlying the Bayesian model of confirmation asserts that, "evidence *e* confirms hypothesis H to the extent that an agent's degree of belief in H is higher given evidence *e* than it was or would be without *e*,"[51] where, of course, the transition from prior to posterior degrees of belief is mediated by Bayes's Theorem. This principle, when applied to a manifold theory, *T*, allows a Bayesian to apportion the blame that accompanies a predictive anomaly *non-uniformly* across the various components of *T* which, in turn, results in a more fine-grained directing of the 'arrow of modus-tollens'[52]. The trick is to assign markedly differing values to the prior probabilities that apply to the various components of T[53]: All else being equal, the larger the prior degree of belief assigned to a sub-hypothesis, the more secure it will stand in the face of anomaly.

The difficulties with the Bayesian model of scientific inference are well documented, and I will not rehearse them here.[54] The important point to keep in mind, is that when faced with multiple explanations of an anomaly that all seem to equally well fit the data, the Bayesian recommendation for how to proceed does not require, or even suggest, an analysis of the testing procedure in which the data was produced[55]. Instead, it

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[51] Mayo D., (1997) *Duhem's Problem, The Bayesian Way, and Error Statistics* (Philosophy of Science: vol. 64), p. 224.

[52] This phrase is borrowed from Imre Lakatos's article *Falsification and the Methodology of Scientific Research Programmes*, published in Lakatos I., Musgrave A., (ed.) (1970) *Criticism and the Growth of Knowledge* (Cambridge Press).

[53] For a more complete course in how to drive the Bayesian machine, see Deborah Mayo's (1997) article, *Duhem's Problem, The Bayesian Way, and Error Statistics*.

[54] For a comprehensive attack on the Bayesian approach to problems in the methodology of science, see Mayo's (1996) book *Error and the Growth of Experimental Knowledge* (Chicago Press); chapters 3,4 and 10.

[55] Some Bayesians might suggest that Bayes' Theorem, in so far as it contributes to an understanding of scientific inference, is intended to be used as a strictly historical tool, devoid of any normative function. I find this sort of project of rational reconstruction not only uninteresting, but also a bit of a misnomer. If a particular scientific inference can be regarded as 'rational' *post facto*, then it surely must be the case that

proposes a retreat into the subjective psychology of the worker in an effort to distinguish between competing explanations on the grounds of their respective 'plausibilities' relative to a system of background beliefs. When faced with the challenges of Duhemian underdetermination, the Bayesian recommendation is to just use 'good sense,'[56] a faculty whose precise make-up, they readily admit, may differ from one agent to the next.

Deborah Mayo's error-probabilistic approach to scientific methodology offers an alternative proposal for how to bridge the Duhemian 'gaps' that plague the simply HD model. The guiding principle of Mayo's account of scientific inference is that we learn from our mistakes. To produce tests that can severely probe the various ways in which we can err is the project of experimental science, and the application of these tests to scientific hypotheses constitutes the mechanism for the growth of our experimental knowledge. This general principle of inference is given technical expression in the following rule:

> Evidence *e* should be taken as good grounds for *H* to the extent that *H* has passed a *severe test* with *e*.[57]

Where *passing a severe test with e* requires that the following two conditions be met:

> (1) *H* fits *e* (for some suitable notion of 'fit'), and

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that inference could be *recommended* to scientists who find themselves in an identical epistemological dilemma. The idea of 'rationality' is, on any plausible reading, itself a normative idea.

[56] Michael Redhead in his (1987) – though aware of the loopholes associated with the Aspect group's tests – suggests that "Duhemian 'good sense' dictates that we should accept the demonstration in the Aspect experiment as a violation of Einstein locality."

[57] Mayo D. *Error and the Growth of Experimental Knowledge*. University of Chicago Press (1996), p. 177.

(2) There is a very high probability that the test procedure would not have yielded such a passing result [as *e*], if *H* is false.

For Mayo, the considerations of experimental design that bridge the gap between low-level experiment and high-level theory constitute the *necessary* background against which assessments of severity can be made. Consequently, when faced with the challenges of underdetermination, the error theorist proposes a return to an analysis of the testing *procedures* involved in the production and modeling of the data. No longer are evaluations of evidential support to be understood as proposed solutions to a 'two-body problem', relating a system of evidence to a hypothesis under test, but rather, as solutions to a *'many*-body problem', involving the evidence, the hypothesis, *and* the testing procedures. The introduction of these intermediate-level considerations into the evaluation of evidential support, allows the error theorist to construe multiple hypotheses that equally well 'fit' the data, as being 'supported' by that data in *un*equal measure.

This last point is important, and so bears repeating: the crucial differences in the Bayesian and error-statistical responses to Duhem's problem, stem from the unwillingness of the former to allow anything more than how well a body of evidence, *e*, 'fits' a hypothesis, *H*, to contribute to an evaluation of the *evidential support* that *e* confers upon *H*. So, when two competing theories predict the same anomalous effect, there is nothing left for the Bayesians, than to try to distinguish between these hypotheses on some grounds independent of the available evidence – thus, their appeal to the subjective degrees of belief associated with each of the competing theories.

For the error theorist, on the other hand, an evaluation of how well a theory fits the data marks only the first step in determining that theory's 'well-testedness'. Before

the findings of an experiment can be said to provide *support* to a particular claim, it is further required that these findings represent the output of a *severe* test of that hypothesis; that is, a test wherein the probability of producing such supportive evidence would be extremely low, were the hypothesis, in fact, false. It is here, in an evaluation of the severity of the experimental procedures involved in the production and modeling of the anomalous data, that the error theorist hopes to distinguish between the competing explanations of an observable effect:

> Error probability considerations provide the basis for distinguishing the well-testedness of two hypotheses – despite their both fitting the data equally well. The data may be a better, more severe, test of one than the other. The reason is that the procedure from which the data arose may have had a good chance of detecting one type of error, but not of a different type of error. What is ostensibly the same piece of evidence is really not the same at all, at least not to the error theorist.[58]

The image of hypothesis testing presented to us by Mayo's error-probabilistic notion of scientific evidence, is one in which progress in evaluating evidential support occurs not through the exercise of some 'rational' algorithm relating an unambiguous set of observational claims to a particular hypothesis, but instead through the identification and elimination of the various flaws in the procedures responsible for the production and modeling of the data. Experimental scientists are, on Mayo's view, engaged in a sort of troubleshooting activity, applying strategies directed towards the development of

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[58] Mayo D., (1997) *Duhem's Problem, The Bayesian Way, and Error Statistics* (Philosophy of Science: vol. 64), p. 235.

experiments that can severely probe for the various errors whose presence would compromise the validity of an inference based upon their findings.

