Proceedings of the Annual Meeting of the Cognitive Science Society

Title

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Journal

Proceedings of the Annual Meeting of the Cognitive Science Society, 10(0)

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Publication Date

1988

INTEGRATED COMMONSENSE AND THEORETICAL MENTAL MODELS IN PHYSICS PROBLEM SOLVING

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> *The whole of science is nothing more than a refinement of everyday thinking. It is for this reason that the critical thinking of the physicist cannot possibly be restricted to the examination of concepts of his own specific field. He cannot proceed without considering critically a much more difficult problem, the problem of analyzing the nature of everyday thinking.*
>
> Albert Einstein, quoted in Miller (1986)

Abstract and Introduction

Cognitive Scientists have recently developed models of physicists' problem solving behavior. Their models propose a rich set of cognitive constructs including procedures (Heller and Reif, 1984), problem-solving schemata (Larkin 1983), categorization rules (Chi, Feltovich & Glaser, 1981), phenomenological primitives (diSessa 1983), forward and backward chaining (Larkin, McDermott, Simon, & Simon, 1980), and qualitative reasoning (deKleer, 1975, Forbus 1986, deKleer and Brown, 1986, and others in Bobrow, ed. 1986). These constructs have proved useful in understanding aspects of physics reasoning.

This paper will provide an analysis of physics problem solving skill that integrates cognitive constructs previously considered disparate. The main point is this: *Commonsense reasoning about situations provides an indispensable resource for coping with physics problem solving complexity.* More precisely, I will argue that the systematic integration of the deep structure of situational and theoretical knowledge can reproduce competent physics cognition. To support this claim I will discuss the capabilities of running computer programs, written in Prolog, that implement several representations and reasoning processes. In addition, I will show how the Prolog models capture the essence of a think-aloud protocol of a physicist recovering from an error while working a novel problem.

The Problem Domain

This research concerns a domain of problems like those found in physics textbooks. (See figure 1 for examples.) In these problems, blocks can be connected by strings, and can touch fixed surfaces. All blocks are assumed to have zero initial velocity. Four kinds of forces appear in this domain, gravity, tension, normal forces and "given" forces. In each problem the goal is to find the unknown accelerations, tensions, and normal forces. A generative grammar (table 1) can produce an infinite supply of problems in this domain.

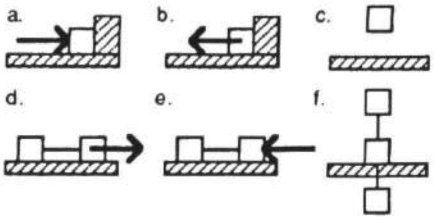

Figure 1: Problems in the Domain

<u>Table 1: Problem Domain Grammar</u>

Problem <- SituatedBlock
Problem <- SituatedBlock, string, Problem
SituatedBlock <- ForcedBlock
SituatedBlock <- surface, ForcedBlock
SituatedBlock <- ForcedBlock, surface
ForcedBlock <- block
ForcedBlock <- force, block
ForcedBlock <- block, force

This domain is interesting because of the difficulties it poses for the theorist. Two levels of complexity in the domain lead to two criteria that a successful theory should meet. The primary complexity resides in the mapping from physical situations to scientific models. Objects like strings and walls do not have a simple representation in Newtonian physics; a first-principles explanation for their behavior can only be expressed in terms of Quantum Mechanics. Physicists, however, approximate interactions involving strings and walls with Newtonian models in order to expedite the solution process. A proposed theory should account for physicists' abilities to reliably generate approximate Newtonian models for observable physical situations.

