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5

ARTHUR G. ZAJONC

Light and Cognition

In 1864 the poet Gerard Manley Hopkins, then a very young man, saw a rainbow. In writing of it Hopkins captured the problem of "emergence" in cognition, an issue central to this conference.

> It was a hard thing to undo this knot
> The rainbow shines but only in the thought
> Of him that looks. Yet not in that alone,
> For who makes rainbows by invention?
> And many standing round a waterfall
> See one bow each, yet not the same to all,
> But each a hand's breadth further than the next.
> The sun on falling waters writes the text
> Which yet is in the eye or in the thought.
> It was a hard thing to undo this knot.

At the close of the *ceri* race in Gubbio we too saw a rainbow arched triumphantly overhead in a cold, gray sky. Like Hopkins, where did we locate the rainbow: in the rain, in the sunlight, in the eye, or in the mind?

Phenomena emerge, they fill the mind with sights and sounds, yet how do they arise? What is our part in their production and what is the part played by an external world? More important to this paper and the conference theme, is the pattern of emergence immutable, myopic, single-minded; or can it, like a Proteus, assume myriad forms calling forth worlds whose emergent properties reflect connections hidden to other forms of ourselves, and are there cogent reasons for doing so?

Motives for change have arisen within many fields, from biology, ecology, atmospheric chemistry, immunology, to my own field of quantum optics. In it compelling new experiments have renewed the challenge that quantum physics made at the turn of the century regarding the strictures of classical forms of thought. By following two threads from recent developments, I hope to strengthen the challenge further and point to characteristics of the novel modes of understanding now required by the facts. Once the need is convincingly demonstrated, the project itself begins, the project of creating the requisite faculties adequate to the understanding of these newly emergent phenomena of science.

The significance of such considerations may seem slight, or to be merely so much academic epistemology, but I would argue to the contrary. Thought and, more basic still, the process of thinking are the progenitors of our civilization, and, like the ouroboros, their effects work back on themselves, rigidifying and reinforcing those modalities of thinking characteristic of an age, hindering the development of new modalities.

Our manner of thinking has shaped the planet and ourselves, and possesses the power to reshape them once more. The monuments of the past speak of traditions that have sculpted not only our exterior landscape, but an interior one as well. The textures and patterns of thought in which we now live are the outcome of hard-fought, spiritual battles that established a general mode of discourse, understanding, feeling, and action. While we may be unconscious of their history, these traditions are part of us and shape our habits of thought and understanding, our very seeing. In our own day, contemporary spiritual battles and new modes of knowledge are emerging. These will require fresh patterns of thought, unknown metaphors, and will also one day shape a future landscape.

In Perugia, Florence, Rome—indeed throughout Italy—we stand always within the aura of antiquity. Its noble institutions, its great artists and thinkers have exchanged the landscape of the

wilderness—so close to us in the U.S.—for that of the garden, or better the protected hillside city, crafted into a work of art. The accomplishments of Dante, Ficino, Giotto, Leonardo, Michelangelo, Raphael and countless others have nourished and defined not only Italian culture, but that of the entire West. We are the inheritors not only of material monuments but cognitive ones as well.

Our Cognitive Inheritance

> Praise to thee, my Lord, for all thy creatures,
> Above all Brother Sun
> Who brings us the day and lends us his light,
>
> Lovely is he, radiant with great splendor,
> And speaks to us of thee,
> O Most High.
>
> Praise to thee, my Lord, for Sister Moon and the stars
> Which thou hast set in the heavens,
> Clear, precious, and fair.

When in 1225 Saint Francis composed these lines of his *Canticle to the Sun* while in the convent of Saint Damian, he was a participant in a long tradition of sacred and mythic knowledge that saw nature as alive and ensouled, that is, as a being. She was still the goddess Natura, as Bernard Silvestris or Alanus ab Insulis called her at Chartres.[1] Persephone still walked the earth. By the thirteenth century, however, the experience was so attenuated that Nature usually appeared only as a figure within Christian allegory. Her presence there, nonetheless, belies a rich and more intense ancestry, one that stretches back to Thales' declaration that "All things are full of gods," and beyond.

In the fifteenth century Marsilio Ficino, that student and interpreter of the "divine Plato," was also part of an ancient tradition, one that he saw as running back through Plato and Pythagoras to Orpheus, Hermes Trismegistus, and Zoroaster. Like St. Francis, he saw God and his multiplicity of angelic beings as manifested through light and the radiant celestial bodies of our universe.

