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Generative Processes in Representations of Problems
Final Report

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Addressing questions concerning representation and restructuring in the domain of mechanics, this research sought to identify basic representational structures involving forces, objects, and motions and to show how people use them to construct predictions and explanations in particular situations. A closely related objective was to examine the nature of representational change, both spontaneous and stimulated by different forms of instruction. We conducted two sets of studies examining the nature and use of physics knowledge on the part of naive individuals--those having never formally studied physics. The first study was descriptive, examining the extent to which naive reasoners about physics can be said to work from theoretical principles, as opposed to constructing ad hoc, local explanations that cannot properly be called theories. The second focused on restructuring as a result of certain kinds of feedback. Subjects appeared

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to have organized ideas about how forces and motions combine, but they made distinctions among situations that would not be needed within Newtonian theory. Results of these studies invite further investigation of both the structure of naive representations and the conditions and processes of restructuring.

Generative Processes in Representations of Problems
Final Report
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University of Pittsburgh/Lauren B. Resnick
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1. Background

This activity represents a portion of a project that was originally funded for joint work by James G. Greeno and Lauren B. Resnick. When Professor Greeno left the University of Pittsburgh in September, 1984, the bulk of the remaining funding was transferred to the University of California at Berkeley. Funding in the amount of $139,869 over three years remained at Pittsburgh to cover the portion of the project entitled "General Principles in Problem Representations: Mechanics" (pp. 23-41 of the original Greeno/Resnick proposal).

This research addressed questions concerning representation and restructuring in the domain of mechanics. It sought to identify basic representational structures involving forces, objects, and motions and to show how people use them to construct predictions and explanations in particular situations. A closely related objective was to examine the nature of representational change, both spontaneous and stimulated by different forms of instruction.

We have conducted two sets of studies examining the nature and use of physics knowledge on the part of naive individuals--those who have never formally studied physics. The first set of studies was descriptive; they examined the extent to which naive reasoners about physics can be said to work from theoretical principles, as opposed to constructing ad hoc, local explanations that cannot properly be called *theories*. The second set of studies focused on restructuring as a result of certain kinds of feedback.

1.1. Consistency and reasoning from theoretical principles.

Two sets of data address the issue of the extent to which subjects make theoretically consistent predictions about the motion of objects under various conditions. In one study sixty subjects were asked to solve 16 qualitative physics problems involving two Newtonian principles. The first principle, the *Rectilinearity Principle*, states that objects continue to move in a straight line when forces that previously constrained those objects to move in a curved path are removed. This principle is subsumed under Newton's First Law. Eight problems involving this principle are shown in Figure 1, with correct, Newtonian, answers drawn in. In each case a correct application of the Newtonian principle leads to the prediction that the object will move in a straight line when released. Many subjects, however, hold a common misconception that the object will continue in a curved path for some time after the constraining forces are removed; for example, the ball moving through the curved tube would continue curving after it is out of the tube.

The second principle involved in our problems is the *Vectorial Additivity Principle*, which states that, if two or more motions are involved, these motions *jointly* determine the object's subsequent speed and direction. Eight vectorial additivity problems are shown in Figure 2, with correct answers drawn in. For both sets of problems, subjects were asked to draw the trajectories the objects would follow after release. A common misconception for problems of this kind is that one of the directions of motion can temporarily or permanently override the others. For example, for the problem in which a person walking while holding a ball suddenly releases the ball, most uninstructed people predict that only gravity will operate and the ball will fall straight down rather than taking a parabolic path to the ground. For the problem in which a bullet is shot from a gun, many people predict that the bullet will move strictly horizontally for a long time because the force of firing creates a motion so strong that it overrides gravity.

During the first phase of the experiment, eight problems for each of these two principles were given to subjects (tested individually). Think-aloud protocols were obtained throughout the experiment. After completing the 16 problems, subjects received further instructions for the second phase, according to which of three experimental groups they had been randomly assigned to: the CONTROL group, the REVISE group, or the CONSISTENCY group. CONTROL subjects received no further instructions. REVISE subjects were asked to review their original answers and make any changes that they wished. CONSISTENCY subjects were also asked to look back over their answers, with the specific goal of trying to make their answers self-consistent.[1] Finally, the third phase of the experiment took place one month later, when all subjects returned for a second test session. They were given 16 new problems, isomorphic to the original ones, plus the original 16 problems. Subjects were asked to solve all 32 problems and then to sort the 32 problems into groups of their own definition. Sorting into groups would reveal the problems the subjects themselves regarded as similar and would, thus, highlight the problem features to which subjects were paying attention. Data available from each subject include: solutions to the 16 original problems from each of the two test sessions, solutions to the 16 isomorph problems from the second test session, *revisions* to the original problems (for REVISE and CONSISTENCY subjects), sorting data, and transcribed protocols of the entire experiment.

Generally speaking, the results obtained replicate and extend the physics misconceptions findings already in the literature. When answers were coded in terms of being correct within a Newtonian frame of reference, only 34% of the original Vectorial Additivity problems were correct, while 71% of the Rectilinearity problems were correct.[2] The opportunity to change answers given to the REVISE and CONSISTENCY subjects did not improve their correctness.