A secondary complexity arises in the process of manipulating mathematical representations — solving large sets of equations is hard. Consider figure 1f. Eight unknown variables appear in this physical situation, potentially requiring the solution of eight simultaneous linear equations. Yet most physicists could determine all the unknowns precisely while solving only a single equation ($T=mg$ for the hanging block). A physicist might explain this situation by saying something like this:

"I can see that the middle block will be supported by the table, the block above the table will fall, and the block below the table will hang on the string. The acceleration of a supported block or a hanging block is zero, while the acceleration of a falling block is a known constant, $g = -9.8\ m/s^2$. The tension in the top string will be zero because it is collapsing under the falling block. The tension in the bottom string will be enough to balance out gravity. This force can be computed by multiplying the mass, m, and the gravitational constant, g."

Note the prevalent use of concepts like supporting, falling, hanging, collapsing, and balancing in this explanation. diSessa (1983) has argued that concepts like these, called phenomenological primitives (p-prims), provide the deep structure for intuitive physical reasoning. While these concepts are have no formal role in Newtonian science, I will show that they can streamline the solution process.

Representational Framework

The complexities of situation-to-theory mapping and of solving large sets of linear equations together point to the need for a representational framework that integrates multiple representations. I propose the framework illustrated in figure 2, called the "Relational Framework." The Relational Framework comprises a *situational representation* and a *theoretical representation*. This framework builds on representational distinctions developed in McDermott & Larkin (1978) and the use of qualitative reasoning pioneered by deKleer (1975), with two crucial additions:

1. Both representations are mental models. (Johnson-Laird , Holland, et. al., 1896, Gentner & Stevens, 1983)
2. Both mental models can use qualitative reasoning. (Forbus 1986, deKleer and Brown, 1986, and others in Bobrow, ed. 1986)

The situational representation contains the kinds of objects, properties, and relations typically found in real world situations. For example, it might include objects like blocks, tables, and strings; properties like heaviness, roughness, and springyness; and relations like on-top-of, next-to, and touching. P-prims allow for structured explanation of behavior in the situational mental model. Qualitative reasoning allows the behavior in situational mental models to be simulated, generating expectations for future behavior.

The theoretical representation contains the kinds of objects, properties, and relations found in a scientific theory. Since this paper is primarily concerned with simple classical mechanics, the theoretical representation will include point masses, momentum, and forces. The conceptual structure of the theoretical model derives directly from Newtonian Mechanics. Qualitative Reasoning can generate predictions about the behavior of a theoretical mental model using the process of envisioning. (deKleer and Brown, 1986)

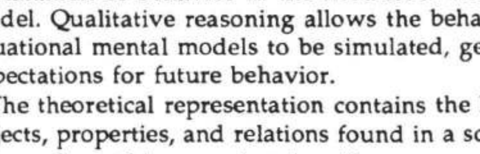

Figure 2: The Relational Framework

The following sections compare the strengths and weaknesses of four models of physics reasoning, each which implements part of the relational framework. The first, the Textbook Solution model (TS) is simple to compute, but lacks the search capability necessary to build the situation-to-theory mapping for all problems in the domain. The remaining three models all use a case analysis search procedure. The Mathematical Case Analysis Model (MCA) can identify a correct theoretical description of a given situation, but leads to an explosion in computational complexity. The Qualitative Theoretical Case Analysis Model (QT) reduces this computational complexity via qualitative reasoning, but often gets trapped in ambiguities. The Qualitative Situational Causal Model (QSC) also reduces the complexity of case analysis via qualitative reasoning, but uses a situational rather than a theoretical representation. While QSC gets trapped in ambiguities less frequently, its knowledge source may contain misconceptions.

These models are presented as competitors to highlight their unique characteristics. However to represent human cognition, several models might be deployed in parallel, as indicated by the parallel envisioning paths in figure 2. A problem solver could exploit the redundancy of parallel models in order to find inconsistencies and trap errors. Alternatively, a problem solver could increase productivity by replacing some mathematical computations with qualitative reasoning. A protocol segment will later illustrate how one physicist integrated Qualitative Situational and Qualitative Theoretical reasoning processes to achieve an efficient and error-free solution.

Textbook Solution Procedures

The Textbook Solution (TS) model allows an examination of the sufficiency of standard textbook problem solving procedures for this domain. Standard textbook procedures *should* be sufficient for this domain, since string tensions and normal forces are part of the standard curriculum.