> Look at the heaven, please oh citizen of the celestial fatherland, at the heaven which was made orderly and manifest by God for the purpose of making [clear the multiplicity of beings]. When you look upward, the celestial entities tell you the glory of God through the ray of the stars, like the glances and signs of their eyes, and the firmament announces the works of his hands. But the sun can signify to you God Himself in the greatest degree. The sun will give you the signs; who would dare to call the sun false? So the invisible things of God, that is, the angelic divinities, are seen and understood particularly through the stars, and God's eternal power and divinity through the sun.[2]

Thus is the universe a cosmos not of matter in motion, but a multiplicity of beings ordered and animated by the Godhead.

Around 1300, shortly after the life of St. Francis, a novel technical device appeared in medieval Europe, one that symbolized an incipient change of enormous proportions. It did no work, nor did it ease the burdens of manual labor, yet it became both in fact and as metaphor the machine that grew to regulate the tempo of human life. I am speaking, of course, of the mechanical clock. There had been clocks of other sorts for centuries before—sundials, water clocks, fire clocks, and sand clocks—but the development of the mechanical clock marks a decisive point in the evolution of the West.[3] I am interested, however, not in the mechanical clock as technology, but as an instance where technology becomes image, wherein a human invention comes to shape the imagination and to provide a basis for understanding the natural world.

Following the discussion of Lynn White, Jr. the introduction of the clock as part of the iconography of Christian theology occurred shortly after the invention of the clock itself.[4] In the short span of one hundred and fifty years, the mechanical clock became the invariant attribute of the principal Virtue of the fifteenth century, Temperance. Like the clock, the human body and soul require regulation by reason; and what was true for the microcosm was true also for the macrocosm. At the end of the fourteenth century, Nicole Oresme, in his *Duciel*, invoked the escapement feature of a clockwork to explain how God regulated the orbital velocities of

the planets. It remained for Galileo to complete the unification of terrestrial and celestial mechanics and so provide the basis for the Deist notion of the mechanization of the entirety of God's creation.

With the gradual perfecting of the clock mechanism, life is no longer regulated by the movement of the sun during the day, or the stars at night. Civilized man is freed from nature and so may order his life, whether mercantile or monastic, by the hours of the mechanical clock. In Lynn White's words, "Human life no longer adapts the mechanism to its need; mankind is in some measure shaped by a machine which it adores."[5]

Thus, close on the heels of St. Francis, Ficino, and the Italian Renaissance, indeed almost within their embrace, were the stirrings of another nascent tradition. It found its fulfillment a century after Ficino's death when the modern world conception was born through Copernicus, Descartes, and Galileo. Like those before him, Galileo too was a student of nature who admired its extraordinary order. He heard in it, however, a different voice, one that spoke the language of mathematics and whose meaning was the principles of mechanics. While many threads connected Galileo with the past, both his contemporaries and we recognize in him the exponent of a new science. It is four hundred years since the birth of modern science. Our world has been profoundly changed by its presence. If the architects and artists of the Renaissance lifted their cities into works of art, we in turn have filled them with the technological offspring of the scientific revolution. Into Perugia's fifteenth-century "Hall of the Notary" we have brought the electronics required for simultaneous translation of English into Italian. Two traditions, two cultures are entwined in the Italian landscape, one that ended in Ficino and another that began in Galileo. I believe we in our time stand at a similar juncture, one in which the tension between these two cultures may find the resolution so urgently needed.

Our cognitive inheritance is twofold. Our aspirations to be good stewards of the earth, to dress creation with the beautiful work of our own hands, and to recognize within nature the goddess Natura, all echo the song of St. Francis. They are born of a participation in cosmos and an experience of self that reaches to a distant past, one in which the divine was everywhere immanent and open to us. The strains of a different song, brilliant and strong, ring out from the technological offspring of the scientific revolution. A clockwork universe excludes human participation except as another component of its vast mechanism. It seems without inherent value or meaning. This dimension of our cognitive inheritance is more recent and more pressing. Both voices still resound, but too often the discord between them leads to misunderstandings and tragedies: at Chernobyl or Bhopal.

