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The EPR Paradox

Einstein's Challenge to Quantum Mechanics

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Chapter 1: The Discovery of the EPR Paradox

The paper of 1935 did not appear out of nowhere. It was the last and sharpest move in an argument that Einstein had been conducting with the quantum theory for nearly a decade, and to understand what its authors were trying to do, the argument has to be reconstructed.

Einstein had been one of quantum theory's midwives. His 1905 paper on the photoelectric effect proposed that light comes in lumps, a suggestion even more radical than Max Planck's original quantization and one that helped earn Einstein the Nobel Prize. He did not object to quantum mechanics because he found it strange or because he could not follow it. His objection was more specific and more interesting: he believed the theory was incomplete. By incomplete he meant something technical. A complete theory, as he framed it in later statements of the position, is one in which every element of physical reality has a counterpart in the theory. If an experiment can be performed whose outcome is certain without the system being disturbed, then there exists something real about the system corresponding to that certainty, and a theory that does not represent it is missing part of the world.

Bohr answered Einstein's challenges at the famous Solvay meetings of 1927 and 1930, and by most accounts he won those exchanges. The photon-in-a-box thought experiment of 1930, in which Einstein proposed weighing a box of light to determine the energy and timing of an emitted photon with arbitrary precision, was dismantled by Bohr using general relativity itself, an argument so elegant that Einstein conceded the point. But conceding individual rounds did not change his underlying conviction, and through the late 1920s and early 1930s his letters show him searching for a version of the puzzle that could not be dissolved by Bohr's artistry, because it would be a fact about the theory rather than a fact about cleverly arranged measuring devices.

Two things then happened in quick succession. Einstein emigrated, taking a position at the Institute for Advanced Study in Princeton, and there he acquired two younger collaborators, Boris Podolsky, a Russian-born theorist, and Nathan Rosen, a young American postdoctoral researcher. Rosen had already made his name in general relativity, where the object now called a wormhole was first examined in a paper by Einstein and Rosen. The three set about turning Einstein's conviction into a published argument, and the construction they produced, submitted in the spring of 1935, ran roughly as follows in plain language.

Consider a pair of particles that have interacted and then separated, one sent to a laboratory here, the other to a laboratory far away. The laws of quantum mechanics, applied to the pair, predict perfect correlations between certain measurements on the two: measure one particle's position and you can predict the distant particle's position with certainty; measure the momentum of the first and you can predict the distant momentum with certainty. Neither measurement touches the distant particle. Now

apply the criterion of reality: if the distant particle's position can be predicted with certainty without disturbing it, its position is an element of reality; the same reasoning makes its momentum an element of reality. Both properties are therefore real at once. But quantum mechanics forbids assigning sharp values to both position and momentum simultaneously; that is the content of the uncertainty principle. Hence quantum mechanics fails to represent real properties that the world possesses, and is therefore incomplete.

Podolsky, by most accounts, polished the writing, and the published introduction frames the argument with a generality Einstein thought excessive. Einstein wrote afterward to his friend Erwin Schrödinger, who was then in Oxford, that the main point had been smothered by the paper's erudition. The essential question, he said, was not the elaborate packaging but a simple one: can the state of one system be considered complete when its description refers to correlations with a distant system? Schrödinger answered that letter with a burst of creativity, giving the strange correlation its enduring name, entanglement, in his reply and the papers that followed it that summer. The same months produced his famous cat, proposed in part as a second, more vivid demonstration of the same uncomfortable territory: quantum description that fails to be a description of a definite world.

The paper appeared in May 1935 under the title its question became known by, in the Physical Review, and it drew an immediate reply from Bohr, published the same year in the same journal under the same title, that historians still find easier to admire than to summarize. What matters for the story is what the physics community did with the exchange, which was very little, and for understandable reasons. Quantum mechanics was conquering one field after another; nuclear physics was exploding, literally, in the same decade; and a dispute about the meaning of the word reality, with no experiment proposed to settle it, was easy to shelve. Einstein returned to unified field theory. Podolsky went to industry and academia. Rosen had a long career in physics. The paradox entered the textbooks as a footnote, a famous objection, duly noted and left unresolved.