Out of this image of hypothesis testing fall certain strategies designed to manage Duhemian problems. First, "blocker" strategies to block or prevent attempts to explain away anomalies by an appeal to the falsity of an auxiliary hypothesis, and second, strategies designed to legitimate attempts to pin the blame on an auxiliary by providing a severe test of that auxiliary's denial. Returning to our discussion of the Bell experiments, the following section will countenance one example of a blocker strategy that involves the establishment of a deductive link between an auxiliary assumption, *A*, and the hypothesis under test, *H*. In particular, the attempt to explain away an anomaly by an appeal to the falsity of *A* will be 'blocked' by the design of an experiment wherein *A* is made to be a *consequence* of *H*.

3.3 : Looking Forward - Blocker Strategies and the closing of the Lightcone Loophole

The general form of Bell's inequality represents a mathematical constraint on the statistical predictions of any local hidden-variable model of the ERP-phenomenon. Its original derivation was based on the assumption that within the context of any such local model, a measurement outcome at one of the hemispheres of an EPR apparatus cannot be influenced by the details of a remote measurement at the other. This assumption of causal independence between the two hemispheres – referred to as Bell's separability condition (*S*) – was said to be characteristic of all strictly local interpretations of the EPR setting, since within the context of the idealized *gedanken*, the two hemispheres of the apparatus

could, in principle, be separated by hundreds of light years, with the specification of the

analyzer settings occurring just instants before the particles arrive. Of course, such a

'space-like' separation is rather more difficult to implement in a real-world laboratory,

and as already noted, the earliest of the Aspect tests were criticized for their failings in

this regard[59] (their experimental designs involved only 'static setups, in which the

polarizers [were] held fixed for the whole duration of a run'[60]). The findings of these

early Bell experiments were thus, strictly speaking, incapable of preferencing a non-local

explanation of the EPR-correlations over a strictly local account of the phenomenon in

which the details of the analyzer settings are communicated across the length of the

apparatus in time for the outcomes of the two measurements to be coordinated.

The specific Duhemian ambiguity referenced in criticisms directed at the

lightcone loophole, arises from the fact that the derivation of Bell's inequality relies not

only on Bell's locality criterion, *LC*, but also on the separability condition, *S*. A violation

of Bell's inequality could thus be explained, while preserving the principle of no-action-

at-a-distance, by rejecting *S*; that is, by positing some sub-luminal, causally efficacious

signal-exchange between the two hemispheres of the EPR apparatus:

It has been emphasized that a crucial point in the derivation of the Bell inequalities is the

assumption of a space-like separation between the measurements [S]. These inequalities could not

be proved if the response of one polarizer depended on the orientation of the other one…In the

previous experiments, such interactions are not precluded… because the settings of the

instruments are made sufficiently in advance to allow for some mutual rapport by exchange of

signals with velocity less than or equal to that of light… Therefore the class of local

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[59] See section 2.6 above.

[60] Aspect A., Grangier P., Roger G., (1982) *Phys. Rev. Letters*, 49, no. 25., p. 1805.

supplementary-parameter theories [theories satisfying LC] that do not fulfill Bell's condition of separability [S] cannot be tested by the previous experiments. [61]

In logical terminology, the reasoning exploited in the above passage can be expressed as follows:

P1) $(LC \, \& \, S) \rightarrow e$

P2) $\sim e$

$\therefore \sim LC \vee \sim S$

Here, the observation of a violation of Bell's inequality ($\sim e$), can at best rule out *either* Bell's locality criterion or the condition of separability.
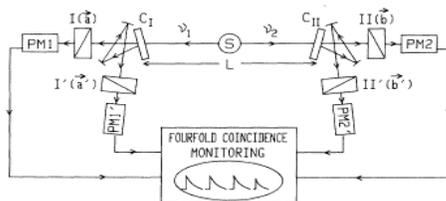
Figure 3.1 : Aspect Group's Timing Experiment with optical switches
Each switching device is followed by two polarizers in two different orientations. Each combination is equivalent to a polarizer switched fast between two orientations.

To resolve this ambiguity – that is, to 'block' the possibility of a Duhemian escape *via* the positing of certain 'non-separable' effects – researchers proposed a shift to dynamic 'timing experiments' in which the settings of the analyzers would be fixed during the flight of the particles. The first of these timing experiments was performed in 1982 by the Aspect group, and employed acousto-optical switches to oscillate the orientations of the polarizers on time scales much shorter than those it would take to transfer a signal (at the velocity of light) from one side of the apparatus to the

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[61] Aspect A., (1976) *Phys. Rev. D.*, vol. 14, no. 8. pp. 1944-5.

other (the modified setup is illustrated in Figure 3.1[62]). This modification is described by

the Aspect group as follows:

> Each polarizer is replaced by a setup involving a switching device followed by two polarizers in
>
> different orientations…Such an optical switch is able to rapidly redirect the incident light from one
>
> polarizer to another… preventing any faster-than-light influence.[63]

The results of this modified form of the Aspect group's original experiment again

revealed a violation of Bell's inequality, and were taken as still more conclusive evidence

of the fundamental non-locality of the EPR-interactions.

However, the strict 'space-like' separation of the measurement events required to

ensure the closure of the lightcone loophole was not quite satisfied by the Aspect group's

modified test. This was because the modulation with which the analyzers were set was

quasi-periodic, and so predictable into the future. An escape through the lightcone

loophole could thus still be made, by positing a communication between the detectors

synchronized with the periodic oscillations of the polarizers.[64] It was not until 1998, in an

experiment performed by a group of scientists working at the Innsbruck Institute for

Experimental Physics, that a strict space-like separation between the measurement events

in an EPR-type experiment was finally achieved:

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[62] Image taken from Aspect A., Grangier P., Roger G., (1982) *Phys. Rev. Letters*, 49, no. 25., p. 1806.
[63] Ibid, p. 1805.
[64] At this point, it becomes hard to believe that scientists would take the possibility of such a 'cosmic conspiracy' seriously. Not only would the hemispheres of the apparatus have to be communicating through some unknown local mechanism, but that mechanism would have to operate in synch with a sinusoidally driven oscillation! Again, the fact that further measures were taken to rule out even this *prima facie* implausible solution demonstrates scientific method's disregard for subjective likelihoods.