One of those who clearly heard both voices and the tension between them was the nineteenth-century American thinker and essayist Ralph Waldo Emerson, patriarch of the Transcendentalist movement.[6] Together with a good many others on both sides of the Atlantic, he recognized that the old order of things (Ficino's and St. Francis's) was fast crumbling about Western man. The spiritual convictions and values of earlier centuries were being challenged by a newer vision of man and nature espoused by the then flourishing savants of natural science. In a letter he wrote:

> Natural science is the point of interest now, and, I think, is dimming and extinguishing a good deal that was called poetry. These sublime and all-reconciling revelations of nature will exact of poetry a correspondent height and scope, or put an end to it.[7]

As the old forms fell, Emerson held that we were freed to create an original, participatory relation to nature, not one mediated through scripture, prophets, and history but experienced directly.

> Why should not we have a poetry and philosophy of insight and not of tradition, and a religion by revelation to us and not the history of theirs?... The sun shines today also. There is more wool and flax in the fields. There are new lands, new men, new thoughts.[8]

"The venerable and beautiful traditions in which we were educated are losing their hold on human belief, day by day."[9] As the old forms rattle, the new falteringly appear. The fashioning of a new tradition, a philosophy of contemporary insight—such was

the project that Emerson, Thoreau, Alcott, and their collaborators envisioned, but left unrealized in their lifetime. It is one that stands before us still.

The Facts of Light

Contemporary motivations for change go beyond the dissatisfactions of the nineteenth-century Romantics. At their best they are grounded in the scientific facts and powerful moral dilemmas of our modern world. The invention of the mechanical clock is a single instance in the extraordinary technological transformation that dawned with its invention. Since then we have seen both the industrial revolution and the recent advent of cybernetics. Each elaborated the clockwork image, expanding its dominion until it appeared to encompass all of existence. Yet are there objects whose nature is so radically non-mechanical that they defy all honest attempts to include them in the catalog of machines? I am convinced there are many, but none is so unambiguously non-mechanical as light.

I begin by referring to the old saw regarding the impossibility of creating a classical model of certain quantum phenomena. Recently the issue has taken on more dramatic proportions with the experimental realizations in several scientific laboratories of what had heretofore been mere thought experiments, only a gleam in the minds of Einstein and Bohr.[10] These include John Archibald Wheeler's proposal of a so-called "delayed-choice" experiment,[11] the Einstein-Podolsky-Rosen experiment, and the phenomena associated with superconductivity so much in the news. Each of these effects, and many others, requires the concept of "quantum superposition," a concept that simply defies our traditional clockwork imagination and challenges us to develop new imaginative modalities. I begin with the specific case of the delayed-choice experiment, an experiment in which I collaborated at the Max Planck Institute for Quantum Optics in Garching.[12]

The experiment dramatizes the so-called wave-particle duality of light. In order to understand its results we need to establish the criteria for the recognition of particles and waves; that is, how do we know whether we have the one or the other? The standard test for a particle is indivisibility. If we can split the particle, then it may have been composed of other particles, or it could be a wave. If, however, the particle is resolutely indivisible then we can declare it unequivocally to have been a single particle. The criterion for a wave is the phenomenon of interference. That is, when two wave-trains cross, the disturbance displays very characteristic maxima and minima. Make a slit with two extended fingers and look through the slit at a source of light. You will notice alternating light and dark bands in the region between your fingers. This is evidence for the wave nature of light. With these two criteria, indivisibility and interference, we are now ready to interpret experiments that will give us the "definitive" answer to the question regarding the nature of light.

A light source has been invented which claims to produce one "particle" of light at a time. How do I test it? I do so, naturally, by attempting to divide the particle in half. The apparatus for this is very simple, merely a half-silvered mirror.[13] It possesses the property of transmitting half the light incident on it and reflecting the remaining half. Obviously if there is, in fact, only a single indivisible "particle" of light, then the mirror will be unable to split the light in two. Rather it will either transmit the light or reflect it. The apparatus is completed by placing two light detectors as shown in Fig. 1. They are of sufficient sensitivity to respond to single "particles" of light. If the "particle" is divisible then the detectors will fire simultaneously, thereby showing that part of the light was reflected and part transmitted. If, however, only one fires for each particle incident on the half-silvered mirror, then we did possess a single "particle" of light.

Several so-called, single-photon sources have been invented and the tests outlined above performed. The results of these experiments confirms that under special circumstances one can produce single, indivisible "particles" of light. It is important to stress the experimentally determined indivisibility of the "particles" as the paradox hinges on it.