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[1] This manipulation was included in order to find out if people not originally consistent in their responding would *become* consistent if given an opportunity to reflect on their answers (REVISE *subjects*). The CONSISTENCY subjects were included to see if people have the *ability* to be consistent, even if they did not have the inclination to be so originally.

[2] This difference was the only significant one ($p < .05$) for the correctness data.

There were no significant differences among subject groups during any of the three experimental phases, so any effects from the experimental manipulation were not in the direction of improved accuracy. REVISE and CONSISTENCY subjects made about the same number of changes to the 16 problems (an average of 3 or 4 changes); therefore, consistency instructions did not seem to prompt more revision. These instructions did, however, produce a bit more "theoretical" revision. For Rectilinearity problems, a theoretical change was one that changed a curved path to a straight path (or vice versa); for Vectorial Additivity problems, a change was judged theoretical if both motions determined the object's path, whereas only one had before (or vice versa). Non-theoretical changes were typically cosmetic ones that did not fundamentally alter the answer's correctness. Generally, results show that subjects are not consistent--and do not become consistent even when explicitly invited to do so--from a Newtonian perspective. That is, they do not apply the correct linearity or vectorial additivity principle in all cases in which Newtonian theory says they should. Furthermore, their sorting data show that subjects make discriminations between situations that are not required within a strictly Newtonian theory.

A second set of data, using a set of problems involving dropped and thrown objects and a set of problems in which subjects had to predict the fall of a pendulum bob after the string is cut, confirm this finding. These problems are shown in Figures 3 and 4. All of these problems involve the vectorial addivity principle, the one in which subjects in the previous study deviated more widely from Newtonian predictions. The dropping and throwing problems were presented verbally. The pendular release problems were presented on a Dandelion computer screen. Pendulum motion was animated, and subjects drew in their predictions using a mouse for both sets of problems. The conditions of administration allowed considerably more probing by the experimenter than in the first experiment and yielded more explicit explanation by the subjects.

Subjects in this second study were only sometimes aware of the mutual influence of the object's prerelease velocity and the downward velocity induced by gravity. For instance, 63% of the subjects ignored the horizontal velocities of the walking-drop and train-drop situations and, instead, expressed the "straight-down belief."[3] However, none of these same subjects suggested that a *laterally-thrown* object (e.g., horizontal throw, upwards throw) would yield a straight-down trajectory. It is as if the passive horizontal motion of the object carried in the train-drop and walking-drop problems is not "owned" by the object; the horizontal component of motion vanishes once the object is released. In contrast, the thrown objects were sometimes thought to carry so much of their own horizontal velocity that the horizontal motion temporarily dominated the downward gravitational motion. Ninety percent of the subjects' initial horizontal-throw predictions involved purely horizontal motion before (in subjects' typical language) either (1) gravity overtook the "throw-force" or (2) the "throw-force" ran out of enough "steam" to begin falling. Although such notions were less dominant for the upwards-throw, about 50% of the subjects believed that the initial upward portion of the throw was unaffected by gravity's pull.

On the pendular-release tasks, subjects rarely predicted a straight-down trajectory for laterally moving pendulum bobs. When such trajectories were predicted, they seemed to be somewhat perceptually driven by the vertical position of the pendulum's string at position C. Some subjects thought that gravity dominates at that position, saying that it is the point of "neutralized *forces*" *or* "*no motion*." Aside from this particular position, subjects generally thought the bob's trajectories resulted from some sort of synergism between lateral and downward motions. Thus, most subjects did conceive of the pendulum bob as "owning" its own lateral velocity. However, the gravitational force and the object's initial velocity were not always *properly* (i.e., *simultaneously*) integrated. Much depended on the particular position, speed, and direction of the pendulum's movement at the moment of cutting.

The results of both studies point to the hypothesis that our naive subjects make

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[3] *Most of these subjects asserted that the direction of the walker or train is irrelevant to the movement of the released objects*, which merely falls vertically beneath the hand that released it. Thus, this prediction is not necessarily the result of a "*frame of reference*" difficulty.

discriminations about situations that produce more locally based predictions than does Newtonian theory. Whereas Newtonian theory needs only a few general principles to describe all the problem situations we have studied, our subjects need more because they believe that the way in which motions combine depends on certain qualities of the individuals' motions. Most striking is the fact that motions can override each other under particular circumstances. These kinds of explanations suggest that subjects are thinking theoretically, but within much narrower spaces of implication than trained physicists. Other contradictions in their predictions, however, seem to derive from intrusions of knowledge sources other than the analysis of component motions. For instance, episodic memories (e.g., baseballs curve downward gradually) often substituted for more theoretical ideas about motion. And, occasionally, faulty perceptions drove inconsistent responding.

2. A Naive Mechanics Theory-Space

Our data appear to fit the assumption that, for most of our college-age subjects, it is natural to decompose motion in terms of three components--upward, downward, and lateral. On the other hand, the subjects do not necessarily "add" the forces in the way that Newtonian physics does, and they do not necessarily represent individual motions in Newtonian-compatible terms. We show in the next several paragraphs the kind of knowledge that we think can account for our subjects' predictions.