Textbook procedures share several characteristics. First, these procedures use a series of representations and transition rules. Larkin and McDermott (1978) identify this series as having four representations, words, a situation sketch, a theoretical sketch, and mathematical symbols. Second, textbook procedures examine only the surface features of a situation sketch. Sample surface features in a sketch would be "the blocks are touching" "a block is on a table," and "a string is attached to a block." Third, textbook procedures do not invoke backtracking or retraction of previously derived information. The four kinds of representations, from words to equations, follow a forward progression, in which each later representation borrows from the earlier one, but does not modify it. The exclusion of backtracking and retraction severely limits problem solving capability in this domain.

The Prolog TS model follows the steps below, adapted from Kleppner and Kolenkow's introductory physics text (1973):

1. Identify systems that can be treated as particles.
2. Identify all forces present.
3. Write an instance of Newton's Second Law in the vertical and horizontal directions for each particle.
4. Write an instance of Newton's Third Law for each equal and opposite force pair.
5. Write additional constraints as necessary.
6. Solve the equations, by keeping track of known and unknown variables.

Steps two and four are accomplished using Heller and Reif's (1984) procedure. The TS model follows the first five steps and outputs a set of n equations in n unknowns. These equations could presumably be solved by a computer using an algebraic algorithm. In this case, the author solved them by hand.

The TS model can solve some simple physics problems. However, a large class of simple physics problems exists which the TS model cannot solve. This class of problems includes many problems involving the normal force and string tensions since these forces can only be approximately represented in Newtonian Mechanics. Finding the correct approximate representation requires a search with backtracking capabilities, not provided for in the TS Model.

The TS model, for example, cannot solve the problem in figure 1f because it does not have enough information. (See table 2 for a step-by-step application of the TS model to figure 1f). The missing information is that the top block is falling, that the other two blocks are stationary, and that the top string has no tension. This information could be inferred by a human problem solver using commonsense, however without appropriately integrated commonsense knowledge, the TS model cannot find the correct solution. One way of integrating commonsense will be discussed later in the QSC model. But first, two models that avoid the need for representing commonsense knowledge are introduced.

Table 2: An Application of the TS Model to Figure 1f

1. The three blocks can be treated as particles in this situation.
2. The top block has two forces, the string tension, T_1 and gravity, m_1g. The middle block has four forces, the string tension T_2, the string tension T_3, gravity, m_2g and the normal force, N. The bottom block has two forces, the string tension, T_4, and gravity, m_3g.
3. $-T_1 + m_1g = m_1a_1$
   $T_2 - T_3 + m_2g + N = m_2a_2$
   $T_4 + m_3g = m_3a_1$
4. $T_1 = T_2$; $T_3 = T_4$
5. No additional constraints given.
6. Only 5 equations in 8 unknowns, no solution possible.

Mathematical Case Analysis

As mentioned above, the root cause of the problems with the TS model is that tension and normal forces do not have a simple Newtonian model. Newtonian Mechanics, however, can make predictions in situations involving complex force functions by invoking case analysis.

Case analysis is a procedure commonly taught in engineering disciplines by which a complicated function, like the normal force, is divided into several distinct operating regions, each which can be represented by a simple function. The tension force for an ideal string, for example, can be separated into four operating regions, mainly:

1. string collapsed; distance < length, Tension = 0
2. string collapsing; distance = length, Δdistance < 1, Tension = 0
3. string taut; distance = length, Δdistance = 0, Tension > 0
4. string breaking: distance = length, Δdistance > 0, Tension = maximum load capacity of the string

(Note: The models discussed here actually use a simpler breakdown for the ideal string which ignores the collapsed and breaking states.)