In our experiment, for the first time, any mutual influence between the two observations is excluded within the realm of Einsteinian locality. To achieve this condition the [measurement apparatuses] were separated by 400 m across the Innsbruck University Science Campus, which in turn means that the individual measurements… had to be shorter than 1.3 μs, the time for direct communication at the speed of light…The duration of an individual measurement was kept far below the 1.3 μs limit using high speed physical random number generators and fast electro-optical modulators.[65]

The shift to dynamic 'timing' experiments as a response to the lightcone loophole, represented a distinct blocker strategy used by scientists to combat Duhemian criticisms. In these timing experiments, a deductive connection is established between the primary hypothesis under test, *LC*, and its inferential interdictor, *S.* In particular, the auxiliary assumption *S* is made a deductive consequence of *LC* and certain features of the experimental architecture: If it is assumed that all *super*-luminal modes of communication are physically impossible (as implied by *LC*), and the polarizers in an experiment are set randomly at speeds fast enough to prevent any *sub*-luminal interaction, then Bell's separability condition follows deductively. The situation is described by Clauser and Shimony:

In all of the experiments performed so far, action-at-a-distance in the relativistic sense is not precluded, since the analyzers are always kept at fixed orientations for periods of several seconds. Thus there is ample time for information about the orientation of one analyzer to be transmitted by some unknown mechanism (consistent with relativity theory) to the other apparatus… thereby influencing its result. It is thus conceivable that such a mechanism is instrumental in producing quantum-mechanical coincidence counting rates…To test this possibility requires an experiment in

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[65] Weihs G., *et al* (1998). Phys. Rev. Lett., vol. 81, no. 23., p. 5040.

which the [analyzer settings] are adjusted with great rapidity while the correlated particles are in

flight… *[I]f the [settings] are adjusted with sufficient rapidity, then the non-occurrence of action-*

at-a-distance [LC], implies separability [S].[66]

So, to return to the logical formulation of Duhem's Problem, we can see that the

ambiguity introduced by the fact that *both* LC and *S* were employed in the derivation of

the generalized Bell's inequality, was resolved by a shift to the following unequivocal

argument form, a form sound in the context of an adequate timing experiment such as

that performed by the Innsbruck group:

P1) (*LC **&** S*) → *e*

P2) *LC* → *S*

P3) ~ *e*

∴ ~ *LC*

Now, although my interpretation of the rationale underlying the shift towards

dynamic formulations of the EPR-experiment has been summarized in terms of a series

of formal arguments, it would be wrong to suggest that progress towards the closure of

the lightcone loophole involved the exercise of some kind of logical ratiocination. It was,

in fact, only through an *in*formal analysis of the particular experimental apparatus

employed by the Innsbruck group, that scientists were led to conclude that no locally

permissible signal exchange could be responsible for the results of their test.[67] This

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[66] Clauser J., Shimony A., (1978), Rep. Prog. Phys. vol. 41., p. 1920. [italics added]
[67] For instance, the strength of the formal argument outlined above, depends upon whether or not it is used
in the interpretation of the results of an adequate timing experiment. This is because it is only within the

observation represents one instance of the more general suggestion that the theoretical import of an observational effect can only be understood with the aid of a detailed account of the experimental setting in which that effect is observed; and this idea is, of course, a cornerstone of Mayo's error-probabilistic notion of evidential support.

Recall that for Mayo, a body of evidence considered apart from the procedures responsible for its production, cannot assist in an evaluation of the evidential warrant of a theoretical claim. So, for the error theorist, a violation of Bell's inequality, when detached from an understanding of its experimental origins, says nothing at all about the possibility of an LHV construction of the EPR phenomenon. It is, instead, only when such a report is construed as the output of some clearly defined testing procedure, that one can begin to evaluate its true theoretical scope. To be more specific, the extent to which a particular Bell experiment can support the hypothesis that its correlational data is due to a non-local physical process, is just the extent to which that experiment represents a *severe* test of Bell's locality criterion; in other words, a test in which the probability of observing a Bell violation would be extremely low if *LC* were, in fact, true.

In section 3.2, it was noted that this call for the output of severe tests to stand at the basis of rational inference, promotes an image of experimental science in which progress amounts to estimating and eliminating the various errors that might infect an otherwise warranted inference. It should be clear that within this image, the shift to a dynamic experimental setting, such as that employed by the Innsbruck group, can be fully explicated as a genuinely progressive advance towards an experiment capable of severely testing Bell's general locality criterion.

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context of such an experiment that an acceptance of premise P2, relating Bell's criterion of locality to his separability condition, is warranted.

The lightcone loophole argues that the observation of a Bell violation in a 'static' experimental scheme does *not* provide strong evidence for the claim that some non-local interaction is behind the observed effect, because in the context of such a setting, there exists the possibility that the reported violation is due to a strictly *local*, non-separable process acting so as to choreograph the observed correlations. However, within the context of an adequate timing experiment, arguments of this sort are rendered inoperable, because to posit such a non-separable process would be *equivalent* to admitting that the two hemispheres of the apparatus communicate *non*-locally. The possibility, then, of *mis*interpreting a Bell violation due to errors that enter through the lightcone loophole, is ruled out within the context of the Innsbruck test, and it is for *this* reason that scientists regarded the development of a dynamically timed EPR-experiment as a genuinely progressive move beyond the static testing protocols of the early Aspect schemes.

Now it is important to note that throughout this whole discussion, no mention has been made of the 'plausibility' with which there might exist the sort of local, non-separable signal that could successfully reproduce the findings of the early Aspect experiments. This observation is particularly troubling from the perspective of the Bayesian approach to Duhem, since, as mentioned above, its suggestion for apportioning blame in the face of anomalous evidence involves an evaluation of the prior probabilities assigned to each of the various theories that combine to predict the anomaly.