Figure 5, Panel A, shows the correct, Newtonian, knowledge of the three components of motion and their combination rules. According to this analysis, downward motion accelerates, is effective immediately upon release of the object, and never stops (until the object hits the ground). In situations that do not involve gravity, there is--technically--no direction of downwardness. However, naive subjects may determine a downward direction and then decide that there is no force and thus no acceleration. Lateral motion is seen to be constant. Like the downward motion, lateral motion is effective immediately and continues indefinitely. The same rules are true for the upward motion as well; it, too, would continue indefinitely if there were no opposing downward force (i.e., gravity). To make correct (although purely qualitative) trajectory predictions with this "theory of motion," it suffices to decide correctly whether the object is experiencing any upward or lateral motion at the moment just prior to its release and whether there is in the situation a gravity force that will initiate a downward motion. One can then use a general rule for combining the relevant motion components.

Changes in knowledge about individual motions can produce the various non-Newtonian trajectories exhibited by our subjects. Figure 5, Panels B, C, and D, provide some examples. Panel B shows a knowledge base with only one change from the Newtonian--the downward motion is thought to be constant. For an object that is released from a moving body (e.g., train, plane, person), this change alone will produce a trajectory that is straight and angled out from the point of release, as shown in the figure. Such predictions occur frequently in our data.

Panel C shows a knowledge base in which downward motion is not effective immediately but enters suddenly after a time lag. Gravity becomes effective only when lateral speed decreases to zero. This version of the knowledge base incorporates an impetus-like view of lateral motion (it is gradually "used up") together with the idea that lateral motion overrides gravity-produced motion. This knowledge base will result in a "road-runner" type of trajectory for moving drop problems, one in which the object first travels horizontally, then abruptly falls vertically, producing a 90 degree angle at the point of change.

Panel D, shows a small variation on the knowledge in Panel C. The downward motion is now believed to become effective gradually. Everything else stays the same. This conception produces a kind of modified road runner trajectory in which there is a small period of curvature between the horizontal and vertical parts of the trajectory. This same knowledge pattern will produce a frequently observed trajectory for upward throw problems, a trajectory in which the object arcs upward, but then curves downward and lands after a purely vertical fall.

The impact of these analyses is that our physics-naive subjects appear to have more consistent theories than initially thought. While they are inconsistent according to strict Newtonian criteria, most subjects are consistent within the terms of their own particular knowledge pattern. The consistency is not absolute, however; there are still intrusions of episodic and perceptual knowledge.

3. Restructuring from Feedback

To the extent that an individual's knowledge of a domain is based on a finite set of principles that are used to constrain predictions in many different specific situations, feedback about predictions in any specific situation ought to produce both local and more general effects. This is because contradiction of any specific prediction should cause a questioning of the principles that produced the prediction; to the extent that the representation of principles changes, predictions for other situations should change as well. We have conducted research examining spread of implication under two kinds of feedback: (1) purely empirical feedback in which subjects are shown the actual (Newtonian) trajectory of an object compared with their own prediction; (2) analogical feedback in which subjects are shown the actual trajectory of an object in a theoretically analogous situation. In the second case, subjects are sometimes left to their own devices for deciding which situations are analogous and are sometimes given additional feedback concerning which situations are analogous to one another.

The studies have used the same two sets of problems shown in Figures 3 and 4--that is, a set of simple dropping and throwing problems and a set of pendulum release problems. Each release position for the pendulum is analogous--in terms of the motions that will combine to produce the object's trajectory after release--to one of the dropping/throwing problems. The analogies are shown in Figure 6.

In the first set of studies, subjects' predictions and explanations for the dropping/throwing problems and the pendulum-release problems were first collected. Subjects were then given individual feedback on their pendulum predictions via a computer display showing the subject's original prediction superimposed upon the correct prediction. Feedback was given position-by-position, beginning with a cut at position B with the pendulum swinging right, and continuing with cuts at C and D of the rightward swing, at E, then at D, C, and B of the leftward swing, and finally at A. After each item of feedback, the subjects were asked what they thought accounted for the difference between their original prediction and the feedback and also whether they would now like to correct any of their earlier predictions on any of the other tasks. This invitation to correct earlier predictions (prior to explicit feedback on those predictions) permitted us to determine whether any reinterpretation that individuals made was purely local or produced implications for other situations as well.

Our major interest is in how and when (i.e., spontaneously or in response to the experimenter's explicit request) predictions were revised as a result of feedback concerning pendulum trajectories. A first observation is that most subjects used the symmetrical nature of the pendulum to make correct predictions for positions symmetrical to a position for which feedback had just been provided. For example, 85% of participants spontaneously corrected their predictions for D-left after receiving feedback on B-right. Overall, more than 90% of possible symmetry-based corrections were made spontaneously. This use of symmetry provides some evidence that subjects conceived of the pendulum as a ***system***. However, it does not tell us whether they were really reasoning in a principled way from one position to another or were only looking for obvious analogies of position, where "the same" prediction could be made.

We can obtain an initial answer to this question by examining spontaneous changes that were not purely symmetrical. There were few such revisions, usually to positions that would come immediately next in the sequence of cuts (e.g., C-right changed after feedback on B-right).

These changes typically eliminated rectilinear predictions (making the next position's trajectory curve as did the one on which feedback had just been given) and eliminated overtly impetus-like features (e.g., following the curved trajectory of the swing for a while, even when there was no upward motion prior to the cut). Examining the protocols for clues to the reasons that these changes were made suggests that participants were *often* ***not*** *reasoning* about underlying motions or forces; rather, they were importing trajectory features from one position to the next. For virtually all subjects, the most surprising aspect of feedback was learning that, at position E, the pendulum bob would fall straight down. But when asked, subjects were successful in developing an explanation of why this was so. This reasoning led them to recognize that there is an instant in which there is no motion in the pendulum. For a few subjects, this realization seemed to provoke some rethinking of pendular dynamics. However, the data from this experiment did not allow us to explore in detail the nature of these changes.

