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3. Reflections Upon a Pond

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As an adolescent I spent my summers in what was then a rural community in New York State's Hudson River valley. In those years it was possible to experience a brilliant canopy of stars in the night sky, and, like a moth drawn to a candle flame, I was fascinated by that sky. I wondered, "What is out there? What is beyond the visible dome of the sky?" This nightly attempt to imagine a beyond quickly became unsettling. I was in effect trying to picture the infinite, and eventually I had to stop myself by turning to more mundane concerns.

I suppose that while facing the human impossibility of imagining a cosmos from without—that is, from a God's-eye viewpoint—I developed a yearning to find a basis for cognitional certainty. It was, perhaps, the promise of at least being able to know the physical world with certainty that gave physics its appeal for me.

Later, however, I faced a different kind of crisis. The physicist, I saw, achieved the experience of certainty by reducing knowledge to pictures of changing arrangements of objects (or object-like entities) in space. In a naive sense this approach did seem to work—cognitive certainty of the reduced world of physics was akin to the unquestioning sureness with which we know the existence of a stone. The result, however, was a world picture that was meaningless because there was no room in it for its self-conscious human knower.

A Pond as Space Creator

Looking into the reflected world of a still pond is like looking through a window. You see a vast space framed by the boundaries of the water. In every way the space of the reflected image appears as limitless as the panorama seen through a window. You can roam with your eyes among the reflected clouds and far distant hills, follow the flight of birds, or examine nearby grasses and flowers. You can even see "underneath" the shore on which you stand simply by leaning out over the water's edge and peering back under your feet, just as you might look down at the view beneath a balcony.

This is not a theoretical matter. But you must actually *look* into still water to appreciate its reflected visual space. Given such an intention, you may marvel at the extent of the space you see. It is particularly astonishing when you look into a shallow puddle. Even here a window opens onto an infinitely large three-dimensional view. Just as a vast visual world presents itself when you look through a small glass window in a wall, so, too, when you bring your eyes close to the puddle and look “through” it, the boundless visual world of reflection opens to your gaze.

To be sure, we are referring here only to a visual experience and not to the sense of touch. Because you can touch the pond’s surface but cannot reach into its mirror space and feel the objects within it, you may think the reflected image lies on the water’s surface. That is, in order to unify your visual experience with your experience of tangible surfaces, you may miss the three-dimensionality of the reflective space. In this case, the impossibility of conceiving a space that is both three- and two-dimensional at the same time restrains you from *seeing* depth in the mirror space. You give the tangible surface priority over the visual experience and actually see the reflected picture *on* the water’s surface, as if it were a painting.

The three-dimensional visual space and the two-dimensional felt surface of the water cannot be understood as qualities of the same object. Since you cannot reach into the mirror space, the objects seen spatially via binocular vision and perspective do not have a tangible counterpart; you only feel a flat surface. However, once you recognize that reflected space is purely visual and that objects seen in it are intangible, then it is easy to experience the full spatial depth of the reflected image.

The oil pastel by the Swiss biologist Jochen Bockemühl illustrates several phenomena of a still lake. On the right are reflections of clouds in a bright sky. On the left grasses growing in the pond extend up through the water’s surface. *The water itself is not seen*. Still water has no image; its presence is known only through the coordination of the various elements comprising the total picture. For example, each blade of grass appears crimped at a position suggesting a single plane of the water’s surface. The water’s depth is indicated by the relation between these crimps, the duller colored portions of the blades that extend from the crimp to the brownish earth at the bottom of the pond, and the angle these underwater portions make with the shadows of the grass seen on the bottom of the pond. The shimmering halo of illumination part way along the shadows of the grass blades brings to mind the disturbances in the water's surface where it is penetrated by the blades. And the boundary between regions where the reflected sky is seen and where we see through the water itself to the pond's bottom intimate the fluidity of liquid water.*

Looking into a pond, we can see either into reflected space or through the water itself, but seldom both at the same time. Where the grasses pass through the water's surface their image is bent. Yet, when we run our hand along a blade of grass we do not feel a crimp or bend where it enters the water. What is more, although we can see our hand move smoothly along the wet blade, we do not feel the blade to be where we see it to be in the water. It is, of course, well known that the visual and felt positions of objects in water do not coincide. Most of us have gotten a sleeve wet reaching for a coin because the pond *appeared* shallower than it really was. In other words, a pond is visually shallower than it is tangibly.