The footnote waited twenty-nine years for its revenge, and the revenge, when it came, did not come from the philosophical side of the argument. It came from Bell, and it converted the whole dispute into an experiment. Before turning to that conversion, it is worth being precise about what the paradox actually claims, because the popular version, involving faster-than-light signals and particles communicating across space, is wrong in ways that matter. That precision is the business of the next chapter.

Chapter 2: Understanding the EPR Argument

The EPR argument is often summarized as proving that quantum mechanics permits faster-than-light influence. It proves no such thing, and the difference between what it proves and the popular summary is the key to everything that followed. This chapter reconstructs the argument carefully.

Begin with the state of affairs quantum mechanics actually assigns to the world. In the

theory, the most complete description of a system is its state, a mathematical object from which the probabilities of all measurement outcomes can be computed. For a single particle, the state specifies, among other things, the spread of possible positions and momenta. Heisenberg's uncertainty principle is not a statement about clumsy instruments; it is a statement that the state itself cannot concentrate probability sharply on both position and momentum at once. A particle can have a sharply defined position, or a sharply defined momentum, and the theory sets a strict joint limit on how much of both it can carry. The founders took this limit to mean that the pair of values does not jointly exist when the state does not represent it: the theory's state is the complete story, and questions about values the state does not encode are questions with no answers.

Einstein's group granted the mathematics entirely and attacked the claim of completeness. Their instrument was a criterion of physical reality stated with disarming simplicity: if one can predict with certainty, without in any way disturbing a system, the value of a physical quantity, then that quantity is an element of reality, meaning there exists a real property of the system corresponding to it. The criterion is deliberately conservative. It does not say that only predictable quantities are real; it says that predictable quantities must be counted among the real. Whatever else reality contains, it contains these.

Now the constructed scenario. Take two particles that have interacted and flown apart, and suppose the interaction left them in a state with exact correlations: when one particle is found at some position, the other is found at a position related to it by a known rule, and when one is found with some momentum, the other carries a momentum related by a known rule. Quantum mechanics permits exactly such states and is proud of them. The crucial feature is that the correlations are perfect. Measure the position of the near particle and, by the rule, you can state the distant particle's position with certainty, exactly as though you had measured it. Measure instead the momentum of the near particle and you can state the distant particle's momentum with certainty. The distant particle is never touched in either case.

Apply the criterion. After the position measurement on the near particle, the distant particle's position is predictable with certainty without disturbing it, so that position is an element of reality. Run the world again with the momentum measurement instead, and the distant particle's momentum is an element of reality. In each run, the distant particle possessed the property in question before any communication could have arrived from the near laboratory, and it possessed it regardless of which measurement the near experimenter chose, since nothing traveled to it. The two properties, position and momentum, cannot both be represented by any quantum state, yet the argument indicates both are real. A theory that cannot represent real properties is incomplete. The conclusion, in the paper's careful wording, is that the description of reality given by the quantum state is not complete, or else, if one insists the state is complete, then the real properties of the two systems are tied together in a way that violates any reasonable idea of separateness.

The deep issue, the one Einstein kept pointing to, is separability: the idea that the

world is made of distinct things, each with its own properties, whose states explain their behavior. In the correlated scenario, either each particle carries its own definite properties, in which case quantum mechanics is missing them, or no such local story exists, in which case the two particles form one inseparable whole whose state is not stitched together from individual properties. Einstein considered the second horn unacceptable, amounting to what he called, in a letter written a decade later, spooky action at a distance. He did not believe quantum mechanics was wrong in its predictions. He believed it was a provisional theory, an impressive but unfinished description of an underlying world in which separability held and the apparent nonlocality would dissolve, just as the spooky action-at-a-distance of Newtonian gravity had dissolved into the local curvature of general relativity.

Two clarifications guard against the standard misreadings. First, the EPR argument involves no faster-than-light signal and claims none. The near experimenter cannot use the correlations to send any message; the distant results, examined alone, look completely random, and the correlation is visible only when the two laboratories later compare records, which they do at light speed or slower. Second, the argument does not dispute a single quantum prediction. It grants them all, and draws a conclusion about what the predictions leave out. This is why Bohr's reply, examined in the next chapter, is so strange to modern readers: it does not correct any physics either. It contests the criterion of reality, the meaning of disturbance, and the framework within which the phrase element of reality has sense. The two sides agree on every number and disagree about what the numbers mean. That situation, in physics, is normally resolved by an experiment, and for three decades nobody could see how an experiment could enter. The resolution of that deadlock is Bell's story, which arrives in Chapter 4.