On the Bayesian account of things, the *first* task that researchers should have charged themselves with when faced with the lightcone loophole was the evaluation of the relative 'plausibilities' of Bell's locality criterion and the separability condition, in light of the available physical evidence. However, if we examine the actual

methodological reactions exhibited by the scientists enrolled in the program, we can see that their attentions were, in fact, pointed in a radically different direction: Instead of asking how probable it would be that the two hemispheres of a generic EPR-type apparatus might communicate through some locally permissible signal – that is, instead of asking of the plausibility of Bell's separability condition – researchers were, instead, concerned to evaluate how likely it would be that the Bell violations produced in their *particular* experimental schemes might have resulted from a local signal exchange, on the assumption that such a signal exchange could, in fact, occur. They did not inquire into the general possibility of non-separable effects, but rather questioned whether such effects could be controlled within the context of their particular experiments.[68]

The performance of an adequate timing experiment by the Innsbruck group, and the observation within such an experiment of a Bell violation, says nothing about the general possibility of non-separable effects capable of orchestrating the strong correlations that were observed in the earlier static versions of the EPR-test. So, on a Bayesian reading, it is very difficult to understand why scientists found the shift toward dynamic experimental settings to be useful for the evaluation of LHV constructions of the phenomenon. Even before the Innsbruck group's test, a Bayesian scientists was faced with a Bell violation and a decision to make as to which of a number of hypotheses to blame for its occurrence. After the test, it seems, she would be faced with precisely the

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[68] The mere existence of the lightcone loophole demonstrated that, with the respect to the early Aspect tests, the answer to this question was 'no'. This suggests yet another difficulty for the general Bayesian reconstruction of the experimental program discussed in this paper. On the Bayesian accounting of things it is difficult to see why scientists placed so much stock in the existence of *ad-hoc*, artificially constructed LHV models of the EPR-phenomenon that could replicate the existing experimental findings, since it is surely the case that such models would be discriminated against in a Bayesian calculation. On the error-statistical view, however, the mere existence of such models serves to demonstrate that the experiments to date could not constitute a severe test of Bell's generalized locality criterion; that is, they could not rule out the whole class of LHV theories from the scientific running.

same dilemma! The point is just that without the ability to appeal to the experimental origins of an observational effect when evaluating the support that that effect confers upon a hypothesis, one is unable to construe a Bell violation produced in one testing scheme, as possessing an epistemological status distinct from that of a Bell violation produced in another. So, the desire to advance towards more probative experimental arrangements – a desire that certainly characterizes the behavior of working scientists – is *not* an attitude endorsed by the Bayesian methodology.

In concluding this section, what I would like stress is that this inability of the Bayesian model of inference to successfully reconstruct the methodological attitudes expressed in actual experimental research, is one of the *least* troubling of its features. More troubling still are the implications for science, when this model is taken not just as a schemata within which to organize and structure historical episodes, but is granted a *normative* status as a guide to actual rational decision-making. When accepted in this latter capacity, the image of scientific reasoning that results is not only unreflective of the attitudes expressed by actual researchers, but is also counter to the most basic aim of scientific activity, namely, to learn about the world.

Recall that the Bayesian suggestion for apportioning blame in the face of anomalous evidence involves an evaluation of the prior probabilities assigned to each of the components of a theoretical manifold. If the prior probability assigned to one component, A_1, is much larger than that assigned to another component, A_2 (and it is believed that no plausible rival to A_1 exists that would make the anomalous result expected), evidence at odds with the conjunction of A_1 and A_2, can be said to provide support for the disconfirmation of A_2. Now, the problem with the application of this

algorithm to the particular ambiguity underlying the lightcone loophole is that, still

keeping with its strictures, *both* the decision to blame the Aspect group's observed Bell

violation on some local signal exchange and the decision to attribute it to a non-local

interaction between entangled particle-pairs, can be construed as rational if sufficient

flexibility is granted to what would count as a reasonable distribution of prior beliefs.

For example, the attitudes expressed by physicists even prior to the 1982 timing

experiment, suggest that Bell's separability condition was regarded as an extremely

plausible assumption. Clauser and Shimony, in their survey of the implications of Bell's

theorem describe the separability condition as a 'highly reasonable' and 'generally

acceptable' postulate,[69] and Aspect *et al.* base their willingness to question its veracity on

nothing more than the fact that '…it is not prescribed by any fundamental physical

law.'[70] Meanwhile, the huge predictive successes of quantum theory would have likely

engendered a confidence in its application to the EPR-scenario, and accustomed

physicists to some of its less intuitive features, including, perhaps its non-local depiction

of the interaction of entangled photon pairs.[71] So, on this reading, it seems, all the

conditions were in place for a Bayesian disconfirmation of Bell's locality criterion at the

time of early Aspect tests.

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[69] Clauser J.F., Shimony A., (1978) *Rep. Prog. Phys.,* vol. 41. p. 1904.

[70] Aspect A., Grangier P., Roger G., (1982) *Phys. Rev. Letters*, 49, no. 25., p. 1806.

[71] This point is less easy to defend. In fact, it is clear that the scientists who were really concerned to examine the implications of Bell's Theorem regarded a transference of scientific credibility from the general successes of quantum theory to the plausibility of a non-local interpretation of the EPR-phenomenon, as unjustified. "Following Bell's results, many readers believed that local realistic theories were *ipso facto* discredited, because quantum mechanics has been so abundantly confirmed in a variety of experimental situations… However, upon careful examination, one finds that situations exhibiting the disagreement discovered by Bell are rather rare, and none had ever been experimentally realized. Moreover… the treatment of correlated but spatially separated systems may well be the point of greatest vulnerability of quantum mechanics." This passage provides an excellent illustration of the fact that scientists do not regard large-scale theories as monolithic structures to be tested all at once, but instead regard them as composites of more localized features to be examined in piecemeal fashion.

On the other hand, the idea that only those signals communicated at speeds less than that of light in vacuum can affect the state evolution of a physical system, is an implicit element in the neo-classical[72], relativistic view of the world; a view, that has been supported to great extent by the existing physical evidence. From this neo-classical perspective, the notion of locality thus appears as an eminently reasonable constraint on any adequate account of physical reality, and if, to satisfy this condition, one is required to posit an unknown mechanism acting so as to reproduce the strong correlational data observed in the early EPR-experiments, then so be it. After all, it would certainly not be the first time that a new physical process had been discovered. And so, it seems if we accept this classical confidence in the notion of locality, an application of Bayesian reasoning could likewise justify the disconfirmation of Bell's separability condition.