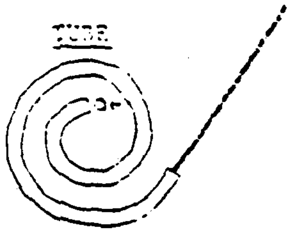
At the conclusion of pendulum feedback, participants were asked if they wished to change their predictions for any of the dropping/throwing problems. Less than 20% of the incorrect predictions were altered, and only half of these changes were "theoretical," according to the criteria described for the consistency studies. The results suggest that most subjects used empirical feedback in a relatively superficial way--importing features of trajectories from one pendulum position to another, especially when supported by the symmetrical organization of the pendulum. Further, almost no transfer to the dropping and throwing problems was observed, which suggests either that participants did not recognize the analogy between them and the pendulum situation or that revisions in pendulum predictions were not based on a revision of general principles of the domain. Finally, the nature of the situation was not one that actively demanded revision, and many subjects may have been more disinterested than unable to think through a theory of motion.

4. Conclusion and Continuing Work

The results of these studies invite continuing investigation both of the structure of naive representations and of the conditions and processes of restructuring. Subjects appear to have organized ideas about how forces and motions combine, but they make distinctions among situations that would not be needed within Newtonian theory. Further research is needed to uncover the sources of these distinctions and to determine whether they reflect an underlying set of principles that are theoretically well formed yet contradictory to Newtonian theory. With respect to provoked restructuring, our data show only rather surface changes as the result of the empirical and analogical feedback provided. The conditions of the studies reported did not allow us to decide whether this kind of feedback is fundamentally *inadequate* to provoke restructuring or whether subjects were simply not motivated to think about the implications of the data provided as feedback. Additional studies to distinguish between these possibilities are being conducted as part of N0014-85-K-0337, "Conceptual Change in Problem Solving and Learning," of which Lauren B. Resnick and Stellan Ohlsson are principal investigators.

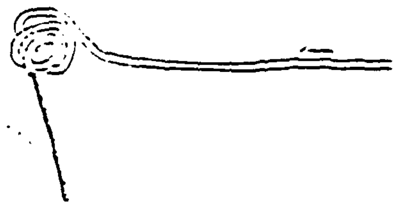
Figure 1
Rectilinearity Problems

TUBE



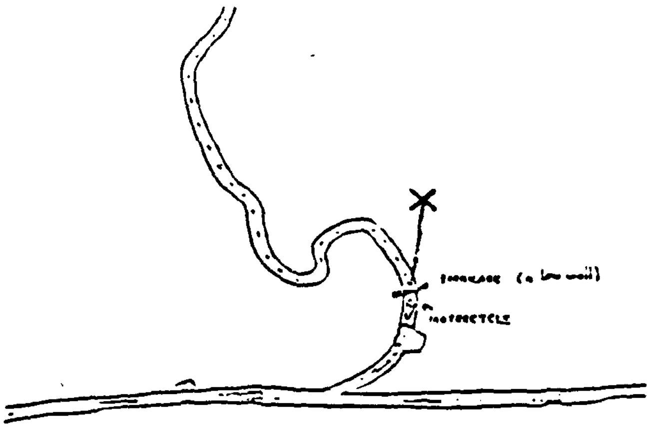
This is a hollow, curved metal tube, which you are looking down upon as it lies flat on the ground. A bullet is shot into the tube at the end indicated, and then shoots out the other end. Draw the path that the bullet takes after it leaves the tube, to the end of the page.

HOSE



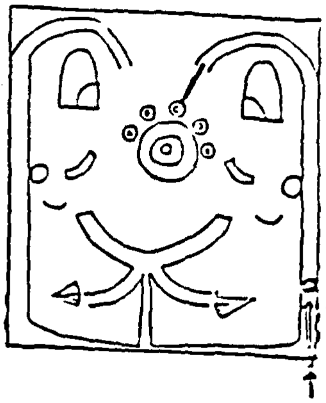
Here you are looking down upon a coiled garden hose, lying on the ground. Someone suddenly turns the water on full blast. Assuming that the hose itself remains motionless, draw the path that the water will take after it leaves the hose.

ACCIDENT



You are making a movie involving a high-speed motorcycle chase scene. At one point, a motorcycle will be going around the curve (as shown) at a high speed, and will crash into a presumably unexpected barricade: a low wall. Even though you will be using stunt people, you need to set up a safety net to catch the driver when he flies off the motorcycle. Mark an "X" to indicate where the safety net needs to be set up on the other side of the low wall. Then, draw the path that the driver's body would take as he flies over the wall to the safety net.

PINBALL

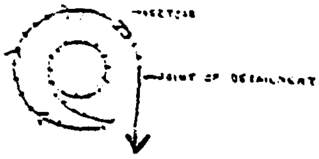


As you are looking down on a pinball machine, a pinball is shot in very rapidly. Assuming the machine isn't tilted, which of the five spots—A, B, C, D, or E—is most likely to be hit first? Draw the path that the pinball takes to the spot that you answered it would hit first.