Chapter 3: Key Characteristics of the EPR Paradox

Several features of the paradox deserve singling out, both because they explain why it survived its own decade and because they define exactly what was later put to the test.

The first characteristic is that the argument is a dilemma, not a single claim. EPR presents two options: either quantum mechanics is incomplete, or the world contains nonseparable connections. The logic forces one of the horns; the paper's authors preferred the first and their opponents preferred the second. Bell's later analysis, remarkably, would find a third possibility nobody had listed, namely that both horns could be false in a way no one had framed, and the century's experiments would then confirm that third option. But in 1935 the dilemma was already a genuine advance: it replaced a soft disagreement about taste with a hard fork about the structure of the world.

The second characteristic is the conservative definition of disturbance. The criterion of reality is built around prediction without disturbance, and the word disturbance is doing careful work. In the standard quantum account, measuring the near particle does not disturb the distant particle in any way; the two-particle state, considered as a

whole, changes, but no local change occurs at the distant laboratory. EPR built the argument precisely so that no one could object that the distant particle was disturbed. Any reply that granted the physics had to grant the undisturbed predictability, and therefore had to grant, by the criterion, the reality of the predicted properties, or else reject the criterion. The paper leaves that choice visible and explicit.

The third characteristic is the use of perfect correlations rather than mere statistical ones. Position and momentum were chosen because quantum mechanics itself guarantees exact relationships between the two particles' values in the constructed state, not approximate ones. The argument does not rely on fragile statistics; it relies on the theory's own exact bookkeeping. This feature made the paradox look airtight in 1935, and it was exactly the feature Bell would later relax, showing that even imperfect, statistical correlations, properly interrogated, contain a measurable signature of the same dilemma. That relaxation is what made experiment possible.

The fourth characteristic is that the paradox is operational, in a quiet way. For all its talk of reality and completeness, the argument is driven by what can be measured and predicted, and its conclusion concerns what must exist behind the measurements. This is why it could be ignored as philosophy by physicists who did not want to talk about reality, and why it could be turned into an experiment by a physicist who rephrased reality-talk as a statement about the statistics of hidden variables. The concepts were waiting, so to speak, in their work clothes, for someone to put them back to work.

The fifth characteristic is what the argument does not assume. It does not assume determinism, a common misreading. The criterion of reality is a sufficient condition, not a statement that only deterministic quantities are real, and the dilemma stands whether or not the underlying world is deterministic. Bell later found that the assumption his inequality actually needs is not determinism but locality combined with the independent, free choice of measurement settings, a subtlety that has generated its own literature. EPR is also often misread as asserting hidden variables; the paper prefers the weaker claim of incompleteness and leaves the repair of the theory unspecified.

A final characteristic, often missed, is the paradox's relationship with relativity. Einstein's discomfort with the completed quantum mechanics was, in his own telling, not aesthetic but relativistic: a theory in which the real state of one region depends on what is done in a spacelike-separated region conflicts with the spirit, if not the letter, of relativity, since no description of the distant region can be considered complete until news from elsewhere arrives. Relativity, he believed, was the deepest principle physics had found, and he expected any final theory to respect its locality. The great irony of the century that followed is that the experiments vindicated quantum mechanics precisely on the point where it seemed most relativistically suspect, while confirming that no usable influence exceeds light speed. The correlations are real, nonlocal, and stubbornly unusable for signaling, a combination nobody in 1935 would have predicted.

Chapter 4: Bohm's Detour: The Theory That Would Not Die

The road from the paradox of 1935 to the theorem of 1964 runs through a detour nobody planned, and the detour has a human story the standard histories flatten into a citation: between EPR and Bell stands David Bohm, and what happened to Bohm is part of what happened to physics.