The point of this example is just to show that the Bayesian solution to Duhem is really no solution at all. If accepted, on the one hand, the *ad-hoc* nature of the non-separable effects posited by critics of the Aspect tests could make rational an acceptance of their results as good evidence for a non-local theory of the EPR-correlations. While on the other hand, the fundamental role played by the notion of locality in neo-classical relativistic conceptions of the world, could condone as equally rational, its insulation from disconfirmation at the hands of the Aspect group's imperfect experimental findings. Thus on the Bayesian account of things, scientists are, in essence, awarded a 'free pass' with which they might blame *any* hypothesis they like for the occurrence of the observed experimental results and still support their decision on so-called 'rational' grounds.

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[72] By 'neo-classical' I mean the stage in the development of relativity theory after the development of the principles of special relativity, but before field-theoretic attempts were made to formulate a consistent, unified account of relativity and quantum mechanics.

So, how can we explain scientists' determination to develop new, 'loophole-free' versions of the experiment?[73] The answer to this question, I have suggested, comes with the recognition that scientific method is entirely dispassionate towards subjective degrees of belief, and is instead concerned with the design and execution of probative experiments that can account for the various sources of error that might infect an otherwise warranted inference.

Imre Lakatos described the project of the falsificationist as consisting in attempts to break a *nut* (the theory under test) with a *hammer* (the experimental evidence) against an *anvil* (background beliefs and assertions). The goal of the scientist then is to try to 'harden' both hammer and anvil so as to facilitate the nut's 'cracking'[74]. While the metaphor is a compelling one, we should be wary of how one chooses to 'harden' their tools. For the Bayesians, this hardening amounts to the assignment of high priors to the background assumptions and evidential claims at work in a scientific inquiry.[75] But for real scientists, engaged in the task of attempting to better understand a particular phenomenon, it involves a careful analysis of the many ways in which their tests might fail to detect certain errors, and the subsequent design and execution of new and better tests that can correct for these failings.

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[73] For examples of the loophole-free proposals see [1] Fry E., Walther T., Li S., (1995) *Phys Rev. A* vol. 52, no. 6. pp. 4381-4395, [2] Kwiat P., Eberhard P., Steinberg A. Chiao R., (1994) *Phys Rev. A* vol. 49, no. 5. pp 3209- 3220, and [3] Huelga S., Ferrerro M., Santos E., (1995) *Phys Rev A* vol. 51, no.6. pp 5008-5011.

[74] Lakatos I., (1970) *Falsification and the Methodology of Scientific Research Programmes*, p. 186. published in *Criticism and the Growth of Knowledge* (Cambridge Press), Lakatos and Musgrave (ed.).

[75] Notice also that the Bayesians can 'weaken' the shell of the nut simply by lowering the prior of the hypothesis under test.

3.4 : Looking Back - Tuning the primary hypothesis in response to the Detection - Efficiency Loophole

In the last section, the shift to 'dynamic' setups in response to the failure of the early Aspect tests to ensure a space-like separation between measurements, was identified as an application of a particular 'blocker' strategy, employed so as to rule out specific attempts to save locality from empirical disconfirmation. More specifically, through the articulation of these dynamic testing schemes, scientists were able to rule out those LHV theories that posited some unknown, local signal acting so as to choreograph the strong correlations observed in an EPR-type experiment.

Now it is important to note that the execution of this sort of progressive move towards improved experimental settings often requires more than just ingenuity on the part of researchers. In the case of the shift towards dynamic tests of Bell's inequality, the significant *technological* advances that occurred in the years that followed the early Aspect tests – in fields such as random number generation and coherent signal transmission – played an indispensable role in the design and execution of an adequate timing experiment.

This recognition of *external* forces limiting the methodological moves available to an experimental worker prompts the question as to what recourse might be adopted when the implementation of a blocker strategy is *prohibited* by technological limitations. In the wake of recognizably imperfect experiments, are scientists forced to sit around and wait for the instrumental support necessary to combat the deficiencies of their tests?

In this section, I will attempt to provide at least a partial answer to this question by discussing one example of a 'retrospective' technique that the researchers engaged in

the testing of Bell's inequality employed to extract from their *flawed* experiments theoretical knowledge. This technique involved bringing the hypothesis under test 'down to meet' the experiment through the assimilation of a series of carefully formulated assumptions into the setting of the idealized EPR-*gedanken*. These 'controlled complications' of the experimental model permitted the formulation of 'weaker' versions of Bell's inequality that *could* be severely scrutinized within the context of existing experimental schemes.

As discussed in section 2.4, the photoelectric tubes employed as detectors in the first atomic cascade experiments, had quantum efficiencies on the order of 10%. This fact, conjoined with the recognition that only a very small fraction of emitted pairs manage to enter the tubes in the first place, suggests that of all the photons exiting the source, only a very small number would be included in the final statistics of the test. As noted in the 2001 *Nature* article by Phillipe Grangier entitled *Count them All*, these low detection-efficiencies opened the door to a series of complaints against the interpretation of the Aspect group's findings as conclusive evidence of a Bell violation:

> The 'detector-efficiency' loophole argues that, in most experiments, only a very small fraction of the particles generated are actually detected. So it is possible that, for each measurement, the statistical sample provided by the detected pairs is biased. For example, in experiments using pairs of photons emitted by atomic cascades, only one pair in every million was used in the measurement. So, to extract a meaningful conclusion from the observed data, it was necessary to assume that a small fraction of data provides a fair statistical sample. This would be similar to allowing one hundred votes to decide a ballot of one hundred million. Not surprisingly, several

local realistic models were built to mimic the experimental results, and the detector-efficiency loophole became the Achilles' heel of experimental tests of Bell's inequalities.[76]

A definitive closure of the detection-efficiency loophole could, of course, be achieved through the implementation of more efficient, photo-detection schemes; however, at the time of the Aspect experiments, the best photodetectors available operated with quantum efficiencies no greater than 20%[77].