The visual discontinuities in objects where they enter water and the apparent shallowness of the water's bottom are aspects of refraction. With refraction, just as with reflection, tangibly experienced phenomena cannot be reconciled with visual experience. In the case of reflection there is no tangible counterpart at all to the visual objects. We destroy the mirror image—that is, we destroy the conditions necessary for clear reflection—when we try to reach into the mirror space with our hands. In the case of refraction the tangible object space and the visual object space do not coincide. We do not see objects where we feel them to be, and vice versa.

A pond presents us with many phenomena. Fish and other creatures live in the water, as do numerous plants. Insects dart on the surface. The water may be cloudy, clear, or colored. Ripples and waves may attract our eyes, and we may hear their lapping at the shore. Our attention may be drawn to shadows, especially where objects project through the water's surface. The visual images of objects seen through the water's surface do not coincide with the felt positions of

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* Stephen enthusiastically points out a multitude of optical effects that are to be found in a picture of a natural situation by Jochen Bockemühl. It is worthwhile to look for and find them; few of us will ever have noticed and understood them all in Nature. Bright reflections such as those of the sky conceal the space inside the water. So where the brown-colored bottom of the pond is seen, as it is on the left side of the picture, this is possible thanks to our facing toward a "dark area" in the vicinity that comes to be reflected by the surface. On the right side, "fingers" of brown extend into the bright sky and such would be explainable by the waves reflecting both sides of a boundary between the sky and such a relatively "dark area" in the surroundings.

The next paragraph is about a comparison of the visual to the tactile. Here, Stephen reminds us of the fact that straight blades appear bent at the surface of the pond. This effect is not conspicuous in the picture. But this is in keeping with experience, for the artist would have had to observe the scene more aslant from the side in order for the bending to be more evident.

those same objects. And, of course, there are the visual objects of the water's reflection space. The mirrored images in this reflection space are less brightly colored than their non-mirrored counterparts.

All these phenomena can awaken questions within us. What qualities of the pond environment are required to support the life of the fish? Or of the insects? Or the plants? What, exactly, is the spatial relation of the visual objects in the water, seen through the water's surface, to their touchable aspect? How does the curvature of the surface at a ripple affect the image seen in mirror space or in the water itself? What qualities of water make it amenable for mirroring? And what is the relation of these qualities to the dimness of the mirror image compared to its ordinary counterpart? How does the water affect the color of an object? Under what conditions do we see through the surface into the space of the water itself, the one in which fish swim? When do we see through the surface into the mirror space where flying birds are visible? Under what conditions may we be lucky enough to notice brilliantly hued spectra at the boundaries of lightly colored rocks lying on the dark earth of the pond's bottom?

Innumerable possible enthusiasms can arise for understanding our experience at the pond. Questions inspired by such enthusiasms are the starting point of science. Scientific concern about the world requires us first to choose among the many possible questions. For example, we shall soon concern ourselves with the spatial character of mirror space. A startling consequence of this intention is that by neglecting the dimness of the reflection *we give up the water itself in our inquiry*. And, of course, at least for the time being, we give up the biology of fish and plants, the physics of refraction, the ecology of fresh water systems, and the display of boundary colors.

The Spatial Character of Mirror Images Seen in Water

Looking into an utterly still pond we observe a striking similarity between the reflected view seen "through" the window of water and the scene above. It's true that when standing at the water's edge and looking into the mirror space we find the reflected image of a person on the shore across from us to differ from the image of the person viewed directly—for example, by being shorter. But any difference disappears when we bring our head down to the water's surface. Then every object above the water has its upside-down counterpart in the mirrored space. Objects in the two spaces are identically arranged except that right and left appear to be reversed. Apparently the difference in image size was due to the vantage point from which we originally viewed them. From the water's surface the perspective of the two spaces is the same.