Bohm was one of the brightest of the American generation that built postwar physics. A student of Oppenheimer's at Berkeley, he had worked on the electromagnetic separation of uranium isotopes for the bomb project, and in 1946 he arrived at Princeton as a young assistant professor with a reputation for clarity. The clarity produced a textbook: his Quantum Theory, published in 1951, remains one of the most readable accounts of the theory ever written, an orthodoxy presented as fairly as orthodoxy can be. The exercise left him unsatisfied rather than confirmed. Writing the doctrine as persuasively as he could, he found himself doubting exactly what Einstein doubted, whether the theory's statistical haze was the world's or the description's.

Then politics intervened with an ugliness the story usually omits. In 1949, in the atmosphere of the security investigations that swept American science, Bohm was called before a congressional committee and asked to name colleagues who had been members of the Communist Party years earlier. He refused, invoking his constitutional protection against compelled testimony, and the country's institutions answered him: Princeton declined to renew his appointment, and he found himself, at the height of his powers, effectively unemployable in the country of his birth. The same national mood that had sheltered the EPR paper's authors in comfortable Princeton expelled the one physicist who was about to do the paradox its first major favor.

The favor was done in exile. A position in Brazil took Bohm to São Paulo in 1951, and there, at the edge of the physics mainstream, in a country whose scientific establishment he was helping to build, he did the thing von Neumann's theorem said was impossible: he constructed a version of quantum mechanics with hidden variables, particles carrying definite positions at all times, guided by a wave that never collapses. The two papers appeared in the Physical Review in 1952. Every prediction of standard quantum mechanics came out intact; the price, as Bohm saw clearly, was that the guiding wave's influence was nonlocal, connecting distant particles in exactly the manner the EPR argument had made visible. Einstein, whom Bohm had hoped to please, responded with interest but not conversion, and the physics community responded with the silence reserved for a heresy that works.

The theory mattered immediately, though almost nobody said so. Von Neumann's impossibility proof, the field's license to dismiss Einstein's program, was now confronted by a working counterexample: a theory of exactly the forbidden kind, reproducing every prediction. A proof cannot survive a counterexample, and the community's choice to ignore Bohm's construction rather than explain it is one of the century's cautionary tales about authority in science. The man who showed the door

was open had been pushed through it by a political panic, and the lesson, that the field's blind spot had a political shadow, deserves its line in the history.

The theory's own ancestry deserves a word, because Bohm's construction was also a resurrection: the pilot-wave idea was Louis de Broglie's, presented and abandoned at the 1927 Solvay conference, where the young French prince of wave-particle duality had proposed exactly such a scheme and been talked out of it by the assembled orthodoxy. Bohm, working from the other end of the century and the other side of an ocean, arrived at the same mathematics independently, and the rediscovery is part of the history's texture: an idea the century's founders had considered and discarded, retrieved by a man the century's politics had discarded, so that the 1952 papers stand at the intersection of two buried things, a theory and a career, each dug out by the other.

Bohm's next contribution is the one the experiments themselves rest on. With Yakir Aharonov, his student, he recast the EPR argument in 1957 in its modern form: instead of the original paper's position and momentum, which experimenters could never realize cleanly, the dilemma was restated for spin and for photon polarization, the correlated pairs that laboratories could actually produce, down to the annihilation photons of positronium decay as a natural source. Every Bell test ever run, from the calcium cascades of the 1970s to the diamond spins of Delft, tests a scenario in the form Bohm and Aharonov gave the paradox. The original argument of 1935 has never been tested and never will be; what the century tested, and vindicated, is the exile's version.

The theory's afterlife outgrew its author's marginal standing: the pilot-wave approach, now usually called Bohmian mechanics, carries a small but permanent community of physicists and philosophers, its trajectory equations derived with increasing sophistication, its textbooks written, its workshops held, its candidates for a relativistic extension still pursued. The community's standing, a respected minority rather than a heresy, is itself a datum about how the field changed, from the era in which Bohm's papers were ignored to an era in which every interpretation, however unfashionable, is expected to state its price and pay it openly, a fairness the century owed the paradox from the beginning and finally learned to practice.