We now turn to the second aspect of the experiment, namely interferometry. The principle of an interferometer is very simple. It is a device designed to divide light into two beams and then to

recombine them so as to show interference effects. Remember interference is proof of the "wave" nature of light. If we succeed in dividing light into two beams and, through recombination, to create interference, then we will have demonstrated that light is a wave. An interferometer (of the Mach-Zehnder type) is shown in Fig. 2. Light of the usual sort (not the single-particle kind) enters the interferometer through a half-silvered mirror, is split into two beams, and, after reflection from two fully silvered mirrors, recombines on a second half-silvered mirror. If one looks on a placard at some distance from the final mirror, one sees light and dark bands, that is, interference, which is clear evidence for light as a wave.

Now the critical moment. Use the single-particle light source as the light source for the interferometer. What will happen? Recall that the success of the interferometer experiment requires that the light be divided at the first beam splitter. By contrast, the success of the particle experiment requires that the light remain undivided for a single-particle source. These are logical opposites. We cannot entertain both ideas at the same time without cognitive dissonance of a rather high order.

We will further heighten the stakes by the following experimental ruse. The experimentalist will at first only set up part of the experiment. The experiment begins with the final half-silvered mirror missing (see Fig. 3). The attentive reader will now recognize an ambiguity in the design. By leaving the final half-silvered mirror out I have described an apparatus suited to test for single particles of light. By inserting the final half-silvered mirror the device becomes an interferometer suited to test for the wave nature of light. Simply inserting or removing the final mirror changes the entire intention of the apparatus. Moreover, I am free to insert or remove the final mirror at any time. This is what Wheeler termed "delayed-choice."

Allow the single-particle source to emit its particles one at a time into the apparatus, and run the experiment in three modes. The first two are simply to insert and remove the final half-silvered mirror prior to running the experiment. What is found? With the mirror removed we find experimentally that half the time one detector fires and half the time the other, but the two never fire together. This is the signature for indivisible "particles of light." Now with the source unchanged, insert the final beam splitter and run the experiment. What do the detectors show? They now display the unambiguous signature of interference. But interference requires the particle to divide at the first half-silvered mirror, which we just showed never to happen with the single-photon source used! Is there some way the particle could, perhaps by "sensing" the intent of the experiment, divide in the latter instance but not in the former? This is a bizarre scenario but one that can be tested by the delayed-choice experiment.

In the third mode of running the experiment we wait to insert or remove the final half-silvered mirror until after the "particle" of light has passed the first half-silvered mirror, that is, we delay our choice of what experiment to run until the light is deep inside the interferometer. Even in these circumstances one still detects an interference pattern when the final half-silvered mirror is inserted, and no interference without it! What this implies is that light must be in an ambiguous quantum "superposition" state during the interval from entry into the apparatus until departure through the final half-silvered mirror (or at least until we choose).

For purposes of clarity I will repeat what I take to be the ultimate results of the experiment. If we think classically (by which in this instance I mean mechanically), we confront a situation that requires an indivisible particle of light to travel a single path to a single detector, and simultaneously requires it to travel two distinct paths to two detectors. This is a logical impossibility. An entity, whatever it is, cannot travel along both a single trajectory and a pair of trajectories at the same time.

The standard conclusion drawn by orthodox quantum mechanics is that one has created a non-classical, quantum (i.e., non-mechanical) state termed a superposition state. Invoking such a phrase does not, of course, constitute an explanation, any more than reference to the somniferous quality of a tablet explains the effect of a sleeping pill. Such language simply locates that which we do not understand. There does exist, however, a precise mathematical meaning to the phrase, "quantum superposition state." Still, the clarity of the mathematical formalism has not translated into a clear understanding of the physical phenomena themselves.

In fact, the suggestion is very often advanced that we must give up understanding in favor of computing. But this is to give up too much. There is an important lesson here, one we should not shy away from, a challenge before which we should not shrink.

Understanding appears to require an image, and the inevitable trend is toward the machine. The imagination of a mechanical universe has provided science with a powerful means of understanding a large but finite range of effects. There exist however, even within the domain of physics, phenomena such as those described above that simply cannot be thought of in mechanical terms without spectacular violations of logic, or simple "common sense." Here enters the arrogance of the tradition. What cannot be imagined mechanically cannot be imagined at all. One can compute, and predict on the bases of computation, but one must forego the old pleasures of understanding, or at least modify our traditional sense of what it means to understand.

Nor is the problem with light limited to the wave-particle question. There are other puzzling features of its apparent nature, such as the lack of a quantum-mechanically acceptable concept of position.[14] Electrons and similar elementary particles formally possess a clear position variable. This is not the case with light. To ask the simple question *Where?* is far more subtle for light than for matter. But this seems consistent with the results of the delayed-choice experiment.