A Prolog model called MCA (Mathematical Case Analysis) uses such decompositions to implement case analysis as a search for a consistent set of linear equations. MCA builds and examines a search tree that represents each possible combination of operating regions for the tensions and normal forces that exist in the system. At each leaf in the tree, MCA generates a representation that assumes each local part of the system is operating in certain regions (or cases). If this representation is globally consistent, then it is a solution. Otherwise that particular combination of operating regions can be eliminated.

To build a scientific representation, the MCA model follows the first four steps of the TS model. In step 5, the MCA model adds a non-deterministic choice of operating region for each normal force and string tension. It outputs a set of linear equations, which are currently solved by hand in step 6. If the equations are inconsistent, MCA backtracks to step 5 and chooses another set of operating regions. Thus if there are *n* complex functions requiring *m* operating regions each, MCA searches a tree with m^n leaves.

Applied to figure 1f, MCA produces the same equations as TS for steps 1-4. In step 5, MCA chooses one of 8 possible sets of operating regions. There are eight sets of operating regions because there are two strings and one normal force, each requiring a breakdown into 2 operating regions, and 2^3 is 8. The resulting additional equations for two of the eight sets of operating regions is shown below in table 3. The first, when combined with the other equations, is inconsistent and must be rejected. The second is consistent, and therefore is a solution.

Table 3: The MCA model, 2 search points for figure 1f

Operating Regions Set A: (inconsistent)
$T_1 > 0, a_1 = a_2;$
$N > 0, a_2 = 0;$
$T_3 > 0, a_2 = a_3$

Operating Regions Set B: (consistent)
$T_1 = 0, a_1 < a_2;$
$N > 0, a_2 = 0;$
$T_3 > 0, a_2 = a_3$

Table 4: The QT model, 2 search points for figure 1f

some equations with operating region A	qualitative form
$-T_1 + m_1 g = m_1 a_1$	$-1 + -1 = a_1$ #
$a_1 = a_2$	$a_1 = a_2 = 0$ #
$T_2 - T_3 + m_2 g + N = m_2 a_2$	$1 - 1 + -1 + 1 = a_2$ *
$T_4 + m_3 g = m_1 a_3$	$1 - 1 = a_1$ *
some equations with operating region B	qualitative form
$T_2 - T_3 + m_2 g + N = m_2 a_2$	$0 - 1 + -1 + 1 = a_2$ *
$T_4 + m_3 g = m_1 a_3$	$1 - 1 = a_1$ *

(# means inconsistent, * means ambiguous)

While this procedure can solve all problems in the domain, it involves solving 8 sets of 8 equations in 8 unknowns. This is a lot of work, even for a computer. Moreover, the MCA model does not support a very satisfying explanation of the solution — the explanation, essentially, is that the computer followed the case analysis procedure and identified a consistent set of equations, which must be the solution because the case analysis procedure is correct. There is no evidence that physicists would use a procedure like MCA to solve this problem.

Qualitative Reasoning, Scientific Representation

The primary virtue of case analysis is that it can bring a situation that includes tension and normal forces into the range of applicability of Newtonian Mechanics. The drawback to case analysis is combinatorial explosion in the number of sets of simultaneous linear equations to be solved. Qualitative Reasoning cannot reduce the combinatorial explosion, however it can reduce the effort involved in checking the consistency of each set of equations.

To apply Qualitative Reasoning to this domain, I follow Reif and Heller's (1982) suggestion to check the consistency of the direction of acceleration predicted by the resultant force with constraints on acceleration. The first step is to make each quantitative $\Sigma F = ma$ equation into a qualitative one. To do this, I replace each quantitative force variable with the number 1 if its sign is positive, and the number -1 if its sign is negative. The left side of the equation is then summed according to the qualitative arithmetic table (Forbus, 1986), yielding a predicted sign for the acceleration. This can be compared with any constraints on the sign of the acceleration.