In the wake of such technological prohibitions, researchers, impatient to learn what they could from the output of their early experiments, proposed a number of supplementary assumptions which, when conjoined with Bell's locality criterion, permitted the derivation of 'weaker' versions of Bell's inequality that *could* be severely scrutinized against the existing experimental results:

> When the search for experimental tests of the Bell inequalities began, it was soon realized that only extremely difficult experiments might actually show violations of the Bell inequalities… The idea was [then] put forward [to] use supplementary assumptions about the behavior of the hidden variables in order to derive inequalities able to contradict quantum mechanics in real experimental settings…[78]

One of the most popular of these supplementary assumptions was the Clauser-Horne 'No-Enhancement' (NE) postulate, which claimed that 'for every pair of source emissions, the

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[76] Granger P., (2001) *Nature* 409, p. 774.

[77] The lower limit on the efficiency of detectors necessary to preclude the possibility of constructing an LHV model capable of replicating the predictions of quantum mechanics for atomic cascade experiments (like those performed by the Aspect group) has now been shown to lie at 83%. See, Garg A., Mermin D., (1987) Phys. Rev. D., vol. 35, p. 3831.

[78] Santos E., (1992) Phys. Rev. A., vol., 46 no. 7, p. 3650.

probability of a detection with the polarizer in place is less than or equal to the corresponding probability with the polarizer removed.'[79]

Accepting NE, scientists were able to derive a version of Bell's inequality that made no explicit reference to the actual rate of pair-production in the source. Such a so-called 'homogenous' inequality could be expressed solely in terms of *coincidence counting rates* (i.e., ratios of the number of occurrences of a particular outcome, to the total number of pairs examined), so that – in evaluating these inequalities – the difficult questions addressing the adequacy of the scrutinized sample as representative of the full ensemble of source emissions, could be left unanswered[80]. Consequently, when compared to the *in*homogenous, generalized Bell's inequalities, these supplemented hypotheses were significantly easier to test:

> The probabilities [countenanced in a genuine Bell inequality] should be measured as ratios between coincidence counting rates and the production rate of the source. However the homogenous nature of the supplemented inequalities allow tests…measuring only coincidence counting rates. Also, the inequality is insensitive to many scale factors, such as detector efficiencies, angular apertures, etc.… All these features are extremely convenient from the practical point of view, and this fact explains why all performed experiments have tested homogenous inequalities. In contrast, testing inhomogenous inequalities demands devices close to ideal. [81]

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[79] Clauser J., Shimony A., (1978), Rep. Prog. Phys. vol. 41., p. 1913.

[80] For instance, the general Bell's inequality: $E(a,b) - E(a,b') + E(a',b) + E(a',b') \leq 2$, where $E(a,b) = p(1,1 \mid a, b) + p(0,0 \mid a, b) - p(1,0 \mid a, b) - p(0,1 \mid a, b)$ is *in*homogenous because it references the genuine probabilities with which a source emission registers a particular outcome at the detector apparatuses. The homogenous form of Bell's inequality derived with the assistance of the no-enhancement assumption is: $E'(a,b) - E'(a,b') + E'(a',b) + E'(a',b') \leq 2$, where $E(a,b) = (N(1,1 \mid a, b) + N(0,0 \mid a, b) - N(1,0 \mid a, b) - N(0,1 \mid a, b))(N(1,1 \mid a, b) + N(0,0 \mid a, b) + N(1,0 \mid a, b) + N(0,1 \mid a, b))^{-1}$, where the N functions represent coincidence counting rates.

[81] Santos E., (1992) Phys. Rev. A., vol., 46 no. 7, p. 3649.

Of course, the practical advantages that accompanied this shift in attention towards homogenous formulations of Bell's inequality were tempered by the fact that, strictly speaking, their violation could refute only a restricted subset of the family of LHV theories; namely, those theories that fulfill, in addition to Bell's locality criterion, the supplementary assumption employed in the derivation of the refuted inequality. For instance, a violation of a homogenous inequality based on the acceptance of NE could at best rule out the specific class of LHV theories that preclude the possibility of 'enhancing' polarizers i.e., polarizers whose presence in the path of a photon, serves to *increase* the chance of that photon's subsequent detection.

Now, there are two distinct interpretations as to why scientists attached value to this sort of fragmentary attack on the class of LHV theories. On the one hand, it might be thought that by restricting the set of empirically viable local theories to those that fail to satisfy an ostensibly 'plausible' assumption, researchers hoped to provide support to the claim that *no* LHV representation of the EPR-phenomenon should be accepted. On this reading, the physicists who introduced the assumptions, did so with the intent to 'bootstrap' their way up to a violation of the most general form of Bell's inequality *via* a Bayesian exploitation of the 'plausibility' of the introduced claim. In demonstrating that the satisfaction of Bell's locality criterion *implies* the falsity of certain physically plausible assertions, scientists – on this portrayal of things – hoped to force the prior probability generally associated with locality below the mark beneath which even the ambiguous output of the early Bell tests could supply its Bayesian disconfirmation.

In support of this interpretation of the role played by the knowledge acquired through the testing of homogenous Bell's inequalities, it can be noted that a significant

debate was had between researchers as to the reasonableness of their introduced

assumptions. Indeed, one of the more interesting polemics occurring in the discussions of

the early Bell tests concerned the likelihood with which the polarizers employed in an

EPR-type experiment might act in such a way as to violate the no-enhancement postulate

(Whereas some scientists proposed that '…the assumption [NE] appears reasonable

because the insertion of a polarization analyzer imposes an obstacle between the source

emissions and the detector, and it is natural to believe that an obstacle cannot increase the

probability of detection',[82] others dismissed this sort of argument as a remnant of the

'naïve mechanistic picture of the photon' – a picture in which the path of the photon from

the source to the detector can be clearly *separated* into first its passage through the

polarizer, and then, its forwarding to the detection device[83]).

What is important to note, however, is that in spite of their beliefs regarding the

plausibility of the introduced assumptions, *all* of the scientists engaged in the program

saw the value – and indeed, the necessity – of formulating an experiment that could test

Bell's inequality *without* the aid of such devices. For instance, Clauser and Shimony,

though optimistic about the plausibility of NE, admit that it provides, 'a certain loophole

to those who wish to defend local hidden-variables theories in spite of the experimental

evidence.' And they go on to advise 'caution' in its acceptance, suggesting that the

considerations favoring its validity, '…are by no means sufficient to prove [it].'[84] Emilio

Santos, Susana Huelga and Miguel Ferrero in their (1995) argue that experiments which

employ supplementary assumptions 'cannot discriminate between quantum mechanics

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[82] Clauser J., Shimony A., (1978), Rep. Prog. Phys. vol. 41., p. 1913.
[83] See, for example Santos E., (1992) Phys. Rev. A., vol., 46 no. 7, p. 3652-54.
[84] Clauser J., Shimony A., (1978), Rep. Prog. Phys. vol. 41., p. 1913-15.

and the whole family of LHV theories…,'[85] and on the basis of this observation, they suggest the performance of updated atomic cascade experiments employing more efficient photo-detection schemes.