Such issues are a small matter, say some. After all, consider the extremes to which you have to go to find a phenomenon that cannot be embraced within the mechanical universe. We can well afford a few borderland phenomena that fall outside of our mechanical paradigm. Yet I fear that these phenomena are multiplying, and, like the few resistant phenomena that ultimately led to the development of quantum mechanics, these too will ultimately require of us serious and responsible attention. Many of the solid-state electronic devices common today, from television to calculator, operate because the mechanical paradigm fails, and perhaps the most spectacular failure will be high-temperature superconductivity.

The single-photon, delayed-choice interferometer ran on one photon at a time. Conceptually you cannot find a cleaner experiment. Its practical consequences, however, are in proportion to the intensity of the light used. Light just never appears as a single photon in nature or in the technical world. With the discovery of superconductivity in 1911 by H. Kammerling Onnes, and now the promise of massive technological implementation of the effect, macroscopic quantum effects of a kind apparently similar to the arcane ones of light may literally drive the engines of industry. The theory of superconductivity requires a cooperative behavior of electrons over distances that, on an atomic scale, are staggeringly large. There again is no classical imagination that can capture the quantum state of a superconductor. Paradoxes and conceptual confusions of the same kind attend any attempt to force the phenomenon into a classical straitjacket.

One can be confident that the pattern will continue to evolve, like a spider weaving its web in ever expanding circles. Just how much of the world and our surroundings are we willing not to understand? Or shall we take up the challenge and begin to imagine in new ways, faltering at first but gradually learning from our mistakes and fashioning other images of nature? How can mathematics capture in its formal net something which our imagination cannot? Should we not follow the lead of our mathematics and create an imaginative faculty of comparable scope and flexibility?

Lynn White, Jr., has traced the origin of the metaphor "a clockwork universe" back to the Middle Ages and to the fabrication of that extraordinary human device, the mechanical clock, that effectively freed man's sense of time from the motions of the heavens and fixed it to the rhythms of a physical instrument. Could it be that the technical innovations of quantum mechanics will engender a similar revolution in thought? Will we come to imagine our universe and ourselves differently for the existence of a revolutionary, quantum technology?

Harbingers of Imagination

If contemporary science points to inadequacies in present-day modes of thinking, we can ask: what will be the shape of the new manner of understanding required by our future? Perhaps ironically, I believe the harbingers of our future mentality, as required

by science and the imperatives of living in our precarious times, will be artists. For centuries they have struggled to create ways of seeing and knowing that often appeared to be at odds with the burgeoning science of our era. I believe that we now truly stand in need, not only as scientists but as a civilization, of their cognitive capacities. In them, when rightly developed, will the two streams of our cognitive inheritance be married.

Few artists have worked consciously with the ideas I have suggested. An exception was the German poet, playwright, author, and scientist Johann Wolfgang von Goethe. Although internationally distinguished by his literary career, Goethe's own evaluation of his life's work diverged from both that of his contemporaries and posterity. He felt that his most significant contributions were not to poetry but to science. In our treatment of Goethe's scientific work, I would have us look not at his impressive contributions to botany, osteology, color science, or meteorology, but to his distinctive method and objective.[15]

Through an exchange of letters in 1798 with his friend Friedrich Schiller, Goethe gained clarity about his methodology, which was becoming, as Schiller termed it, a "rational empiricism."[16] Of his process of investigation Goethe wrote to Schiller that one passed through three stages:

1. The empirical phenomenon, which everyone finds in nature, and which is then raised through experiments to the level of

2. The scientific phenomenon by producing it under circumstances and conditions different from those in which it was first observed, in a sequence which is more or less successful.

3. The pure phenomenon now stands before us as the result of all our observations and experiments. It can never be isolated, but it appears in a continuous sequence of events. To depict it, the human mind gives definition to the empirically variable, excludes the accidental, sets aside the impure, untangles the complicated, and even discovers the unknown.[17]

It is essential to note that each of the three stages is referred to as a phenomenon, the latter of a higher order than the former, until finally one attains what Goethe variously termed the "pure" or "archetypal phenomenon." In this mode of inquiry never does one slip off into abstract, mathematical representations of the phenomenon under study, nor is it a "question of causes, but of conditions under which the phenomena appear."[18] In these two ways Goethe appears to distinguish himself radically from orthodox views of the scientific method and its goal. For Kant, as for most since, science without mathematics is not science at all. Moreover, if one is not searching for causes, then what can be the objective of scientific inquiry?