The QT Prolog model carries these steps out computationally. The first five steps are the same as in the MCA model, however in step six the equations are converted to qualitative form and checked for qualitative consistency. Table 4 shows the result of the QT model applied to figure 1f. The equations with a hash mark (#) are inconsistent, while the equations with an asterisk (*) are ambiguous. The QT model shows operating region A to be inconsistent. However operating region B, found consistent by MCA, cannot be proved consistent by QT because it is qualitatively ambiguous.

The QT model has two major advantages over the MCA model. First, the QT model can identify inconsistent sets of equations without extensive algebraic manipulation — it needs only to compute the sign of acceleration from each instance of Newton's Second Law and compare the result to constraints on the acceleration. The QT model therefore reduces the amount of computation needed to solve a physics problem in this domain. Second, the QT model lends itself to understandable explanations. For example, one could explain the contradiction in operating set A in table 4 as follows:

"There are two forces on the topmost block, gravity and the tension on the string. Since both act downwards, the block will accelerate downwards. However, there can only be tension in the string if the blocks at either end are moving at the same rate. Since the block on the table is not accelerating and the block above it is, the blocks at either end of the string are not accelerating at the same rate. The assumption that there is tension in the string therefore leads to an inconsistent prediction."

The disadvantage of the QT model is that it often yields ambiguous results, as is the case with operating region b in table 4. While the next model, the QSC model can also create ambiguities, it does so less frequently.

Qualitative Reasoning, Situational Representation

All three previous Prolog models share two important characteristics: (1) they operate primarily on a problem representation based on scientific entities like force and mass, and (2) the reasoning in the models is constraint-driven, rather than causal. This section presents the Qualitative Situational Causal (QSC) model. As its name suggests, QSC reasons causally about a situational model. As the Prolog model demonstrates, QSC can make certain crucial inferences more efficiently and effectively than the reasoning components discussed previously.

The QSC model distinguishes between two classes of interactions, *tendency-producing interactions* and *constraint-producing interactions*. (These terms are introduced to avoid confusion between commonsense and scientific use of the word "force.") Tendency-producing interactions (t-interactions) are the ultimate causes of motion. T-interactions have a value that is independent of state of other interactions in the situation. Gravity and given forces are the t-interactions in the present domain.

Constraint-producing interactions (c-interactions), on the other hand, are conditional of the presence of other interactions. The two c-interactions in this domain are string tension and the normal force. These interactions respond to applied forces so as to maintain some state of affairs (a constraint). Strings react to applied forces so as to keep to connected objects at a particular separation. The normal force reacts to applied forces so as to keep one surface from passing through another.

As with the MCA and QT models, the QSC model is based on case analysis. (See table 5.) However, unlike these models the QSC model does not first perform steps 1-4 of the textbook solution model, because the QSC model operates with the situation representation directly.

Like the previous models, QSC non-deterministically chooses and evaluates a set of operating regions, using one choice of operating region for each c-interaction. To evaluate a set of operating regions, QSC checks each c-interaction for local consistency, assuming the other c-interactions fixed.

Each consistency check requires evaluating a statement like "The string is loose, and if the string were not there the blocks on either end of it would not move apart." To evaluate this statement, the QSC model must calculate the motion of the blocks on either end of the string. The QSC model makes the motion calculation qualitatively, and causally. The calculation is qualitative because the QSC model computes only the sign of the acceleration (by using the qualitative arithmetic table to sum t-interactions). The calculation is causal because only t-interactions are included. To eliminate c-interactions from the calculation, propagation rules are applied. These rules in effect say that t-interactions will propagate through taut strings, but not through resisting walls.

Like the MCA and QT models, the QSC model might have to search 8 sets of operating regions to solve figure 1f. Table 6 shows an English translation of the behavior of the model on this problem. Only two sets of operating regions are shown, corresponding to the operating regions chosen in previous examples.

Table 5: C-Interactions For Strings and Surfaces

Surface c-interaction

case a: There is pressure on the block from the surface, and if the surface were not there the block would move through the space occupied by the surface

case b: There is no pressure on the block from the surface, and if the surface were not there the block would not move through the space occupied by the surface.