The exile's own story kept its strange arc. Moving from Brazil to Israel and then to a professorship at Birkbeck College in London, Bohm co-discovered, with Aharonov, the effect that bears both their names, the magnetic influence of a field on electrons that never touch it, one of the most beautiful results of the century and a proof that his instincts for deep questions had survived everything. His later decades turned toward philosophy, a speculative picture of reality as an unbroken whole, an implicate order, ideas the physics mainstream kept at arm's length even as his 1952 theory enjoyed a small renaissance among the foundations community. He died in 1992, two years after Bell, having seen the loophole-closing experiments begin and his own early heresy become a permanent, respected minority position.

The detour's lesson is the chapter's closing one. The decade between Bohm's theory and Bell's theorem is usually told as a delay, but the delay had a cause: a community

that believed an impossibility proof it had not checked, and that had just demonstrated, in Bohm's case, how its institutions treated dissent. Bell, reading Bohm carefully where others would not, asked the question the counterexample demanded. Without the exile in São Paulo, the theorem of 1964 might have waited another generation, and the story of this book is therefore not only about ideas: it is about the conditions under which ideas get their hearing, and about a man who, denied his country and his career's center, handed physics the piece it had been missing.

Chapter 5: The Science Behind the Paradox

When the paper reached Copenhagen, Bohr spent six weeks, by the recollection of his colleagues, in an unusually agitated state, drafting and redrafting his response, which appeared the same year in the Physical Review under the same title as EPR's. The reply is one of the most discussed and least understood documents in the philosophy of physics, and its core moves can be stated plainly even where its prose cannot.

Bohr's answer to the dilemma was to reject the criterion of reality, or more precisely, to reject the framework in which it makes sense. The phrase without in any way disturbing the system, he argued, contains an ambiguity that dissolves the EPR reasoning. In the correlated scenario, the near measurement does not mechanically disturb the distant particle, but it does change the conditions that define what can meaningfully be predicted about it. The correct unit of analysis, Bohr maintained, is not the distant particle but the entire experimental arrangement, the two laboratories together with their apparatus. Within that whole, the choice of which measurement to perform on the near particle determines what kind of prediction is licensed about the far one, and no meaning can be attached to the properties of the far particle considered in isolation, before and apart from the whole arrangement. To EPR's claim that predictability-without-disturbance establishes real properties, Bohr answered that the very concept of a property of the distant particle, detached from the experimental context, is what quantum mechanics has taught us to abandon.

Modern readers usually find this response unsatisfying, and it is important to see exactly why. Bohr does not dispute any prediction. He does not explain the correlations; he accepts them and reinterprets what there is to explain. His position is that the EPR criterion smuggles in a classical assumption, namely that the world is made of objects each carrying its own definite properties, and that quantum mechanics has shown this assumption false in a way the criterion's wording cannot register. This is a coherent position. It is also, in a precise sense, untestable as stated, because it offers no observable difference between a world in which the criterion holds and one in which it fails. The deadlock persisted for a generation precisely because both positions were, at the level of every conceivable measurement, observationally identical.

Two responses from the same year round out the picture. Schrödinger, corresponding intensively with Einstein, coined the term entanglement for the correlations, declaring that the phenomenon was not one of quantum theory's obscure byways but its defining trait, the one that marks its departure from classical thought. He also

introduced the image of the cat that same summer, a companion demonstration that the quantum description, taken as a complete account of a definite world, leads to absurdity. A subtler contribution came in Schrödinger's papers on the same theme: the observation that the distant particle, in the correlated scenario, seems steerable, its statistics controllable in some sense by choices made at the near laboratory, though always in a way that no signal can carry. Decades later, steerability would be made precise as a distinct tier of quantum correlation, stronger than mere entanglement in one respect and weaker in another, and it now names an active research field of its own.

While the philosophers argued, physics moved on. Quantum electrodynamics, nuclear physics, and solid state physics absorbed the attention of the field, and the paradox became textbook material, summarized in a paragraph, attributed respectfully to Einstein, and set aside as untestable. An influential roadblock deserves mention, because it shaped attitudes for decades: in 1932, John von Neumann had published an argument purporting to prove, with full mathematical rigor, that no theory of hidden variables could ever reproduce the predictions of quantum mechanics. The proof contained a flawed assumption about how averages of quantities combine, an assumption reasonable enough to escape scrutiny for twenty-three years, and its authority convinced many physicists that Einstein's program was not merely incorrect but provably dead. Few checked the proof, as few check proofs whose conclusions they welcome. When the flaw was finally exposed, it was exposed by the same man who reopened the entire question, in the same paper.