CIRCLE ONE: A B C D E

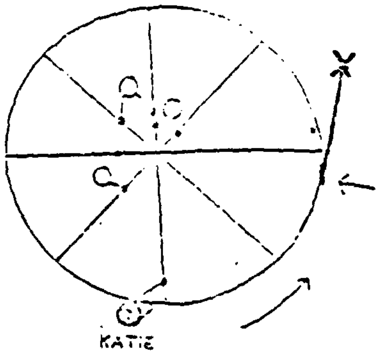
Figure 1 Rectilinearity Problems (continued)

STREETCAR



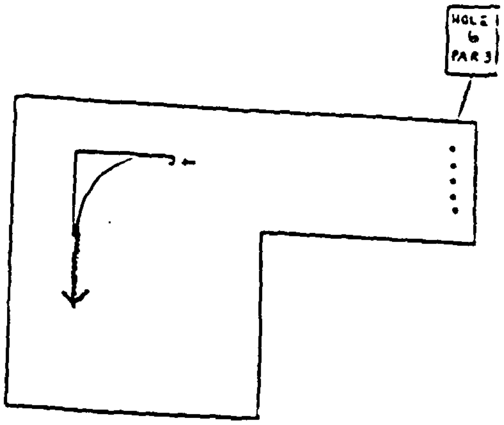
In this diagram, you are looking down at a streetcar which is coasting slowly along the track. At the point indicated in the diagram, the tracks have been removed and the streetcar derails. Draw the streetcar's path after it leaves the track at derailment.

MERRY-GO-ROUND



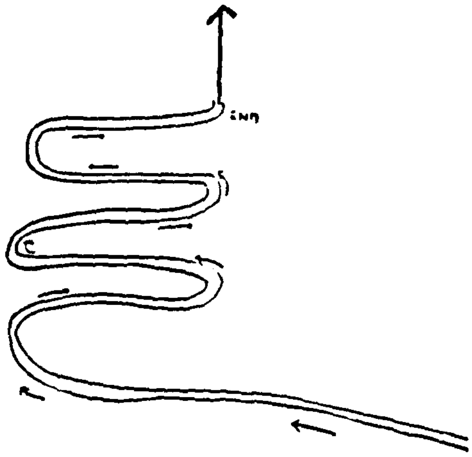
You are looking down at a little merry-go-round in a playground. There are 3 children already on it, and Katie is off of it, beginning to slowly push it. When Katie reaches the point indicated by the arrow, she suddenly stops, and her hat flies off. If you ignore any air resistance on the hat, where does it land? Also, draw its path from Katie's head to the ground, as it appears from above.

GOLF



At Hole 6 of the miniature golf course, a person is about to putt his second shot. His ball is at the location indicated in the diagram. He is about to putt the golfball in the direction shown by the arrow, so that the ball will follow the curve. Assuming this person knows what he is doing, draw the approximate location of the hole in order for this person to make Hole 6 a par-2 hole (that is, in order to get the ball into the hole on the second putt).

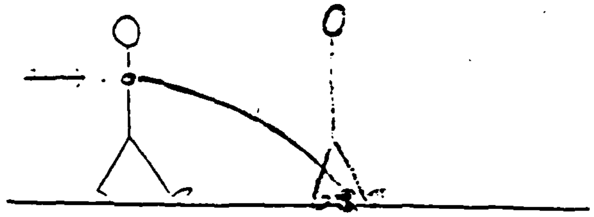
CREEK



You are looking down upon a very sluggish creek, which is meandering through some side-winder type bends. If the "creek" suddenly ended at the point shown but the water could somehow keep going, where would it continue? Draw the water's path from the "END" of the creek to the edge of the page.

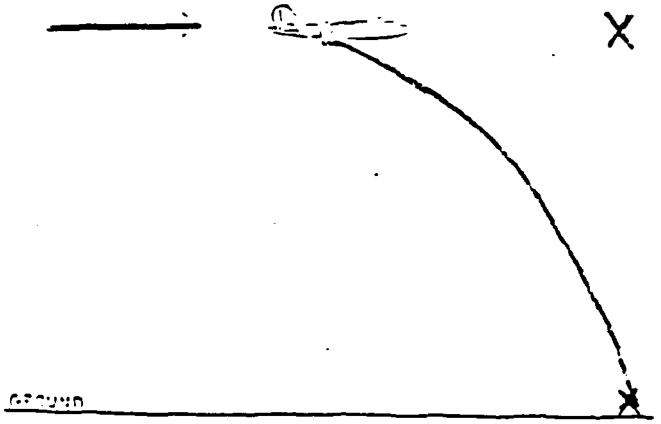
Figure 2
Vectorial Additivity Problems

DROPPING



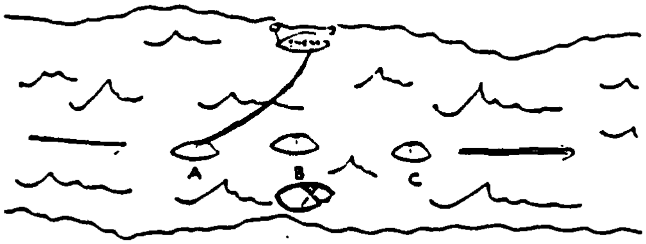
Here you are, walking along slowly with constant speed, holding a ball outstretched in your hand. At the point shown in the picture, you drop the ball. Draw its path to the ground, and draw where you would be in relation to the ball when it hits the ground. You keep walking the whole time.