In either space right and left reverse if we imagine a person to rotate, head over heel, in the manner of a clock hand moving from a twelve o'clock to a six o'clock position. This rotation produces a right side up image and an upside down image resembling the mirrored image and its original. But the right-left reversal produced by this clock rotation is *not* true in the case of the reflecting surface. It is because of the visual expectation of right-left reversal that mirrored images of people may look slightly peculiar and we commonly say, incorrectly, that right and left are reversed in mirroring. We imagine right and left to be reversed in a reflected image only because we imagine the reflection to be achieved through a physical movement—as if we had walked into the mirror and turned around—and what we see doesn't fully agree with this. Reflected images are not obtained through such physical movement and do not obey its laws.

The laws of perspective represent a systematics of human experience of space. The most important of these experiences is that of distance: things appear smaller as they get farther away from us. But there are other, less familiar aspects of perspective. For example, imagine walking along the edge of the reflecting pond parallel to a distant hill. If you focus directly on a cow resting in the pasture between the hill and the pond, you will see the oak tree on the hillside moving along with you, parallel to your direction of motion. But, if you focus instead on the distant oak tree, you will see the cow moving opposite to your direction of motion. You can have exactly the same experience with the cow and tree in the mirrored space.

Another aspect of perspective is that parallel lines appear closer together as they progress into the distance. The rails of a railroad track appear to meet at a faraway point. At the pond you can have this experience by lying down on your back and looking up at the trunks of nearby trees, or by lying on your stomach and looking at the reflected trees. In either case, the tree trunks converge toward a distant point in the sky—the zenith or the reflected zenith. When you lie on your stomach (with your head over the water), your own reflected eyes mark the location of the reflected zenith.

Nearby objects—whether viewed directly or in mirror space—not only appear larger, but also suffer foreshortening. For example, when you stand at the edge of the shore and look at your reflected image in the water, you can completely obliterate the view of your face with one foot, even though the foot is narrower than your face. Your foot and leg dominate the image of a shortened body, illustrating how things appear smaller as they get farther away.

Apparently the reflection space obeys the same laws of perspective as ordinary space. In fact, looking along the length of a tree on the opposite shore of a pond, from the top of the tree down through the water's surface to the top of the reflected tree below, the experience of perspective is seamless. There is no visual discontinuity in looking from one space to the other.

Perspective implies spatial *relations* between the objects themselves and between the objects and the viewer. The apparent scale of objects and the distance of separation between them is interpreted according to these relations. Since the fifteenth century painters have used the laws of perspective to paint two-dimensional representations of visual, three-dimensional experience. But such representations work only for a single viewpoint. When a painting is viewed from any vantage point other than that from which it was painted, the image is distorted, because the perspective is incorrect. The pond's mirror space, in contrast to the perspective of a two-dimensional painting, remains perspectively consistent with ordinary space as we move from one point of view to another. Unlike a painting, the pond's mirror space is a true, three-dimensional visual space.

Recognition of the elements of perspective in a scene depends upon our ability to visually distinguish forms, relative sizes, and motion. This ability depends upon complex mental interpretation of sensory input connected with the musculature of the eyes. Even when viewing stationary objects, the eye makes very fine scanning movements that constantly shift the position of the image on the retina. When viewing forms, for example, our eyes move along significant lines, provided that the lines are large compared to the retinal macula. While we are not usually conscious of these movements, we can become aware of how our eyes trace the outlines of an object or follow it as it moves relative to the background or foreground. This is the visual analog to running our hands along the surface of an object to learn its shape and size, and moving our hands along with an object to detect its motion.