So if researchers generally opposed the notion that a violation of a homogenous Bell's inequality could represent sufficient cause to reject the whole class of LHV theories, how are we to understand the significance that they attached to the construction and testing of these weaker hypotheses? The answer, I suggest, begins with the observation that while scientists are committed to the development of rigorous testing procedures in which the various errors that might invalidate an inference are fully accounted for, when such testing procedures fail to live up to one's original theoretical aspirations, the knowledge that they *can* provide is not *de facto* depreciated. Scientists are, after all, ultimately in the business of learning about the world, and sometimes such learning does not adhere to the scripted scenarios in which hypothesizing always precedes testing. The failures of the Aspect group's early tests to provide definitive evidence of a Bell violation, did not prevent scientists from learning a great deal about the nature of the EPR phenomenon from their results. This basic point is conceded by Emilio Santos in his (1992):

> …[T]he existence of criticisms [against their validity] do not imply that experimental tests of inequalities involving supplementary assumptions have been useless. On the contrary, they have been highly valuable, but their real value has been to provide constraints on the possible LHV

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[85] Huelga S., Ferrero M. and Santos E., (1995) Phys. Rev. A., vol. 51, no. 6. p. 5008.

theories. For instance, the performed experiments on polarization correlation of photon pairs provide a lot of information about possible LHV theories of optics.[86]

So, Although the Aspect tests could not demonstrate in definitive fashion that the EPR-correlations are *not* due to some local physical process, they could say a great deal about what such a process, if responsible, would have to look like. This idea suggests a second interpretation – markedly different from that outlined above – of the methodological role played by the supplementary assumptions introduced by researchers to produce weaker, and more accommodating versions of Bell's inequality. On this interpretation, the assumptions do not function as 'weights around the neck' of the generalized locality criterion, detracting from its plausibility and making it more vulnerable to a Bayesian refutation, but rather as *tools* with which scientists were able to extract what theoretical content was contained in the existing experimental data. This latter reading is preferenced in the following passage by Santos:

> Introducing assumptions (e.g., fair sampling, no enhancement), in addition to [Bell's locality criterion], in order to get testable inequalities, amounts to restricting the family of LHV theories to be tested. Such additional assumptions, allegedly plausible, have been used for the analysis of all available tests. However, as plausibility is not a scientific criterion, it seems to me that a proposal where it is clearly exhibited the restricted family of LHV theories to be tested, is less misleading than using the word "plausible."[87]

Understood this way, the strategy of complicating an experimental model so as to allow for the development of testable hypotheses is in keeping with a commitment to

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[86] See, for example Santos E., (1992) Phys. Rev. A., vol., 46 no. 7, p. 3652.
[87] Santos E., (2004) Phys. Lett A, vol. 327, p. 34.

severe testing as the basis of experimental science. Where the development of new, more sophisticated experimental schemes is impracticable due to technological limitations, new questions are posed, and hypotheses put forward, that can be severely scrutinized against the existing data. Faced with the difficult task of establishing objective knowledge in the face of Duhemian obscurity, scientists rely upon a *dialectical* 'give-and-take' between their experiments and their theories: while new and better testing schemes are designed to live up to the lofty demands of a theoretical inquiry, weaker, less demanding hypotheses are developed to accommodate the various limitations of the far-from-ideal milieu of the laboratory.

In what remains of this section, I will discuss, briefly, the current status of the detection-efficiency loophole as it applies to more recent formulations of the Bell experiment. In a report published in the February 2001 edition of *Nature*, M.A. Rowe and colleagues describe the results of their attempt to instantiate the EPR-*gedanken* through the production of 'trapped' Beryllium ion-pairs, as representing a 'clear violation' of the generalized Bell's inequality[88]. In their experiment, the measured ions, confined along the axis of a linear Pail trap, are 'entangled' using stimulated Raman transitions, and then separated. Once apart, their energetic states are determined by bombarding each with a 'detection' laser-beam, and observing the number of photons that scatter off of the ion. In a dark state, or 'up' state, the ions scatter very few photons, and in a bright state, or 'down' state, they scatter many more. The correlations detected between the 'up' and

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[88] Rowe M.A., *et. Al*, (2001) *Nature*, vol. 409. p. 790-3.

'down' states of these 'entangled' ion-pairs reveal a violation of the Bell's inequality by approximately eight standard deviations[89].

What is important to note about the Rowe experiment, is that since the examined ion-pairs were engineered and controlled on an individual basis, the problems of detection-efficiency that plagued the earlier cascade experiments – including the Aspect tests – are defused in the context of their testing scheme. No longer is the employed source sporadically and uncontrollably projecting pairs in all directions for the experimental apparatus to 'catch' and analyze. Instead, 'each entangled ion-pair is prepared on purpose, and observed at will,'[90] so that no supplementary assumptions of the sort described above are required in the analysis:

> The result [reported here] was obtained using the outcomes of every experiment, so that no fair-sampling hypothesis is required. In this case, the issue of detection efficiency is replaced by detection-accuracy… Our detection efficiency was high enough for a Bell's inequality to be violated without requiring the assumption of fair sampling, thereby closing the detection-efficiency loophole in this experiment.[91]

3.5 : Conclusion

I have spent most of this chapter trying to argue that the methodological reactions of the researchers engaged in the testing of Bell's inequality betray a fundamental commitment to objectivity in scientific inference. This commitment manifests itself both in an

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[89] The reported result of $S_{expt} = 2.25 \pm 0.03$ stands in clear violation of the generalized Bell's inequality, which asserts $-2 \leq S \leq 2$.
[90] Grangier P., (2001) *Nature* vol. 409, p. 774.
[91] Rowe M.A., *et. Al*, (2001) *Nature*, vol. 409. p. 791.

indefatigable impetus to develop new and improved experimental settings – ever approaching the ideal of Mayo's 'severe' tests – and in a careful exactitude in the evaluation of the genuine discriminative power possessed by an existing body of evidence. In combination, these attitudes support a vision of scientific inquiry that is both forward-thinking and conservative. It is an image which denies the identification of scientific activity with the testing of fixed, unyielding hypotheses, emphasizing instead the *dialectical* relationship between theoretical claims and the experiments aimed at their evaluation.