JET



A jet is flying along very rapidly at a constant speed, carrying a bomb. It releases the bomb at the instant it is at the place shown in the picture. Draw the location of where the bomb's target is on the ground, in order for the bomb to hit it. Ignore air resistance. Then, draw the path that the bomb takes to reach its target, and the location of the jet when the bomb hits the ground.

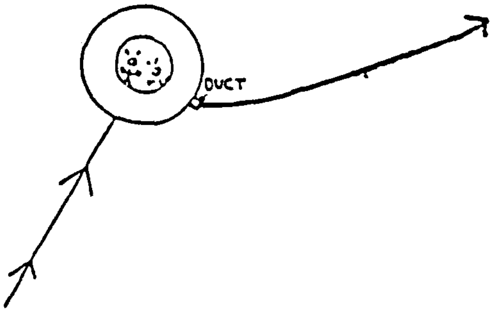
CANOES



You are looking down upon some Indian canoes, one of which is moored to the bank of the river while the other three are moving rapidly downstream. Which of the three canoes—A, B, or C—should toss a flaming rock directly sideways at the locations where they presently are in the diagram, in order to successfully attack the moored, enemy canoe? Ignore air resistance. Also, draw the rock's path from the moving canoe to the moored canoe, and draw the location of the moving canoe (the one that has tossed the rock) when the rock hits the enemy canoe.

CIRCLE ONE: A B C

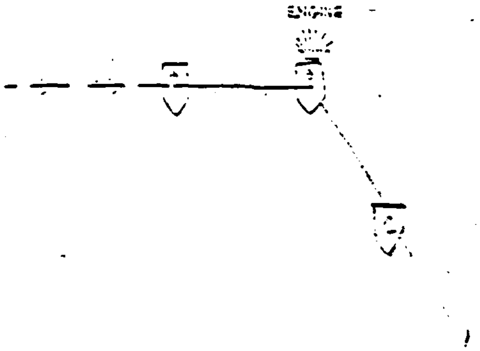
MARTIANS



You are looking down upon a flying saucer which is leisurely coasting at a constant speed through deep space, in the direction indicated. When the flying saucer reaches the spot where it is at in the diagram, the Martians inside throw some garbage out of the duct labeled in the picture. Draw where the garbage goes after it leaves the flying saucer (mark it with an "X").

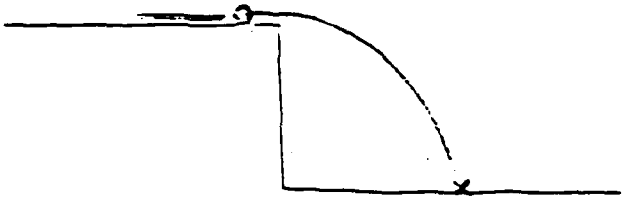
Figure 2 Vectorial Additivity Problems (continued)

ROCKET



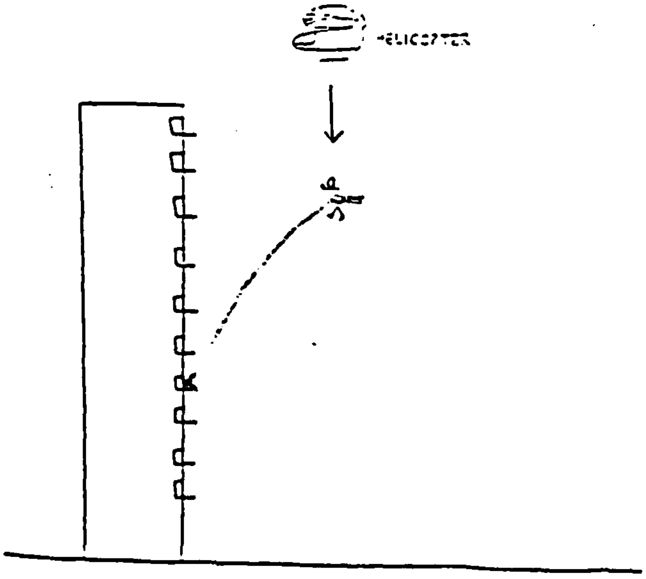
A rocket is moving along slowly sideways in deep space, with its engine off, from point A to point B. It is not near any planets or other outside forces. Its engine fires a powerful blast at point B for two seconds, causing the rocket to travel from point B to some point C. Draw in the shape of the path from B to C. (Show your best guess for this problem even if you are unsure of the answer.) Then, draw the path from point C (after the engine is turned off).

CLIFF



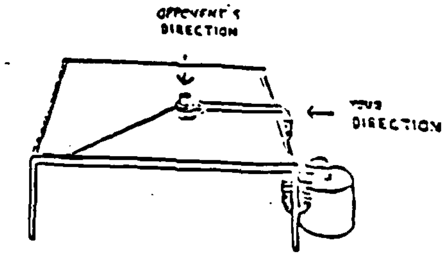
The diagram shows the side view of a cliff. The top of the cliff is perfectly smooth, and a metal ball is rolling along it very rapidly with constant speed. Where would the ball land on the ground? Draw its path.

