Problem-Based Learning Meets Case-Based Reasoning

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Abstract: The modern education community agrees that deep and effective learning is best promoted by situating learning in authentic activity. Many in the education community have put in place constructivist classroom practices that put students into situations where they must make hypotheses, collect data, and determine which data to use in the process of solving a problem or participating in some kind of realistic analysis or investigation. Research in case-based reasoning (CBR), which provides a plausible model of learning from problem solving situations, makes suggestions about education that are consistent with these educational theories and methodologies and which can provide added concreteness and detail. In this paper, we show how CBR's suggestions can enhance problem-based learning (PBL), which is already a well-worked-out and successful approach to education. The computational accounts CBR provides of reasoning activities, especially of knowledge access, access to old experiences (cases), and use of old experiences in reasoning, suggest guidelines about materials that should be made available as resources, the kinds of reflection that will promote transfer, qualities of good problems, qualities of the environment in which problems are solved (e.g., affordances for feedback), and sequencing a curriculum. The two approaches complement each other well, and together, we believe they provide a powerful foundation for educational practice in the constructivist tradition, one that at once combines lessons learned from classroom practice with sound cognitive theory.

1. Introduction

The modern education community agrees that deep and effective learning is best promoted by situating learning in authentic activity. Anchored instruction, project-based learning, problem-based learning, and other constructivist approaches to classroom practice all focus on putting students into situations where they must make hypotheses, collect data, and determine which data to use in the process of solving a problem or participating in some kind of realistic analysis or investigation (Barrows, 1985; Blumenfeld, et al, 1991; CTGV, 1993; Williams, 1993). Research shows that students participating in these kinds of learning activities are more motivated to learn, that what they learn is more usable than the knowledge learned by students carrying out rote activities, and that they tend to better learn higher order thinking skills than do students in other learning situations (Blumenfeld, et al., 1991; CTGV, 1993; Hmelo, 1995).

Designing such activities well requires an understanding of what needs to be learned and the kinds of experiences that will lead to such learning. But making learning activities work well requires that their use in the classroom be informed by lessons of practice. The classroom is complicated. Social issues, personality issues, capabilities of teachers, the comfort of the classroom, and other issues all play a role in student learning, muddling the best educational designs or allowing poor ones to work despite their weaknesses. Designing effective learning activities thus requires (1) cognitive (and social) theory to provide guidelines about learning, (2) classroom methodology, or lessons of practice, to provide guidelines about operationalization, and (3) trial, analysis, and refinement (Linn & Songer, 1988) over time aimed toward operationalizing the activities well. Logic tells us that the more operational cognitive theories are, the easier it will be to put their guidelines into practice; and the closer the match between the guidelines for learning and the classroom methodology, the more chance that each could contribute toward better understanding of the other.

This logic, plus a desire to put the educational philosophy of case-based reasoning into practice and a need to advise faculty at Georgia Tech about how to help their students learn from problem solving activity, has led us to begin to put into place a marriage between problem-based learning and case-based reasoning. Case-based reasoning (Schank, 1982; Kolodner, 1993), which originated as a methodology for implementing computer programs that could solve problems based on their past experiences, provides a cognitive theory that situates learning in reasoning about real-world situations. The computational accounts it provides of reasoning activities, especially of knowledge access, access to old experiences (cases), and use of old experiences in reasoning, provide suggestions about what makes a good problem, the range of problems students should solve, the kinds of materials and resources students need to use, ways to manage the complexity of hard problems and the kinds of reflection that should be encouraged. Some of CBR's principles have been used to inform the design of stand-alone learning environments (Schank, et al., 1993), but when we wanted to put its principles into practice in classrooms, we found that CBR was lacking in telling us about the teacher's role and other issues of classroom practice. We thus sought an educational methodology that would provide principles of practice to go along with CBR's educational principles.

We chose problem-based learning because of its parallels to case-based reasoning. Problem-based learning (Barrows, 1985) provides a classroom methodology that situates learning in problem-solving activity. It has been in use in medical schools for twenty years and specifies activities of students and teachers that promote learning from problem-solving experiences. It originated from the intuitions of excellent teachers and has evolved into a well-developed system of practice through systematic refinement. Problem-based learning gives reflection on problem-solving activity a central role, and specifies roles for students as researchers who discover knowledge and teachers as facilitators of this constructivist process.

