# Physical world of the child

The physics concepts that children develop earliest, such as "velocity" and "action," have proven to be the same concepts that have best withstood the "revolutions" in science.

Jean Piaget

A child's view of physics is not as "childish" as we might think. On the contrary, it raises a series of problems that might interest an historian of science[1] or even a physicist who, comparing the present state of physics with earlier stages of development, asks why certain ideas have been better able than others to resist the upheavals that have occurred in physics since the turn of the century. In our studies of children we have observed them playing with simple toys, questioned them about their perceptions and posed problems for them to solve. From these studies, we have learned something of the way a child's mind develops mathematical and physical concepts—such as topology, speed, time and causality—as well as something of the nature of the ideas themselves.[2]

## Historical or logical order?

We note first that, naturally, explanations spontaneously invented by children are often similar to concepts known and abandoned long ago. "Antiperistasis," with which Aristotle explained the motion of projectiles, is a striking example: The projectiles go forward rather than fall, because the air they displace pushes them from behind. A child of six or eight often explains the movements of clouds in this way, in terms of the "wind" the clouds produce as they move forward, or explains the trajectory of a ball in terms of the air displaced when the ball is thrown, which produces a draft. Similarly, we frequently find that children invent ideas reminiscent of the "impetus" theory or other theories from before the time of Galileo.

But frequently, and more interestingly, the sequence of these physical or physicomathematical ideas does not correspond to their chronological, historical order (from the Greeks to the present) but, on the contrary, to the logical order that links the fundamental to the derived. As an example, we shall look at ideas about space and geometry, which concern physicists as well as mathematicians. We know the historical order of these ideas: First to be developed were the linear relations of Euclidean geometry (with many earlier versions in Egypt, among other civilizations); next, beginning with the

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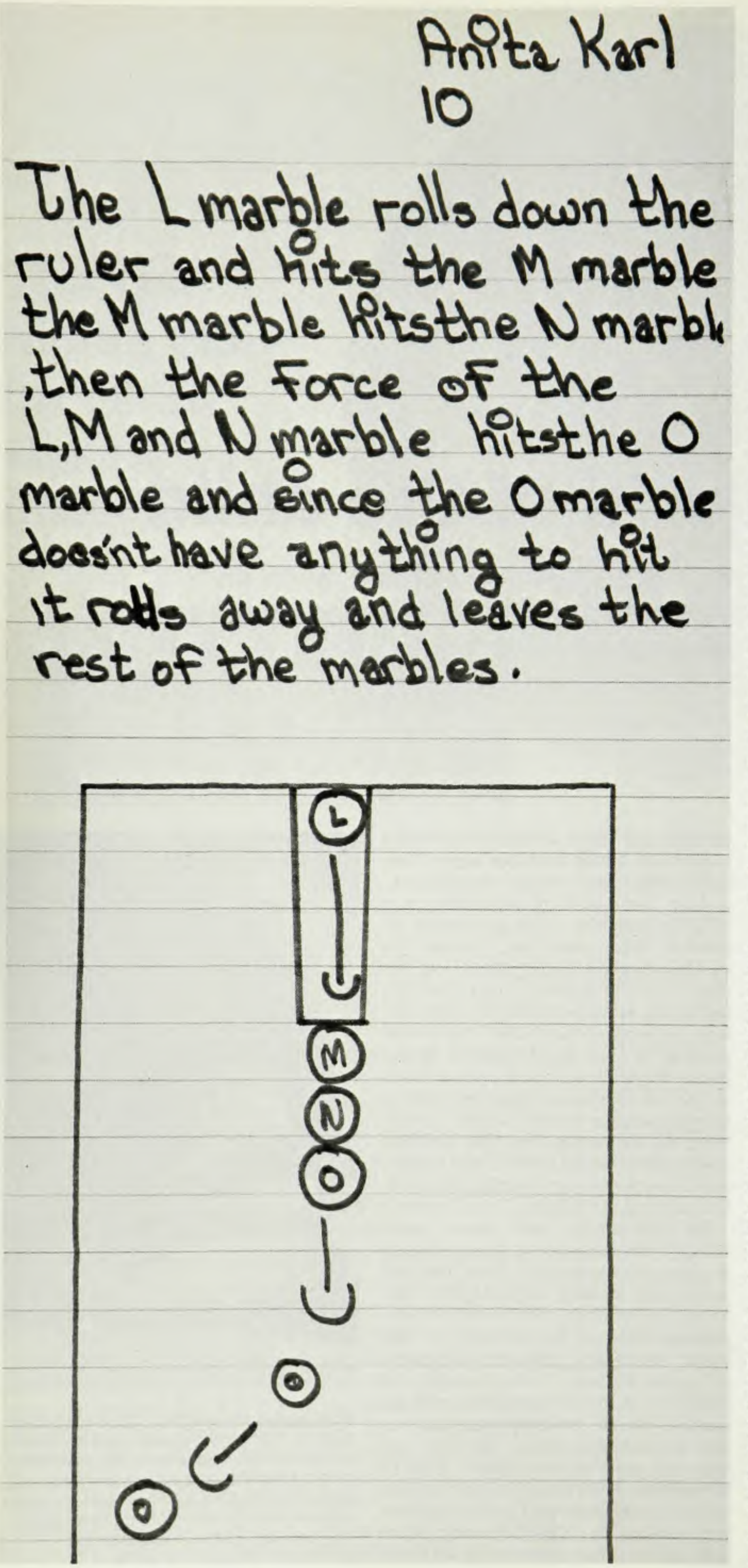
**What pushes the marble?** The way children describe the forces between marbles shows that very young ones, four or five years old, cannot grasp the concept of transitivity. Older children, from seven or eight on, give explanations that show they do understand this concept. (See the explanations reproduced on pages 24 and 26.)