String c-interaction

case a: The string is taut, and if the string were not there the blocks on either end of the string would move apart.

case b: The string is loose, and if the string were not there the blocks would not move apart.

Table 6: The QSC Model

Operating region set a:
both strings case a, surface case a

1. For the top string, if the string were not there would the blocks move apart? Assuming the string not there, there is only one t-interaction acting on the top block, gravity. The top block will therefore move downwards. The middle block is touching a resisting surface, therefore it is not moving. The blocks are moving closer together, so the answer is no, and this set of operating regions is inconsistent. The other c-interactions do not need to be evaluated.

Operating region set b: top string case b, bottom string case a, surface case a.

1. If the top string were not there, would the blocks not move apart? As in number 1 above, the top block would move downwards, so the answer to this question is yes.
2. If the bottom string were not there, would the blocks move apart? There is only one t-interaction acting on the bottom block, the force of gravity. The bottom block will there move downwards. As in number 1, the middle block will not move. Since the blocks are moving apart the answer is yes.
3. If the surface were not there, would the block move through the space it occupies? There are two t-interactions acting on the middle block, the force of gravity acting on it, and the force of gravity acting on the bottom block, propagated through the taut string. Both are downward so the block would move downward through the space occupied by the surface. The answer is yes.

Since the answer to all three questions is yes, this set of operating regions is consistent.

As table 6 shows, the QSC model can positively identify both inconsistent and consistent operating regions for this problem. Once a set of consistent operating regions is identified, the QSC model can proceed with the textbook solution (TS) model. In step 5, the operating regions discovered by the QSC model guide the addition of suitable constraints. The equations can then be solved for a mathematical solution if desired.

The QSC model fails only when two t-interactions act on the same body, and even then only under certain circumstances. When this failure occurs, it amounts to a failure of the qualitative logic because of an ambiguity. These ambiguities occur less frequently in the QSC model than the QT model, because the QSC model effectively eliminates all c-interactions, while the QT model represents each c-interaction as a force.

In addition, QSC models can fail in the presence of misconceptions. However, diSessa (working paper) has suggested that physicists adjust their p-prims through learning so that the p-prims more accurately reflect causal processes in the world. Thus physicists could apply p-prims without necessarily invoking misconceptions. Moreover, when physicists' p-prim representation is integrated with their theoretical representation, physicists can gain the efficiency of qualitative situational representations, without losing the robustness of theoretical representations.

Protocol Analysis

The models above will now be applied to the analysis of a physicist's think-aloud protocol. This protocol resulted from an interview with a University of California, Berkeley physics graduate student with significant teaching experience. In the interview, the subject was shown the sketch in figure 3, and asked "what's happening." The transcript of his response appears in table 7.

Roschelle and Greeno (1987) includes an extensive analysis of this protocol, the highlights of which are summarized here. In step one, the subject quickly comes to a narrow focus of attention, which is remarkable given that 13 forces would appear in a theoretical representation of the situation. Instead, we conjecture that the subject uses a p-prims and a situational representation. This hypothesis is supported is step 2, when the subject envisions the motion of the situational model. In step 3 the subject builds a theoretical model of the situation, and envisions it. In step 4 the subject recognizes that the results of situational and theoretical envisioning conflict. Finally, in step 5 the subject finds a bug , "friction opposes motion" in his theoretical model and replaces it with a the correct rule, "friction opposes relative motion."

This protocol is an excellent example of the relational framework, because it shows the continuous interplay between situational and theoretical mental models, as well as the role of situational deep structure in coming to a quick focus of attention. It can be modeled quite effectively with elaborations of the QSC, TS and QT models.