BURGLAR



An ingenious burglar has just been released from a helicopter hovering directly overhead in the picture. When he is at the location shown in the diagram, he activates the propulsion device around his waist. He intends to land on one of the ledges of the high-rise apartment building. Which one does he land on? Draw his path to the ledge.

PUCK



The apparatus shown in the diagram is an air hose, which you can use to move a large dry-ice puck on an air hockey table. The air hose delivers single, short, and relatively weak bursts of air. Your opponent has just set the puck slowly into movement in the direction indicated by the arrow. If you deliver an air burst at the point where the puck is right now, where will the puck move? Draw its path until the edge of the table.

Figure 3 Dropping and Throwing Problems.

Instructions:

For each of the following descriptions, feel free to utilize the provided pencil and paper to draw the following motions or to assist you in getting your thoughts together. However, please remember to describe verbally (out loud) everything that you draw or write. As before, you are welcome to change any of your descriptions and predictions, for any situations, whenever you'd like

In each of the following situations, you may consider effects of wind-resistance and air-flow to be negligible. (That is, *you may ignore them, if you so wish*.)

Standing-Drop

Please describe, as completely and accurately as you can, the motion of a heavy object that has been dropped off a cliff by a standing person. (Assume that the person holds the object out over the cliff's edge and releases it.) Include every type and level of description (e. g., temporal, positional, physical, general, specific, quantitative) that occur to you. Finally, in the space below, please provide a drawing of whatever you think the motion would look like.

Walking-Drop

Please describe, as completely and accurately as you can, the motion of a heavy object that has been dropped off a cliff by a man who is briskly walking parallel to it. (Assume that the man is holding the object out to his side, in an outstretched arm, and over the edge of the cliff, when he releases it.) Include every type and level of description (e.g., temporal, positional, physical, general, specific, quantitative) that occur to you. Finally, in the space below, please provide a drawing of whatever you think the motion would look like.

Monorail-Drop

Please describe, as completely and accurately as you can, the motion of a heavy object that has been dropped out of the window of a quickly moving monorail (a highly elevated train). Include every type and level of description (e.g., temporal, positional, physical, general, specific, quantitative) that occur to you. Finally, in the space below, please provide a drawing of whatever you think the motion would look like.

Generic-Throw

Please describe, as completely and accurately as you can, the motion of a heavy object that has been thrown. Include every type and level of description (e g., temporal, positional, physical, general, specific, quantitative) that occur to you. Finally, in the space below, please provide a drawing of whatever you think the motion would look like.

Figure 3, continued

Straight-Up-Throw

Please describe, as completely and accurately as you can, the motion of a heavy object that has been thrown (exactly) straight upwards. Include every type and level of description (e.g., temporal, positional, physical, general, specific, quantitative) that occur to you. Finally, in the space below, please provide a drawing of whatever you think the motion would look like.

Horizontal-Throw

Please describe, as completely and accurately as you can, the motion of a heavy object that has been thrown (from a cliff) exactly horizontally (i.e., straight outwards). Include every type and level of description (e.g., temporal, positional, physical, general, specific, quantitative) that occur to you. Finally, in the space below, please provide a drawing of whatever you think the motion would look like

Upwards-Throw

Please describe, as completely and accurately as you can, the motion of a heavy object that has been thrown (from a cliff) upwards, but not straight upwards. Include every type and level of description (e.g., temporal, positional, physical, general, specific, quantitative) that occur to you. Finally, in the space below, please provide a drawing of whatever you think the motion would look like.

Straight-Down-Throw

Please describe, as completely and accurately as you can, the motion of a heavy object that has been thrown (exactly) straight downwards. Include every type and level of description (e.g., temporal, positional, physical, general, specific, quantitative) that occur to you. Finally, in the space below, please provide a drawing of whatever you think the motion would look like.

Downwards-Throw

Please describe, as completely and accurately as you can, the motion of a heavy object that has been thrown (from a cliff) downwards, but not straight downwards. Include every type and level of description (e.g., temporal, positional, physical, general, specific, quantitative) that occur to you. Finally, in the space below, please provide a drawing of whatever you think the motion would look like

Figure 4 Pendular Release Problems.

Instructions:

In each of the following tasks, you will be asked to make predictions about what happens to a swinging pendulum's (heavy) bob when the string that supports it breaks. In addition, you'll be asked to "think aloud" -- to explain why you think the predictions that you provide are appropriate and accurate.

Before each prediction, you'll get to see the pendulum swinging several times, then stop at the position that the bob would be released. From this release point, you'll be asked to "draw" the path of the pendulum's bob (by using a series of connected dots) on the computer screen. (By the end of the experimental session, you'll have received feedback on both your paths and your explanations.)

At any time during this experiment, you may change your mind about either a path that you've drawn or an explanation that you've provided. At your slightest whim, you can return to any problem, at any time, to have another look at it -- just ask the experimenter.

<Because this session is audio-taped, please take care to (1) say the name of whatever you're describing or pointing at and (2) refer to each problem by a unique name (for instance, you might call B--> "B-right").>

You can imagine that the pendulum is about a yard (one meter) in length, and that the bottom of the screen represents the ground. Furthermore, in each of the following situations, you may consider effects of wind-resistance and air-flow to be negligible (That is, you may ignore them, if you so wish.)