The two approaches complement each other well, and together, we believe they provide a powerful foundation for educational practice in the constructivist tradition, one that at once combines lessons learned from classroom practice with sound cognitive theory. In this paper, we explore how these two views complement each other, presenting each in turn, and then synthesizing them and describing the implications of their synthesis. Each adds to the other; CBR adds reason and specificity to some of PBL's practices and suggests some new ways of accomplishing PBL's goals, while PBL provides for CBR a vehicle for putting its philosophy into practice.

2. Problem-Based Learning: A Model of the Practice of Learning from Problem-Solving Activity

In problem-based learning, students learn by solving problems and reflecting on their experiences. PBL is used substantially at medical and business schools (Barrows, 1985; Williams, 1993). Students learn by solving authentic real-world problems; in medicine, this means diagnosing and managing patient cases. Because the problems are complex, students work in groups, where they pool their expertise and experience and together grapple with the complexities of the issues that must be considered. Coaches guide student reflection on their problem-solving experiences, asking students to articulate both the concepts and skills they are learning, and helping them identify the cognitive skills needed for problem solving, the full range of skills needed for collaboration and articulation, and the principles behind those skills. But coaches do not tell students what to do or show them how to solve problems; rather students decide how to go about solving problems and what they need to learn, while coaches question students to force them to justify their approach and explain their conclusions. In this way, skills needed for life-long learning are also acquired. Research shows that students in problem-based curricula are indeed learning facts and concepts and the skills needed for critical problem solving and self-learning (Hmelo, 1995; Norman & Schmidt, 1992).

In its classical form (Barrows, 1985), students take no classes, but rather work on a series of 100 problems over their first two years of medical school. Small groups of 5-7 students and a coach meet to discuss a patient case. Cases are presented to students in an authentic way; the presenting symptoms (those the patient reports) are first presented to students, and as the students feel they need more information about a patient, they ask for it. A patient record holds all such information and is indexed by questions that traditionally come up in a medical consultation. Problem solving begins with an attempt to interpret what is wrong with the patient; it continues with an attempt to manage the patient's care. Students keep track, on a set of white boards, of facts they know, hypotheses they have about what might be wrong, ideas about treatment, and issues they do not yet understand and need to learn more about (learning issues). They follow a methodology of first, writing down what they know, then generating hypotheses, then identifying the things they still need to find out about the patient and the issues they need to learn more about. After considering the case with their naive knowledge, students divide up the learning issues they have generated among the group and research them. When they get back together, they return to their problem-solving activity, this time using what they have learned through research to move farther forward in their solutions. They reconsider their hypotheses and/or generate new hypotheses in light of their new learning. This cycle continues until students are satisfied that they have solved the problem. They are then presented with the expert opinion on the problem and discuss its pros and cons if different than their conclusion.

3. Case-Based Reasoning: A Cognitive and Computational Model of Learning from Problem-Solving Activity

The term *case-based reasoning* refers to reasoning based on previous experience. It might mean solving a new problem by adapting an old solution or merging pieces of several old solutions, interpreting a new situation in light of similar situations, or projecting the effects of a new situation by examining the effects of a similar old situation. In short, case-based reasoning means using the lessons learned in old situations to understand or navigate new ones. The basic premise underlying CBR is the preference to reason using the most **specific** and most **cohesive** applicable knowledge available. Inferences made using specific knowledge are relatively simple to make. Inferences made using cohesive knowledge structures, i.e., those that tie together several aspects of a situation, are relatively efficient. Cases, which describe situations, have both of these properties. In addition, they record what is possible, providing a reasoner with more probability of moving forward in a workable way than is provided by using general knowledge that is merely plausible. Furthermore, reasoning based on previous experience seems natural in people; an understanding of how it is done well and effectively can provide guidelines for helping people to effectively use this natural reasoning process.