Goethe's response to the last remark would certainly be to point to the archetypal phenomenon which is for him the endpoint of scientific investigation. He recognizes that many will wish to reach beyond the phenomenon to hypothetical entities or supposed causes, but for him the archetypal phenomenon represents the point of culmination beyond which one should not go. In that moment "the human mind can come closest to things in their general state, draw them near, and, so to speak, form an amalgam with them."[19] In one of his "Maxims and Reflections" Goethe describes the process in a similar manner as follows:

> There is a delicate empiricism which makes itself utterly identical with the object, thereby becoming true theory. But this enhancement of our mental powers belongs to a highly evolved age.[20]

Thus it is that Goethe holds always to experience, to phenomena, even when reaching to the theoretical level. To understand this it is perhaps helpful to recall the original meaning of our word "theory." It is derived from the Greek *theoria* which means "to behold." Goethe was in this and other ways like the Greeks. To understand, one must see, envision, behold in the mind as well as in the external world. In fact, are not these two, inner and outer, subject and object, like cause and effect, caught up into a single unity in the phenomenon? By "making itself utterly identical with the object" one's experience becomes true theory.

> The ultimate goal would be: to grasp that everything in the realm of fact is already theory. The blue of the sky shows us the basic law of chromatics. Let us not seek for something behind the phenomena—they themselves are the theory.[21]

As unusual as it may at first seem, the point of all scientific inquiry is to behold a phenomenon as theory. Nor is this goal alien to the history of science—it stands behind every scientific discovery. When Newton perceives in the falling apple the orbit of the Moon, he is seeing "fact as theory." He had puzzled long and tenaciously to win from nature his vision of the coherence we now all can learn to see after him. Galileo in the cathedral of Pisa, in seeing the swinging chandelier, saw the isochronous pendulum of a clock. What is it that allows such theoretical seeing?

First of all we should realize that all of our seeing is structured and informed by us. We do not have raw sense impressions, we see red, green, blue; we see particular objects from wood shavings to hand-held calculators. These already possess a conceptual character. Our observing is always, as Hanson calls it, "theory-laden."[22]

Out of the practice of science Goethe saw the possibility for developing new cognitive faculties, ones whose emergence would bring with them the perception of novel and hitherto unseen coherences within nature. Our manner of thinking limits and even forms the very world we experience. Cognitive science has taught us much concerning the hidden forces that shape our individual and culturally shared view of the world. Goethe proposed that by staying with the phenomena, varying their conditions of appearance, experimenting with them but holding the phenomena always in view, cognitive capacities would arise suited to the proper understanding of them. "Every new object, clearly seen, opens up a new organ of perception in us."[23]

With the new organs so fashioned, understanding arises in what Goethe termed an *aperçu*, and "such a discovery is infinitely fruitful."[24] Moments such as these, whether experienced by Newton, Goethe, or any passionately inquiring scientist, are artistic moments. It is a kind of seeing into nature. For Emerson, the poet's task was nothing more than this: To walk within nature not as a spy, but as the transcendency of her own being, and so to articulate in words what she performs for and within us.[25] Emerson realized the kinship between artistry and the exhilarating moment of scientific discovery when he wrote: "And never did any science originate but by a poetic perception."[26]

If we would create the capacities for understanding our future, then we must dwell precisely in the tensions, the paradoxes, the annoying anomalies of our time. Only thus will we develop the faculties suited to understand the nature of light and, I believe, see the way through our perilous times. We may think with Goethe that such "mental powers belong to a highly evolved age," but I believe that ours is the dawn of that age. The prerequisites are there: the mandate of orthodox science to develop our imaginative capacities, and the dictates of our conscience if we would avoid the technical calamities that threaten our well-being and survival. On nearly every front we are being called on to re-imagine the world we inhabit. It simply awaits an act of courage for us to begin, and patient perseverance for us to succeed in the self-conscious education now in our hands.

* * * * *

The builders of the beautiful, stained-glass windows of Chartres saw light as a Christ-like emanation from God which in passing through the colored glass they had fashioned, reenacted the mystery of Mary, of the Incarnation. The infinite became finite. God made man. This too is part of the story of light. Into the fabric of light are woven patterns at every hierarchical level, sensory and spiritual. The faculties with which we see it can impoverish it, but we are forever challenged to reshape ourselves, to stand within the full phenomenon of light and color so that organs may be formed that correspond to it at every level of its being, whether that be the quantum level of modern physics, or the spiritual level of St. Francis, Ficino, and the Chartres masters.