Sample Problems:

B-->

The pendulum is swinging in an arc between A and E. During a swing **toward the RIGHT**, at **position B**, the string breaks and the bob is suddenly released. Using the mouse, please draw the path (from the release-point to the bottom of the screen) that the bob will follow after the string breaks. Please describe the path (by thinking aloud) as accurately as possible, and then explain how you decided what the drawing should look like.

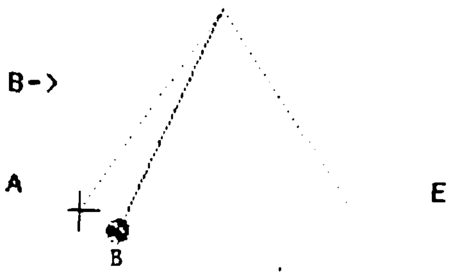
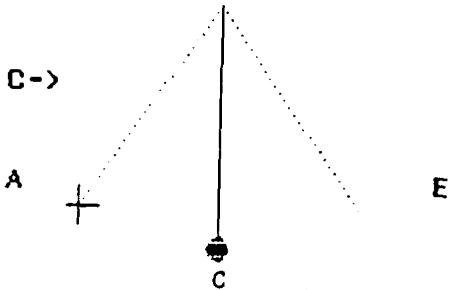


Figure 4, continued

C->

The pendulum is swinging in an arc between A and E. During a swing toward the RIGHT, at position C, the string breaks and the bob is suddenly released. Using the mouse, please draw the path (from the release-point to the bottom of the screen) that the bob will follow after the string breaks. Please describe the path (by thinking aloud) as accurately as possible, and then explain how you decided what the drawing should look like.



<and so on, until . . .>

A

The pendulum is swinging in an arc between A and E. While the bob is AT position A, the string breaks and the bob is suddenly released. Using the mouse, please draw the path (from the release-point to the bottom of the screen) that the bob will follow after the string breaks. Please describe the path (by thinking aloud) as accurately as possible, and then explain how you decided what the drawing should look like.

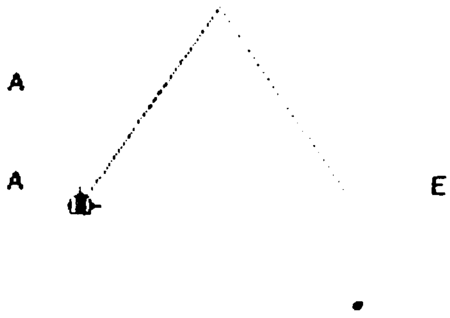


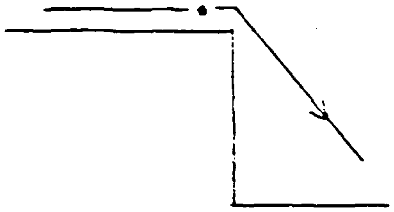
Figure 5 Mechanics Theory-Spaces.

a. The "Newtonian Space"

Direction	Speed(unless opposed)	Starts	Stops(unless opposed)
Down	Increases	Immediately	Never
Lateral	Constant	Immediately	Never
Up	Constant	Immediately	Never

b. One Change from Newtonian

Direction	Speed(unless opposed)	Starts	Stops(unless opposed)
Down	Constant	Immediately	Never
Lateral	Constant	Immediately	Never
Up	Constant	Immediately	Never



c. Several Changes from Newtonian

Direction	Speed(unless opposed)	Starts	Stops(unless opposed)
Down	Increases	Suddenly, with time lag	Never
Lateral	Decreases	Immediately	When used up
Up	Constant	Immediately	Never

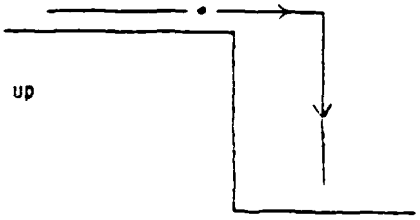
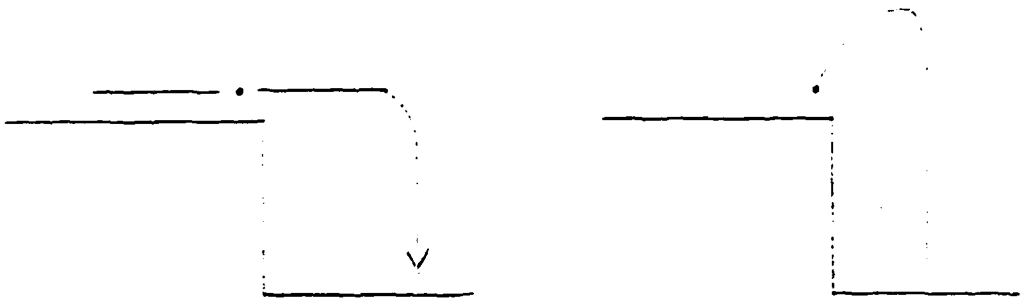


Figure 5, continued

d. A Variation on the Knowledge in c.

Direction	Speed(unless opposed)	Starts	Stops(unless opposed)
Down	Increases	*Gradually, with time lag*	*Never*
Lateral	Decreases	Immediately	When used up
Up	Constant	Immediately	Never



(Horizontal Throw)

(Upward Throw)

(• = point of release)

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