As a counterpoint, I have tried to argue that the Bayesian model of rational retainment is incapable of accounting for the methodological attitudes expressed in real scientific research. When faced with the obstacles posed by methodological underdetermination, researchers, unwilling to base the rational merit of a scientific inference on how well the inferred hypothesis fits with their already established background beliefs, instead opt for the *hard road*, developing severe tests whose output can provide unambiguous support to a particular theoretical claim.

Had the scientists involved in the testing of Bell's inequality taken seriously the Bayesian model of rational inference, *any* theoretical conclusions they might have drawn from the evidence provided by the Aspect tests, could, with sufficient manipulation of the priors, have been constructed as rationally warranted. This 'anything goes' attitude, in turn, would have made pointless subsequent attempts to address the loopholes associated with the Aspect group's findings, and would have likely stunted, if not halted altogether the experimental progress that ultimately led to the articulation of the improved testing protocols of the Innsbruck group and Rowe *et al*.

Now, one might ask why such a development towards more sophisticated experimental schemes was really so important, given that the claim suggested by the Aspect group's original findings – namely, that Bell's inequality is violated in certain EPR-type scenarios – has only been *vindicated* by the performance of these subsequent tests. Couldn't the scientific community have saved itself a lot of time and effort, by simply accepting as conclusive the Aspect group's reported successes on the grounds of Duhemian good sense?

Questions of this sort are indicative of an exceedingly narrow conception of the role that experimental research plays in the growth of scientific knowledge. If experiments are to be conceived of as simply the testing ground for theoretical hypotheses, then it is natural to think that once a particular claim has been established, subsequent tests of that same hypothesis can offer no additional contributions to our scientific understanding of the world. But in actuality, the contributions offered by advances in experimental research amount to more than the mere provision of new testing schemes within which previously unqualified hypotheses can be scrutinized. It is also from within the laboratory that scientists extend their technological repertoire, and become familiar with the more curious and intriguing features of a phenomenon. This familiarity, in turn, allows researchers to begin to question the role that such a phenomenon might play in applications belonging to a variety of scientific disciplines. In this sense, then, the laboratory is every bit as much a *play*ground as it is a testing ground, and it is in this playground that scientists really 'get to know' the objects that they study.

In the case of the Bell tests, recent experimental developments have led not only to the production of more sophisticated settings within which to test the generalized form

of Bell's inequality, but have also advanced our understanding of how to engineer and control 'entangled' particle-pairs. For example, the experiment by Rowe *et al.*, in addition to its contribution to the ongoing debate over the non-local character of the EPR-correlations, has provided scientists with a great wealth of information – both theoretical and technological – which may turn out to be crucial to the implementation of quantum encryption techniques, as well as other applications of quantum information processing:

> … Rowe *et al.*'s experiment is a vivid demonstration of the high degree of sophistication that has been reached in the control of 'engineered' quantum systems…This opens fascinating possibilities for manipulating the quantum state for many-particle quantum systems. Such systems are the basic elements for achieving long term goals in quantum information, such as building a quantum computer. [92]

So, the advantages of developing these new experiments extend well beyond their potential to provide definitive evidence of a Bell violation. They also afford researchers the opportunity to procure a more sophisticated and intuitive understanding of the limits and capabilities of entangled particle pairs to function in quantum information processing.

Now, to return to a point that I have been stressing throughout this chapter, had scientists employed a Bayesian strategy in response to the Duhemian challenges facing the interpretation of the Aspect group's early findings, they would have in essence been given a 'free pass' to accept as rational whatever reaction best accorded with their already established system of beliefs. The attitude enforced by an acceptance of the Bayesian

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[92] Grangier P., (2001) *Nature* vol. 409, p. 775.

model of rational inference thus *suffocates* any demand to produce more probative testing schemes, and it is primarily through the various attempts to live up to this demand, that scientists manage to learn about the world. It is therefore, of the utmost importance that the 'bar' on scientific confirmation be placed exceedingly high – a demand which, at the very least, requires a model of evidential support in which not every inference can be deemed rational – if not because such a placement accommodates our best philosophical understanding of scientific rationality, then because the various techniques that scientists are forced to deploy to meet up to this bar are conducive to the growth of theoretical knowledge.

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VITA

Anubav Vasudevan

Address: 435 West 119th St. Apt. 7A
                 Apartment #7A
                 New York, NY 10027
Phone: (917) 547-9834
E-mail address: av2137@columbia.edu

Education:

Virginia Polytechnic Institute and State University, Blacksburg, VA
Master of Arts in Philosophy, expected 2005

Virginia Polytechnic Institute and State University, Blacksburg, VA
Bachelor of Science in Physics (Second Major: Philosophy), 2002
Summa Cum Laude

Honors and Professional Memberships:

Phi Beta Kappa – National Academic Honor Society, member, 2000
Sigma Pi Sigma – National Physics Honor Society, President, 2000-01
- *William H. Williams Award* for academic excellence in Philosophy, 2002
- *H.Y. Loh Award* for academic excellence in Physics, 2002
- *C.H. Wan Scholarship* for active engagement in research in stochastic processes, 2001
- *Hugh D. Ussery Scholarship* for academic excellence in Physics, 2001
- *Daniel C. and Delia F. Grant Endowed Scholarship* for academic excellence in Physics, 2000

Teaching and Research Experience:

Graduate Teaching Assistant, *Virginia Tech*
2002 – Present, Blacksburg, VA
Instructed recitation sections for introductory courses in Philosophy. Courses include: *Knowledge and Reality, Morality and Justice*, and *Global Ethics*.

Research Assistant, *Virginia Tech*
1999-2002, Blacksburg, VA
Developed a program that models non-equilibrium system evolution (programmed in C). Awarded with C.H. Wan Scholarship for active engagement in research in stochastic processes.

Presentations:

Vasudevan A., *Phenomenology of Driven Ising Models with Enforced Defect Boundary Conditions.*
Presented at Condensed Matter Group Seminar, Blacksburg, VA. Summer 2001.