A good example of case-based reasoning comes from architecture. An architect is designing an office building with a long naturally lit atrium in the middle and a circular row of offices surrounding it. She wants the office to get as much light as possible so daytime energy consumption can be minimized. She remembers the design of a library that has no atrium but where the designer solved the problem of bringing in sunlight by constructing exterior walls of glass. She realizes that this solution can be used in the current building -- the office space can be separated from the atrium by a circular glass wall. But upon further thought, she remembers the problems that a courthouse had, in which a glass wall was used in a row of offices with heavy public traffic. While the offices were well lit, the constant presence of the public interfered with the privacy and work of the office workers. The library did not have this problem because the glass wall faced a wooded area. While the first case provides a means of dealing with her new design, the second case, and its difference from the first, alerts her to a potential problem with that solution. Comparing these two cases with the current one, she realizes that the potential for the problem exists, but to a lesser degree. While the atrium is not deserted like the woods, it is not a heavily-trafficked area either. She decides to use the first solution but modifies it slightly by using translucent glass bricks instead of clear plate glass for the wall.

While originally derived to explain reasoning and problem solving, the cognitive model underlying case-based reasoning also provides an explanation of the role memory plays in reasoning -- how memory is accessed during reasoning and how reasoning contributes to changes in the content and organization of memory. Thus, CBR addresses the ways experiences are recalled to be used in reasoning, the use of old experiences in reasoning, and the ways in which new experiences are analyzed, indexed, and stored in memory.

Learning, in the CBR paradigm, means extending one's knowledge by incorporating new experiences into memory, by re-indexing old experiences to make them more accessible, and by abstracting out generalizations from experiences. Thus, a major issue case-based reasoning addresses is *the indexing problem*: identifying old situations that are relevant to a new one. Two sets of procedures allow such recognition to happen: (1) those that operate when cases or experiences are encoded and inserted into long-term memory and (2) those that operate at retrieval time. At insertion time, a reasoner interprets a situation and identifies at least some of the lessons it can teach and when those lessons might most productively be applied. The case is labeled according to its applicability conditions, i.e., the circumstances in which it ought to be retrieved. The most discriminating labels on a case will be derived by a reasoner that has taken the time and effort, and that has the background knowledge, to carefully analyze a case's potential applicability. At retrieval time, a reasoner uses his/her current goals and understanding of the new situation as a probe into memory, looking for cases that are usefully similar to the new one. The extent to which a reasoner is willing or able to interpret the new situation determines the quality of the probe into memory. An uninterpreted situation is likely to yield poorer access to the contents of memory than is one that is more embellished. The more creative a reasoner is at interpreting a situation, the more likely he is to find relevant knowledge and experience to use in reasoning about it.

CBR gives failure a central role in promoting learning. During reasoning, when the reasoner's expectations fail, it is alerted that its knowledge or reasoning is deficient, and a need to learn arises. Similarly, an unsuccessful outcome or solution warns the reasoner of a deficiency and therefore a need to learn. Failure at applying an old case in a new situation triggers explanation that might result in reinterpreting (reindexing) old situations and/or discovering new kinds of interpretations (indexes). Crucial to interpreting failure is useful feedback from the world. A reasoner that is connected to the world will be able to evaluate its solutions with respect to what results from them, allowing indexing that discriminates usability of old cases and allowing good judgments later about reuse.

4. CBR and PBL: A Synthesis

PBL and CBR have much in common. Both point toward a constructivist mode of education, in which one learns by extracting wisdom from one's experiences. Each focuses on different but complementary aspects of the experience. The methodology of PBL asks students to solve problems and then reflect on what they have learned from the experience. The problems students solve serve two purposes: they become cases for use in later reasoning and they are vehicles for learning. Case-based reasoning suggests that learning well from experience requires assessing what lessons an experience teaches and predicting the circumstances when those lessons might be appropriately applied, adding to PBL's call for reflection specificity about what particular things to reflect on. CBR also makes suggestions about the kinds of problem solving experiences a learner should have. CBR suggests furthermore the importance of acquiring feedback on decisions made, in order to be able to identify the holes in one's knowledge.

Overall, there are many areas where CBR and PBL together make more concrete suggestions about educational practice than does either one alone: identifying the qualities of good problems, the kinds of materials and resources that ought to be made available to students as they are generating learning issues, qualities of the environment in which problems are solved, managing the complexity of solving hard problems, encouraging the kinds of reflection that promote transfer, facilitating cognitive flexibility, and sequencing the curriculum.