Table 7: One physicist's protocol for figure 3

1. This one is very interesting because it illustrates a very important point which is that friction isn't always in the wrong direction -- or the right direction. The thing that bothered me right away is the extra mass sitting here [on top]. And the question is: what's going to happen with the extra mass.
2. Well if there's everything accelerating to the right ,then so will this top mass.
3. And on the other hand , your first temptation is to draw a force diagram in your head and you say 'OK the thing's moving to the right, so friction is to the left.' Except that friction is the only force moving it —
4. — so right away you reach a problem.
5. The answer is ... that friction opposes relative motion, so the friction's going to go in whichever direction it needs to point to oppose the motion between the little mass and the big mass it's sitting on. And that happens to be to the right if the big mass is moving to the right.

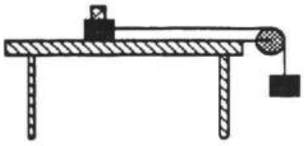

Figure 3: Extra Block Sketch

The QSC model already contains situational reasoning capability for blocks, strings, and supporting surfaces. Two additional rules would be needed to produce the prediction of motion to the right (protocol segment #2). First, a rule is needed to handle the c-interaction of a pulley. This rule would be analogous to the rule that propagates t-interactions through strings. The only difference is that the pulley c-interaction changes the direction of the t-interaction as it goes over the pulley.

A second rule is needed to handle the c-interactions between two blocks that can slide relative to each other. This rule would propagate t-interactions that are parallel to the sliding surfaces through the surface-to-surface contact. This rule models the behavior of friction in transmitting force.

Using these two rules, QSC will predict that the extra block moves to the right, because the only t-interaction on the extra block is the gravitational interaction that has been propagated though the pulley system and the surface-to-surface contact.

In order to generate a theoretical representation, the TS model needs rule for identifying and representing friction. There are two forms of this rule in the protocol, "friction opposes motion" and "friction opposes relative motion." To model the protocol, first one rule and then the other is added to the TS model.

The QT model already has the capability to predict the direction of acceleration based on a theoretical representation. If the friction on the extra block is to the left, QT will predict motion to the left, as in the protocol.

One additional relational component necessary to model this protocol is a procedure that compares the predicted behavior of the QSC and QT models. In this case, the procedure would compare the direction of motion in the situational representation with the direction of acceleration in the theoretical representation. With the buggy friction rule in effect, this comparison will fail. With the correct friction rule in place, this rule will succeed. Table 8 shows the sequence of events corresponding to the protocol.

Notice that the physicist uses multiple representations in two ways in this problem. In protocol line #2, he uses QSC reàsoning to avoid the work of determining the motion of the pulley system via a scientific representation. Later, in protocol line #4, he uses situational reasoning in parallel with scientific reasoning to identify an error. It is especially interesting that in this case the physicist's situational representation was correct while his initial scientific representation was wrong!

Table 8:Computational Model of the Protocol

1. The QSC model predicts motion to the right.
2. The TS model builds a theoretical model using the rule "friction opposes motion."
3. The QT model predicts acceleration to the left.
4. The comparison procedure detects a conflict.
5. The programmer, acting in the place of a complex retrieval process, replaces the buggy friction rule with the correct one.
6. The TS model re-builds the theoretical model.
7. The QT model prediction acceleration to the right.
8. The comparison procedures finds the models to be consistent.

Conclusion

Discussions of p-prims and situational reasoning have generally been restricted to the question, "what's wrong with novices?" The QSC model suggests another question to which p-prims and situational reasoning might be the answer, mainly *"what's right about experts?"* In particular, the Prolog models discussed above have shown that the integration of situational and theoretical deep structure can result in performance that is both efficient and robust. The protocol example is a strong example of efficient and robust problem solving; while the subject analyzes the situation quickly, he is simultaneously able to detect and correct a bug in his theoretical model. The development of parallel situational and theoretical representations, as well as the use of qualitative reasoning, makes expert competence possible without sacrificing expert performance.

Acknowledgements

Thanks to Jim Greeno, Andy diSessa, Peter Pirolli, and Alan Schoenfeld for enthusiasm, ideas, and scaffolding. Thanks also to Susan Newman and others at the Institute for Research on Learning for reading early drafts of this paper.

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