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17. Johann W. von Goethe, "Empirical Observation and Science," (Jan. 15, 1798) in *Scientific Studies*, ed. and transl. Douglas Miller (Boston: Suhrkamp Publishers, 1988), 24-25.

18. Ibid., 25.

19. Ibid.

20. Ibid., 307.

21. Ibid., 307.

22. N. R. Hanson, *Patterns of Discovery: An Inquiry Into the Conceptual Foundations of Science* (Cambridge: Cambridge University Press, 1958).

23. Goethe, *Scientific Studies*, 39.

24. Goethe, from a letter to Soret, December 30, 1823, quoted by Rike Wankmuller in the *Hamburger Ausgabe* of *Goethes Werke*, vol 13, 616.

25. Emerson, "The Poet," in *Complete Works*, op. cit. vol. 2.

26. Emerson, *Complete Works* vol. 8, 365.

FIGURE LEGENDS

FIGURE 1. "Particle Test": A pulse of light is incident on the beam splitter (BS), which is a half-silvered mirror. If the light is a wave, then half will go towards detector x and half towards detector y. If the light is a single particle, then it will go either towards x or towards y, but not both.

FIGURE 2. "Wave Test": A pulse of light is incident on beam splitter one (BS1). If it is a wave, then as before half will go along path x and half along path y. Mirrors (M) are used to recombine the two beams onto beam splitter 2 (BS2). The resulting "interference" phenomenon is proof that the light traveled both paths.

FIGURE 3. "Delayed-choice Experiment": (1 and 2) A light pulse enters an interferometer of the type shown in Fig. 2, except that the final beam splitter is missing. By leaving the final beam splitter out, one discovers which route the quantum followed. (3B) By inserting beam splitter two (BS2), interference arises and the quantum is shown to have traveled both routes.