4.1 What makes for a good problem?

Experiences with medical PBL have led to a number of guidelines about what makes for good problems. In order to learn real-world reasoning skills, problems are purposely complex, ill-structured, and open-ended, lending themselves to several interpretations and/or solutions, and painting a cohesive, holistic view of an issue or situation. This is for several pragmatic reasons, most important in order for students to learn skills and facts in situations of realistic complexity. It is important, also, that problems be realistic, that they resonate with the experiences and knowledge of students, and that they are problems the students want to solve. This is to insure that students will become engaged in the activity and will be motivated to learn, and will be capable of getting started based on what they already know. Also important is that problems are complex enough to have several interrelated parts, all important to a good solution. This is necessary so that the learning issues that students generate are related enough so that they have background, having researched one issue, to understand the explanations of fellow students when they report about other learning issues, and so that, having researched a single learning issue, they have an increased understanding of the problem as a whole. And problems should promote conjecture, argumentation, and peer criticism, by lending themselves to multiple interpretations or solutions, sometimes depending on which of a variety of conflicting perspectives students take on. The intuition here is that collaboration and collaborative learning will work best if students have something to work out together and if they have an authentic need to ask each other to justify their points of view.

Student roles and goals should be made clear in a problem as well. They might be asked to act as physicians and come up with a solution to a problem, as medical students are asked to do, or they may be asked to act as scientists, engineers, or consultants of some kind to create a product or performance (e.g., Barrows & Kelson, 1995; Boud & Felletti, 1991; Ram & Hmelo, 1995), e.g., design an experiment to evaluate some evidence or produce a marketing plan.

An added benefit, if problems fit the criteria listed, is that, in general, they will require students to integrate knowledge from across multiple disciplines. In medical problems, students may deal with anatomy, physiology, and pharmacology in a single case; a chemistry problem might elicit consideration of biology at the same time students are learning chemistry; a design problem might integrate mathematics, life science, and earth science.

CBR adds several things to this already well-articulated list of descriptors, based on its finding that failure is a powerful motivator of learning and that connections with the world that afford feedback are critical to learning. These two findings suggest several things about good problems. (1) The most effective problems for learning will be those where students can acquire feedback along the way that allows them to recognize the holes and misconceptions in their knowledge, refine their knowledge and reasoning strategies, and evaluate the goodness of their knowledge and reasoning strategies. (2) Problems should present difficulties for students, to give them an opportunity to see where the real complexity in situations or domains lies. (3) There is much to learn from situations where problems are not solved correctly or well. Students do not always have to be successful at solving problems, as long as they are learning from the experience. These statements also make a suggestion about the products of problem solving experiences. It is important for the product or performance asked for in a problem to be something that provides the kinds of feedback that allow students to identify issues that need to be addressed or identify holes in their knowledge or reasoning. Of course, if students fail in negative ways, they will give up and lose confidence. It is important, therefore, that difficulties and failures be orchestrated in gentle ways and that students understand their role in learning.

4.2 Materials and resources

PBL tells us that it is important that resources used during early inquiry into a problem supply authentic information about the problem situation and make that information available in an authentic way. The patient case is used for medicine, where patient signs and symptoms and the results of tests are indexed by typical questions asked during a medical examination. For an engineering or design problem, the kinds of materials that would typically be available to a practicing engineer or designer working on the problem need to be made available to learners.

But PBL does not provide all the guidance that might be needed to identify important issues or relevant subgoals. Nor does it identify materials and resources that will help students to solve a problem. Case-based reasoning provides guidelines on these things. Cases recalled during everyday reasoning can serve several purposes. They can point out issues to focus on, suggest solutions to problems, warn of potential pitfalls, support projection of the effects of a chosen solution, and so on. While a person working alone has only his or her own experiences to use as cases to guide reasoning, when working with others, the range of experiences of those in the group can all contribute to reasoning about a situation. The case-based reasoning community has turned this observation into a guideline for using case-based reasoning to help people solve problems: case-based design aids (Domeshek, Kolodner & Zimring, 1994) and other kinds of case libraries (Bell et al., 1993, Kass et al, 1993) store the cases or experiences of others (often experts) for problem solvers to peruse while reasoning. Human reasoners can use such systems to augment their own memories. Had the architect in the example above not known of examples of buildings with good daylight lighting, she would probably have looked in architectural magazines or files to find such examples and reasoned with them as if they were her own experiences. This is typical of the way expert designers get started solving problems; case libraries make such examples readily available.