Renaissance and Pascal, the ideas of solid geometry; finally, and only as recently as the 19th century, we have discovered the fundamental role of topology.

When we look at the theoretical or logical order of these ideas we find a quite different progression: First come ideas and intuitions of topology (such as the "homomorphic group" and the concepts of "neighboring" and "closure"); from these we get solid geometry on the one hand and general concepts of measurement (with Euclidean geometry as a special case) on the other.

If we study the way children develop ideas about space we note that children younger than four years, on the average, do not distinguish between squares, circles, triangles and so on in their drawings; they simply represent them all with closed curves, although they do distinguish them from open figures, such as crosses or ring fragments. If we give the child samples to copy, such as a large circle and a small one in three combinations—the small one inside, outside or adjacent to the large one—he gives us three different, correct drawings although still unable to copy a square, circle and so on. Only later does he develop some understanding of perspective and measurement; he appears to discover the ideas of solid and Euclidean geometry nearly simultaneously. The child's progress, then, follows the reverse of the historical order, conforming rather to the logical one.

### Differentiated and undifferentiated

This observation leads us to a more general problem. Among the concepts of physics, we find some that can be divided into two psychological categories: those concepts that are "undifferentiated," because each appears to be a combination of several simple ideas, and others that are described as "differentiated," because they enter into the composition of the "undifferentiated" concepts. "Speed," for example, is an undifferentiated idea, whereas time and distance are differentiated. In dynamics, "action" is undifferentiated, whereas quantitative ideas about motion, work and so on are differentiated.

We are now ready to pose this problem of psychological development, and to pose it independently of historical development, because we have seen that the historical and psychological orders are not always the same: Do ideas about the physical world start with the elaboration of differentiated concepts, because they are simpler, and then only later combine into relationships that form the apparently more complex ideas that we call undifferentiated, or, on the contrary, are the

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**Jean Piaget** with children

undifferentiated concepts formed first (justifying the name we have given them) and later broken down into differentiated ideas?

In the case of speed or velocity $v$ ($=s/t$) and its two components distance $s$ and time $t$, the answer is clear. In 1928, Einstein, presiding over a meeting of philosophers of science in Switzerland, advised us to determine whether the idea of velocity psychologically precedes that of time or follows it. After many experiments with very young children, we have found early notions about velocity that are purely ordinal and so independent of any observations of time or distance. These intuitive ideas have to do with "passing" or "overtaking": A moving object A is first behind and then in front of another moving object B. All children, however young, say that A travelled "faster" than B. Clearly, this kind of intuition is based only on the sequence of events ("before" and "after") and on the relative position ("behind" and "in front of") but not on any quantitative evaluation of time or length. These quantitative evaluations, and their relation $s/t$, come only later. Frequently, in fact, the child wrongly employs the concept of velocity, even when he wants to measure length, showing a confusion between elongation and displacement.

When we turn to dynamics, we find similar results. Relatively early, children can recognize the equivalence of two "actions," for example *throwing* a heavy object from point A to point B and pushing the object, without releasing it, between the same two points, even though *pushing* takes longer and the required force is not exerted all at once. There are many other evidences of early ideas about action, in the physical sense of the term. But it is only when they are older that children can work out an elementary composition of forces or solve simple work problems (for example, that carrying $n$ units of weight up $m$ steps is equivalent to carrying $2n$ units up $m/2$ steps). Here again, undifferentiated ideas are apparently earlier than differentiated ideas.