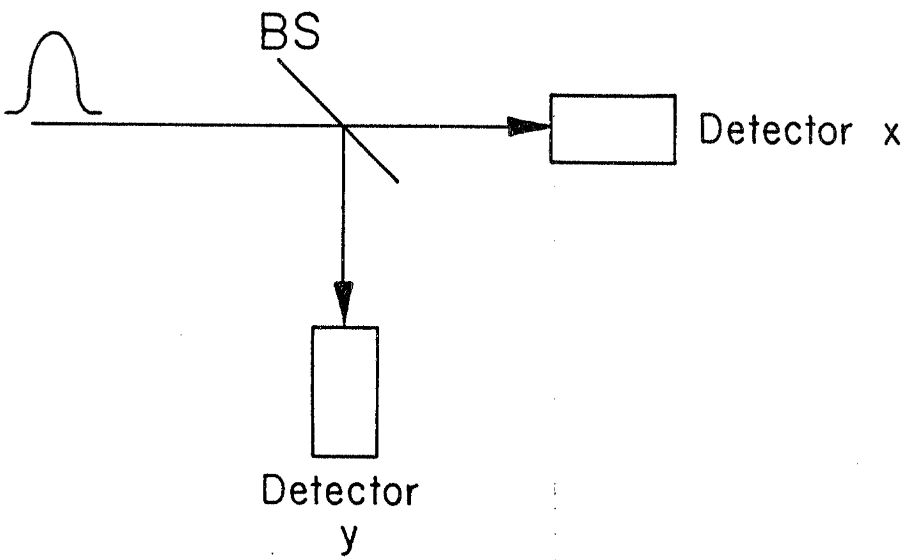

Figure 1

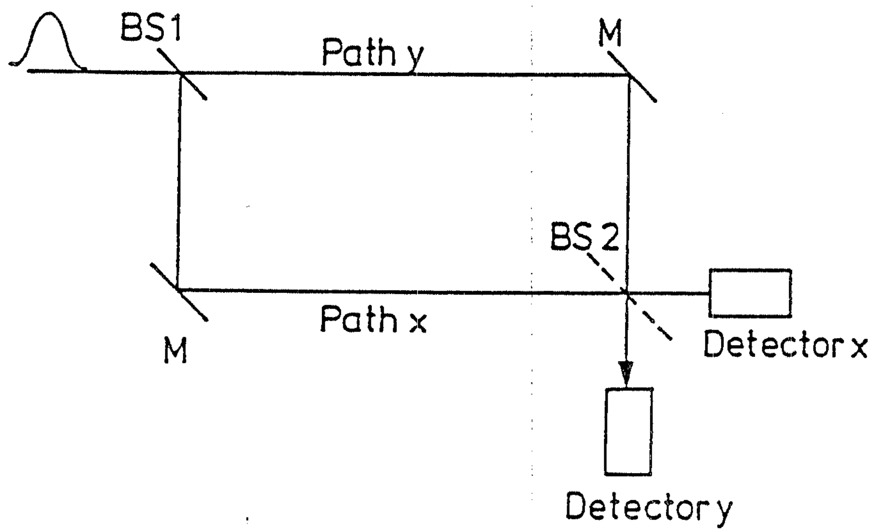

Figure 2

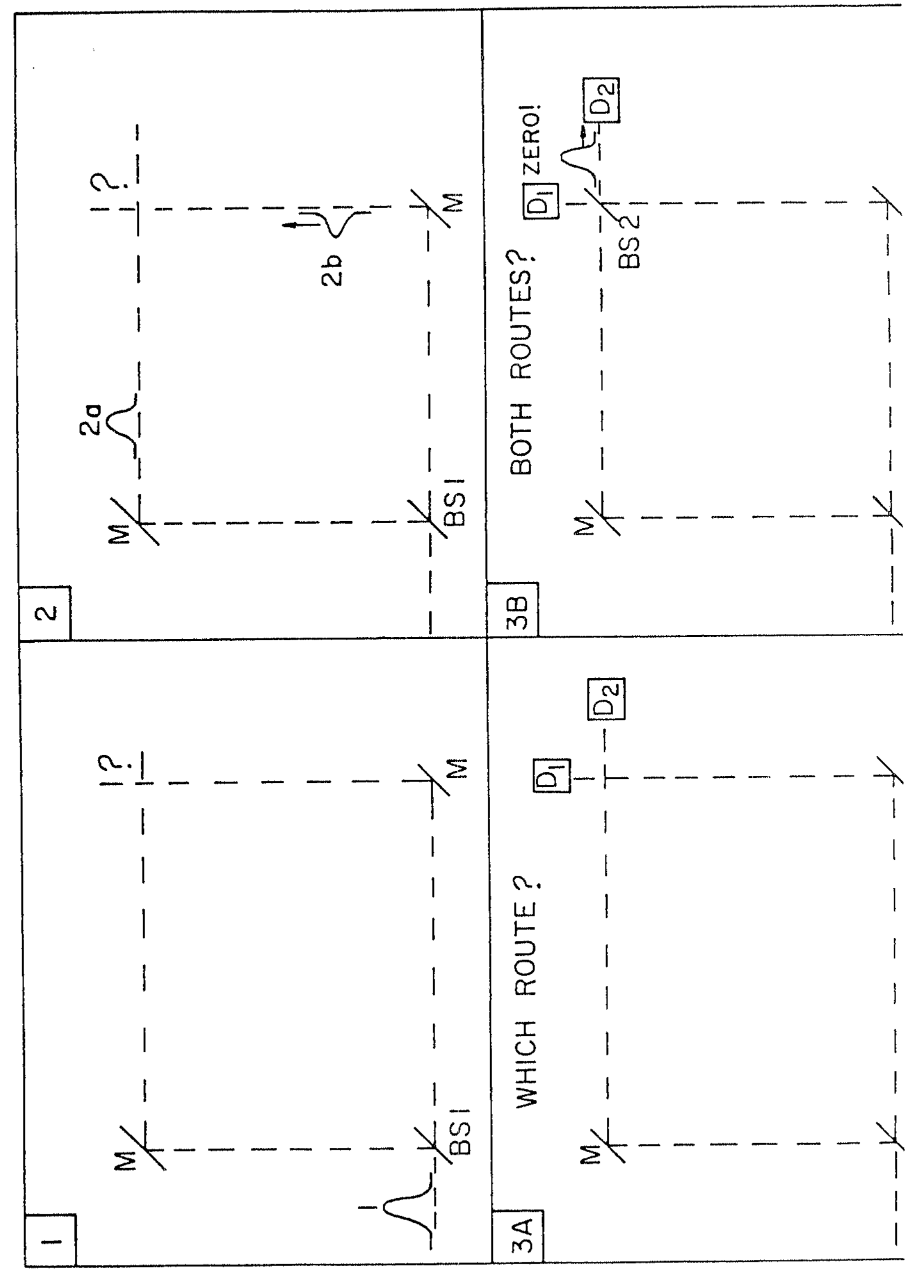

Figure 3