Case-based reasoning suggests making case libraries available to learners as they are solving hard problems. PBL suggests that the cases in the case library be indexed in ways that will promote identifying issues that need to be addressed to come up with a good problem solution (learning issues) and that will suggest potential solutions or parts of solutions or ways of addressing issues. Case-based reasoning suggests that, in addition, it is important to include cases that can help with projecting effects of potential solutions and to index cases to facilitate such reasoning.

4.3 Managing complexity and promoting successful problem solving

The PBL approach asks students to solve very hard problems. But the methodology also provides ways of managing the complexity and helping students to be successful. Complexity is managed in a variety of ways. (1) Students work together in collaborative groups, pooling their expertise, experience, ideas, and time. Students can build on each others' strengths. Working in groups also promotes learning how to articulate and justify; one cannot work successfully in groups without being able to understand others and to make oneself clear to others. (2) Coaches are trained to help students manage the complexity of problems. They help them to manage their collaborations well, to stay on track in solving problems, and to reflect on their experiences at critical points. Particularly critical to promoting successful problem solving is asking for reflective summaries at times when they feel that it is time to bring together all the disparate pieces of the deliberations. Also critical is helping students draw the connections between learning issues they have identified and the ways in which those learning issues will help them accomplish their problem solving goals. (3) The white boards and the methodology for problem solving that students are taught help them organize their deliberations. White board columns help them keep track of what they know, ideas they have had, and what they still need to do and learn. (4) Students are expected to solve problems only to the level of detail they are prepared to deal with at the time. Thus, they may revisit the same problem early and late in the curriculum and come up with very different solutions.

To this CBR adds several suggestions. (1) Students should learn to carry out case-based reasoning well. It is a natural process, but one that is often done poorly. A major difficulty lies in realizing that suggestions made by cases must be verified. Other difficulties are in recognizing what to focus on, carrying out adaptations, and determining which of several recalled cases might be most applicable. Using CBR well can be learned, we believe, by carrying it out and reflecting on its use, just as PBL does to facilitate learning other cognitive skills. (2) Several kinds of tools to help manage the complexity should be made available to students as they are deliberating: on-line libraries that provide cases of similar situations which help students generate and test issues and ideas, tools for comparing and contrasting cases to each other, and tools for articulating what is important.

4.4 Reflection

Reflection is a major part of PBL activity, and several kinds of reflection are built into its practice. (1) At several points in the case, the students pause to reflect on the data they have collected so far, to generate questions about the data, and to hypothesize about underlying causal mechanisms for the patient's problems. The coach pushes students to reflect in this way when they are having difficulty moving on, in order to bring students back into the discussion who have not been participating, when much has been done and a summary seems in order, and when students believe they are at a transition point. This reflection helps students summarize, helps them recognize where they still need to concentrate efforts, and helps them develop causal models of mechanisms underlying the explanations they are constructing. (2) Before leaving to research learning issues, students discuss how they might go about doing the research and the kinds of resources they might use. When they return, before they go back to solving the problem, they discuss their experiences with those resources. (3) At the conclusion of solving each problem, the facilitator helps the students to reflect on the experience to abstract the lessons they learned. Focus here is on concepts learned, their participation as collaborators and problem solvers and how they might improve, and reasoning used to solve problems, with some additional summary, perhaps, of resource access and use. They might also reflect here on why their solution was different than that of the expert. Reflection helps learners identify what they are learning, turn experiences into cases, and extract causal models from what they are learning; it is used to promote transfer and cognitive flexibility.

Case-based reasoning makes suggestions about accomplishing several of these goals. First, it provides guidelines about what makes a good case and therefore how to help students turn their experiences into cases that will be useful to them in later problem solving. The extent to which an old situation was interpreted determines the extent to which it can be useful. (1) With only a description of a problem situation and its solution, an old solution can be repeated. (2) Knowledge of whether the solution succeeded when applied gives the reasoner a basis for deciding whether or not to reuse an old situation. (3) If, in addition, the reasoner knows what happened as a result of applying the solution, it can make more reasoned judgments (e.g., does that result make sense in my new situation?). (4) If, in addition, factors responsible for the result (success or failure) are known, the reasoner can make even more reasoned judgments (e.g., are the aspects responsible for failure in the old situation present in the new one? If not, the same failure might not recur). CBR's analysis of the quality of cases tells us about the quality of the feedback students need on their decisions and about the depth of the reasoning they should do as they are analyzing each of their experiences.