These results have an interest for physicists who want to relate the origins of ideas with their present place in physics itself. Certain ideas, as we have noted, have resisted the revolutionary scientific theories of relativity and quantum mechanics, whereas others have been significantly modified. It turns out that those ideas that have been most resistant to change are those we have called undifferentiated: In relativistic physics, velocity has become a kind of absolute, with time and distance relative to it. In quantum theory, action has become a fundamental concept. Is this by chance, or can we say that the more fundamental and therefore more resistant ideas are the ones most deeply imbedded in psychological development, as we have seen is the case with topology? We shall leave it to the physicists to answer this question, noting only that such a relationship, if it exists, is understandable biologically: The formation of ideas is certainly influenced by our own bodily structure, which is the root of human activity but is itself subject to the same physicochemical laws as any other material object.

### Explanations of causality

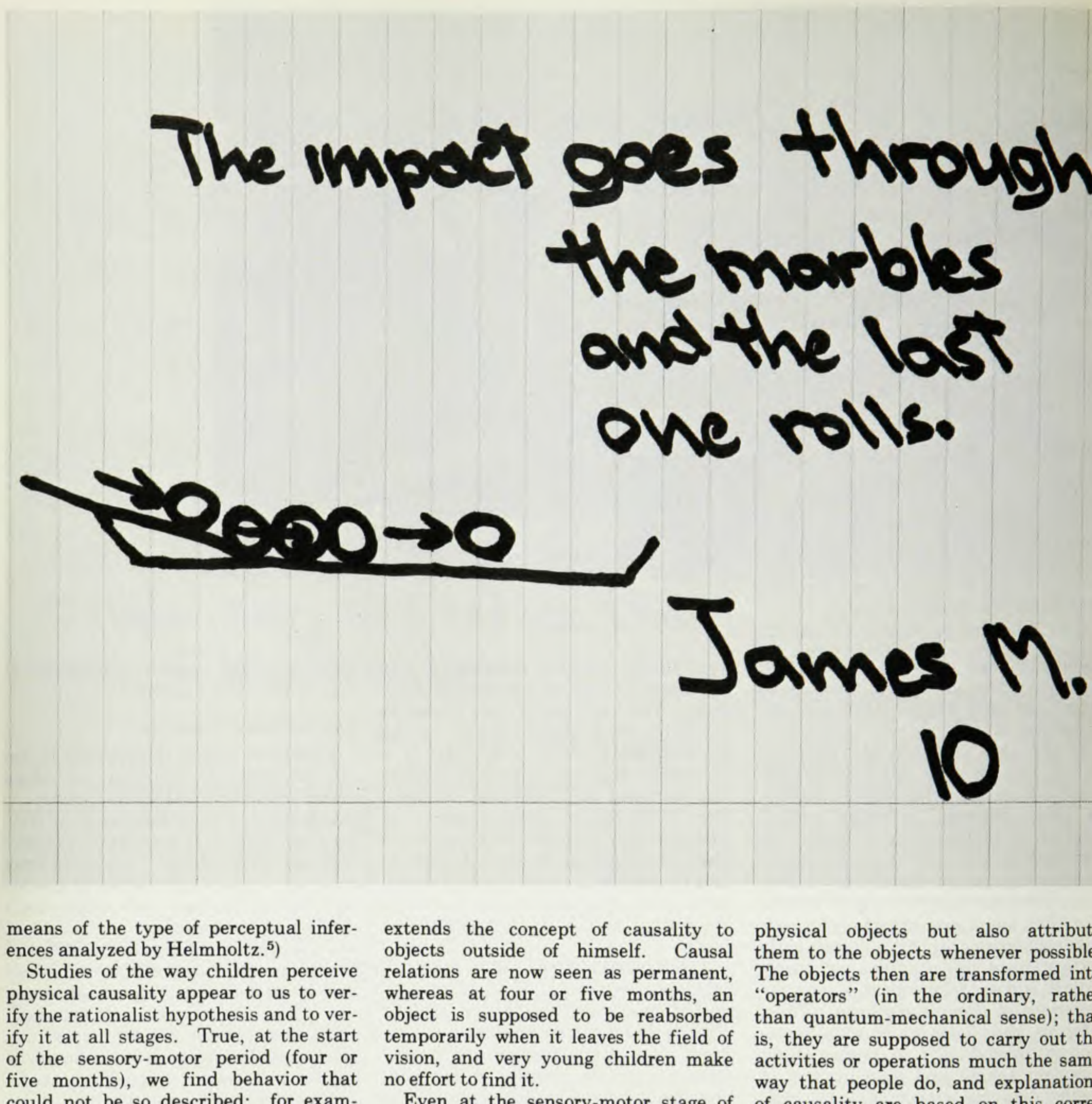
Finally we look at the problem of the psychological development of ideas about causality. Our hypothesis is that analyzing their formation in children will help us to learn more precisely about these ideas.[3] We recall first that the many interpretations of causality can be grouped into three main philosophical categories:

▶ Those that recognize no "result" and no inherent connection between cause and effect but only ordered sequences of events. The impression of "process" or of connection is due to the associations brought about in our own minds by these repeated ordered sequences. (Hume and logical positivists)

▶ Those that grant the existence of an observed connection between cause and effect, as we know to be the case for our own personal actions, with a generalization of these ideas to the actions of objects on one another. (Maine de Biran)

▶ Those that grant a direct connection between cause and effect, a connection that is not observed but always logically deduced. (rationalism since Descartes and Leibnitz)

These interpretations appear to be the only possible ones. (Even A. Michotte's[4] ideas of "perceptual causality" can be interpreted in these three ways. In Michotte's studies, we in fact never see anything transmitted between the "agent" and "passive" objects; we see only that something has happened and reconstruct the event by




means of the type of perceptual inferences analyzed by Helmholtz.[5])

Studies of the way children perceive physical causality appear to us to verify the rationalist hypothesis and to verify it at all stages. True, at the start of the sensory-motor period (four or five months), we find behavior that could not be so described: for example, the infant pulls a cord that hangs from the cradle roof to shake objects hung from the roof, then pulls the same cord either to swing an object that hangs two meters away (and has just stopped swinging) or to make a whistling noise behind a screen continue. At first, this kind of behavior seems to verify Hume's hypotheses (ordered sequence between anything and anything else) *as well as* that of de Biran (role of one's own actions in pulling the cord, without external causality) and not one to the exclusion of the other.

But we should take special note of the kind of behavior that appears at six to eighteen months. This behavior is characterized by a "spatialization" of causality; the child, recognizing causality in his own actions, generalizes and extends the concept of causality to objects outside of himself. Causal relations are now seen as permanent, whereas at four or five months, an object is supposed to be reabsorbed temporarily when it leaves the field of vision, and very young children make no effort to find it.

Even at the sensory-motor stage of human development, then, ideas of causality develop in terms of the child's concepts of space (he has learned the rules of displacements), of time (the order in which the displacements occur), of the permanence of objects, and so on. In other words, the child's ideas of causality develop from his experimental observations and inferential constructions, with the inferences becoming more important as the child grows older, in agreement with the rationalist hypothesis.

During later stages (from four or five to eleven or twelve years old) we notice a development whose significance is immediately clear. As the children formulate the logical and mathematical operations that are characteristic of intelligent inferential behavior, they not only "apply" these operations to physical objects but also attribute them to the objects whenever possible. The objects then are transformed into "operators" (in the ordinary, rather than quantum-mechanical sense); that is, they are supposed to carry out the activities or operations much the same way that people do, and explanations of causality are based on this correspondence.

A rather simple example, that of mediated transmission of motion, will help us to understand the process. The child is given a row of marbles, A, B, C . . . G, with A touching B, B touching C and so on. Another marble X rolls down an incline and hits A, the first in the series. Young children generally expect that all the marbles, A through G, will roll away and are astonished to see that only G, the last one, rolls away.

Four or five-year-old children give fanciful explanations. They say, for example, that marble X travelled behind the others and hit the last one. The five-and-a-half or six-year-old child transforms what he has seen into a series of direct transmissions: X hit A, which moved forward and hit B, which moved towards C, and so on. By the age of seven or eight, the transmission becomes indirect or mediated: Marble X gives A an "impetus" or "force," and this force passes through all the marbles, A through G, and G then rolls away.

But between the ages of six and eleven, this transmission although clearly "mediated" in that the intermediate or middle members supposedly transmit the motion across themselves, remains at least partly external. Each marble A to F is still supposed to be set into motion by a light unseen push from its neighbor. The young subject maintains this belief, even when he holds the marbles or coins with his fingers and observes evidence to the contrary. It is not until the child has reached the age of eleven or twelve that his understanding of the transmission becomes wholly internal and no longer partly internal and partly external; he has the idea of energy transmission by molecular impulses or vibrations and no longer believes in "neighborly" pushes.