Before meeting him, it helps to have Bell's inequality in plain clothes, because the arithmetic is genuinely simple and its simplicity is the source of its power. Imagine a game with two players in sealed rooms who cannot communicate. A referee asks each player one of two possible questions, call them vertical or diagonal, and each must answer yes or no. The players may agree on any strategy beforehand, but the strategy can be nothing but a table listing what each will answer to each question, a set of properties fixed in advance. Suppose the game is scored so that the answers match in certain combinations of questions and differ in others, in a pattern chosen by the referee. A short counting argument, the kind a bright schoolchild can check on paper, shows that with any pre-agreed table of answers, the players cannot win the game more than three times in four rounds on average. The bound is the inequality. Quantum mechanics hands each player an entangled particle instead of a table, and with the particles the pair wins noticeably more often than the bound allows. No pre-written table, in any corner of the universe, produces those odds. That is the whole engine of the story that follows: a schoolroom counting argument, a measured frequency, and a gap between them that no local arrangement of pre-existing answers can bridge.

The roadblock had an earlier critic, and her obscurity is its own lesson: Grete Hermann, a German mathematician and philosopher, published in 1935, in the very season of the EPR paper, an analysis demonstrating that von Neumann's impossibility proof rested on an assumption about how averages combine that no real theory need accept. Her critique was correct, it was in print three decades before the flaw was

rediscovered, and it was ignored as thoroughly as the paradox itself, because the community that welcomed the theorem's conclusion had no appetite for auditing its premises. The double lesson of the 1930s, that the century's safest-seeming impossibility proof and its most famous paradox were both mishandled by the same confident generation, is the founding irony of this whole history.

That man was John Bell. Bell, an Irish physicist working at CERN, was a quantum realist in private, sympathetic to the pilot-wave ideas of Louis de Broglie and David Bohm, which reproduce every quantum prediction using particles with definite trajectories guided by a nonlocal field. Bohm's theory, published in 1952, was a standing counterexample to von Neumann's theorem, since it was exactly the sort of theory the theorem had declared impossible, and Bell, who had taken the trouble to understand it, wanted to know how the trick was done. The answer, he suspected, was that Bohm's theory paid a price: nonlocality, with the properties of one particle depending on the arrangement of distant apparatus. Bell asked the question that should have been asked in 1935: is that price avoidable? Could any theory of pre-existing local properties, however cleverly constructed, reproduce the quantum predictions for the EPR correlations? His 1964 paper, written during a sabbatical in the United States, contains the theorem that no such theory exists. The proof converts the EPR dilemma into an inequality, and the inequality into a number that experimenters can measure. The details of that conversion are the subject of the next chapter, and they changed the paradox from philosophy into the most carefully tested proposition in the history of physics.

Chapter 6: Observation and Measurement of EPR Correlations

Bell's theorem works by comparing two kinds of prediction for an EPR experiment. A quantum state assigns the two particles correlations stronger than any pre-assigned local properties can produce. Specifically, if the two experimenters each choose among a few measurement settings and record the statistics of agreement between their outcomes, then any theory in which the outcomes are determined ahead of time by local properties agrees on an inequality: a particular combination of the agreement rates cannot exceed a fixed bound. Quantum mechanics predicts that the combination exceeds the bound, by a specific, computable amount. The two sides therefore disagree about a number, and a number can be measured.

The first measurement took eight more years. John Clauser, a graduate student at Columbia who had read Bell's paper and found the physics community's indifference to it inexplicable, joined with Stuart Freedman, Michael Horne, and Abner Shimony's group to refine Bell's inequality into a directly testable form, now called the CHSH inequality after the four authors of the 1969 paper. In 1972, Freedman and Clauser performed the first Bell test at Berkeley, using pairs of photons produced when calcium atoms cascaded between energy levels. The quantum prediction won, violating the local-realist bound by several standard deviations. The result, which

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Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.