CBR also makes recommendations about the how to effectively index experiences, especially to promote transfer. Transfer refers to the ability to use knowledge in situations other than those in which it is learned. PBL aims for students to be able to successfully use knowledge acquired during problem solving and to be able to use the complex skills acquired during problem solving in a variety of circumstances. The transfer literature (e.g., Salomon & Perkins, 1989) tells us that transfer requires looking forward at the time of an experience or at the time knowledge is acquired to consider the circumstances in which it might prove useful and looking backward when solving a new problem to consider whether such an experience has been encountered before. CBR's computational explanation of looking forward and backward provides more concrete suggestions about how to look backwards and forward. Looking forward, it suggests, should include identifying what lessons an experience teaches and predicting the circumstances when those lessons might be appropriately applied (Kolodner, 1993). Looking backward involves incrementally making plausible elaborations on a new situation; when such elaboration is not fruitful, attempting to reassess the situation from a different point of view and re-represent it; and when that is not fruitful, using more complicated search strategies to search for related types of situations.

Case-based reasoning also makes suggestions about promoting cognitive flexibility. Cognitive flexibility refers to knowing a concept in its full complexity so as to be able to effectively use it in novel situations. Since a single experience with a concept shows only one way it can be used, cognitive flexibility theory (Spiro, et al, 1988) suggests that concepts be revisited from several points of view. CBR suggests that knowledge will be more accessible, flexible, deeply learned, and accurate if learners have the opportunity to encounter (first hand or by report) multiple situations in which the knowledge is used and multiple ways in which similar situations are addressed, and if students have the opportunity to reuse and try out knowledge gained through experiences. Making case libraries available to learners not only can help them generate ideas and solutions, it can also promote flexibility. Since developing flexibility requires recognizing that a concept used earlier is applicable in a new problem, CBR suggests that problems be written in such a way that they promote reminding of earlier problems in which the same concept was used and that coaches help students notice that concepts are being reused and abstract from the range of ways in which the concept is encountered.

4.5 Sequencing the curriculum

When PBL is used most effectively, it provides the curriculum (Barrows, 1985). Thus, it is important that problems cover the material that the curriculum needs to cover. As the discussion above points out, for purposes of developing an authentic understanding of concepts, flexibility, and transfer, problems that form a curriculum should be chosen so that key concepts are visited over a number of cases. Case-based reasoning adds to that a suggestion about what coverage means (Kolodner, 1993). Providing coverage in a problem solving domain means that students should encounter typical problems in the domain, typical solutions, typical situations in which each problem and solution occur, typical reasoning pitfalls, and several important atypical situations as well.

5. Implications

Merging PBL and CBR has several implications. First, it suggests ways to refine PBL to aim toward better learning. Second, this analysis plus analysis of why PBL works (e.g., Hmelo, 1995) can contribute to an understanding of how to move PBL to new environments. PBL was developed for professional education, where students are mature reasoners already, and where solving problems is the entire curriculum. Changes in practice are needed if students are doing PBL as only one course, if students are less mature reasoners, and if there is no homogeneity among students in terms of their life goals and interests. To move PBL to such environments, there's a need to understand the cognition behind its essential features. Third, the combination of PBL and CBR makes several suggestions about the design of software to facilitate learning from problem solving activity. The analysis we've done suggests several functions the software should have. (1) It needs an environment for keeping track of problem solving deliberations. PBL suggests that this be done on white boards. Electronic white boards have the added advantage of allowing connections to be marked between items in the different columns, and, in general, allowing connections to be made between white board entries and their justifications and other products of deliberations. (2) Case libraries should be available in the environment. (3) The software environment might provide the same kinds of scaffolding of problem solving that coaches support. This is especially important for situations in which facilitators are not available for individual work groups. (4) It might also provide scaffolding of the kinds of reflective activity that encourage transfer. Looking forward, for example, might be facilitated by asking students to create electronic cases based on their experiences to help others solve later problems. We are aiming toward implementing these principles in McBAGEL (Narayanan, et al, 1995), our experimental software environment. We are piloting the environment, along with refined PBL practices and problems we have developed, in several middle school and undergraduate classes in winter and spring, 1996.

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