Binocular ("two-eyed") vision is another powerful means by which we experience three-dimensional space, particularly the dimension of depth. Here, too, spatial perception depends on mental assimilation of experience connected with the musculature of the eyes, but now what counts is the change in the angle formed by the slightly differing lines of sight from our two eyes. Smaller angles of binocular view signify greater depth. The activity involved is similar to moving our hands closer together or farther apart to discover the thickness (depth) of an object. We can be quite aware of the effort it takes to make binocular adjustments. That effort is like reaching into or around tangible objects with our limbs. When we see spatially, apparently we use our eyes analogously to our limbs. We can know form, distance, and depth by exploring lines and surfaces with either our arms or our eyes. The tangible and visual experiences gained in this way are compatible with each other.

The spatial consistency between touch and sight enables us to extend our "reach" visually beyond what is possible using only our limbs. In ordinary space, experiences of depth gained through perspective and binocular vision are consistent with and reinforce each other.

We can tentatively conclude from all this that a mirror space is visually identical to the ordinary space in which we live, and that there is no purely visual way to distinguish one from the other. Given this initial surmise, we can now proceed to an unusual demonstration.

The Law of Reflection

Reflection space, like ordinary space, is governed by the familiar laws of perspective. Further, the apparent sizes of objects in ordinary space seem identical to their apparent reflected sizes. We already remarked on this when we bent down until our face almost touched the water and viewed the person on the opposite shore.

At the Exploratorium in San Francisco (and a number of other science museums around the country), you can stand at one edge of a vertical, floor-mounted mirror, with the mirror's plane bisecting your body. If you are at the right vertical edge of the mirror, your body's left half is in front of the mirror surface. A friend standing next to the mirror at its opposite edge now sees what appears to be your complete image, but it consists of two left halves, one in the mirror space and the other in ordinary space. If now you raise your left leg off the ground, your friend sees both legs raised and unsupported. You appear to be levitating.

By looking at objects and their mirrored counterparts from a position close to the plane of the mirror, you can compare the two spaces from nearly identical viewpoints. You thereby eliminate perspective differences between the two scenes, so that corresponding images in tangible body space and mirror space appear to be identical in size. Evidently, the size differences we encountered when comparing ordinary objects and their pond-mirrored images were due to perspective; we stood well within one of the spaces instead of at their mutual boundary.

In tangible body space it is easy enough to measure the size of an object by comparing it with a meter stick placed alongside. But we can't slip a meter stick into mirror space (other than by reflecting it) in order to compare image sizes in reflection space with those in ordinary space. This is clear in the case of a glass or polished-metal mirror, but the pond is more complicated because we can push the measuring stick through the water's surface. Of course, the water's space in which tangible bodies get wet is not the mirror space. Even so, we might imagine inserting the meter stick into the water adjacent to a mirror image and in that way measuring the size of the reflection. But even assuming that the pond is deep enough, the attempt fails. Its futility becomes apparent as soon as we notice that the markings on the submerged part of the stick appear closer together than the markings on the dry part. This is the refraction mentioned in the previous section; everything, not just the bottom of the pond, appears closer to the surface than it is felt to be when we reach in with a hand.

Nevertheless it is possible to discover the geometric laws that relate tangible body space to its associated mirror space. We can in fact show that the two spaces are not merely similar, but identical. To do so we need a semi-reflecting surface—both reflective and transparent. An ordinary piece of glass windowpane will suffice when looked at from a glancing angle. With the glass pane horizontal in a sunlit room, place a cup right-side-up on the glass surface. When viewed from above—that is, when viewed from the tangible body space of the cup—a reflection of the cup can be seen below through the glass pane. Indeed, we can walk completely around the glass and observe the mirrored cup from all sides in its three-dimensionality.

Now, from below, insert a second, inverted, cup into the reflected image of the original cup and hold it there. From every viewpoint the tangible cup held below the glass, as viewed from above, coincides with the reflected image of the upper cup. And the same is true when, upon kneeling and looking up from below the glass, we compare the reflection of the lower cup with the original cup resting above the pane. That both tangible cups coincide with the boundaries of the mirrored images as observed from all possible directions shows convincingly that images in mirror space and ordinary space are visually identical. They are related to each other according to the law of mirror symmetry. In mirror symmetry corresponding pairs of points lie equidistant from and perpendicular to the mirror plane.