What interests us in all this behavior is the start of the concept of mediated transmission, and the reason it first appears at the age of seven or eight. The reason it starts at this age appears to be clear: Only at this age do children start to understand the mathematical property "transitivity": $a = c$ if $a = b$ and $b = c$. Before seven or eight children cannot conclude that $a = c$ unless they see $a$ and $c$ together. Once transitivity is grasped, it is attributed to the marbles. Each marble transmits the push it has received to the following marble, as $b$ transmits equality from $a$ to $c$.

What can we say about the purely internal transmission that begins at eleven or twelve? Until this age, transitivity is only applied to macroscopic equivalences or differences (that is, to physically observable relationships) and not yet to inferred equivalences and differences, as recent studies have shown.

## Action and reaction

The concepts "action" and "reaction" provide a second example of the links between the development of logical-mathematical operations and that of causality. When a moving ball A hits a stationary ball B, making it move, the child quickly learns to predict that the heavier A is, the more force it will have and the further it will push B. But if we make B heavier, the youngest subjects think that it too will go further because it is stronger. According to them, this force or weight adds to A's weight, reinforcing its effect. The majority of five-and-a-half to six-year olds, however, already predict that a heavier B will "restrain" the effect of A; this behavior is an early idea of the resistance concept.

But the children are still very far from seeing this resistance as a "reaction" in the sense of a force directed opposite to that of A; their ideas are concerned only with slowing down or loss of speed.

In an experiment some years ago (with Bärbel Inhelder) we used a U-tube filled three-fourths full with liquid, with a piston pressing down on the right side. Children up to the age of nine or ten predicted that if we increased the weight of the liquid on the left-hand side (by switching to a denser liquid), the liquid on the left would climb higher. Here again, children see the weight as *adding* to the weight of the piston to increase its effect. Only at the age of eleven or twelve do children understand this increase in liquid weight as causing a reaction *opposite* to the direction of the piston's action.

In a more recent study, with Gilbert Voyat, we gave the subjects a piece of modeling clay. The experimenter pushed with a metal rod fitted at its end with a disc, while the child did the same from his side. The question was: Will one of us drive his rod in further than the other, and, if so, which one? Children up to the age of eleven or twelve naturally answer that the adult is stronger and will drive his rod in further. But from the eleven or twelve year olds we begin to get elegant explanations: When you push strongly, I resist strongly, and when I push gently, you resist gently, so that we get compensation.

Why does understanding of the effects of reaction come so late? The explanation is that the phenomenon "reaction" is in fact a group of four operations (a "Kleinian" group)

- ▶ direct operation—increase in action
- ▶ inverse operation—decrease in action
- ▶ reciprocal operation—increase in reaction
- ▶ correlative or dual operation of the direct operation; inverse of the reciprocal operation—decrease in reaction

The child's understanding of logical and propositional operations does not include a grasp of these coordinated inversions and reciprocities until he is eleven or twelve, explaining his delayed attribution of them to physical causality.

We could cite many other cases of logical-mathematical operations whose comprehension children come to rather late, so that a similar delay occurs in understanding them in terms of causality. Distributivity $[n\ (x + y) = nx + ny]$ is one of these operations. In explaining the elongation of a rubber band, for example, children persistently fail to comprehend the distributivity of the stretching; they confuse elongation of objects and parts of objects with their displacement. This confusion is also evident when we show the child two rulers and move one of them. The displaced ruler supposedly becomes elongated, which shows us that children persistently believe in nonconservation of length.

A remarkable kinship exists, then, between the development of logical-mathematical operations in a child's mind and his development of causal explanations for physical phenomena, and it exists for two interdependent reasons: Both kinds of understanding are characterized by certain "processes," because the operations transform their objects in the same way that causes do, and both involve conservation or invariance. Operations do not transform everything at once but always leave certain properties invariant while modifying others. Causality, in the same way, implies a transmission that conserves some quantity (such as $mv$ or $mv^2/2$) while modifying others.

Given this general parallel between the various combinations and coordinations of intellectual operations (such as transitivity, distributivity, transformation groups), it is natural to "attribute" them, and not only "apply" them to objects. In other words, we have here not simply the elaboration of a language, as logical positivism would like us to believe, nor the use of convenient but subjective simple models. What we see is rather an inexhaustible pursuit of the objective structures that are hidden under observables, that our logical-mathematical coordinations try to reach deductively and whose results are then confirmed by experience.

Causality is never a visible relationship but always, from childhood to the higher forms of scientific thought, an inferential reconstruction. Understandably, the only means of explanation at our disposal is a continuous attribution of our own mental processes to analogs we believe we find again in the real world.

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