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Integrating Case-Based and Model-Based Reasoning

A Computational Model of Design Problem Solving

Ashok K. Goel

My Ph.D. dissertation (Goel 1989)[1] presents a computational model of experience-based design. It first reviews the core issues in experience-based design, for example, (1) the content of a design experience (or case), (2) the internal organization of design cases, (3) the language for indexing the cases, (4) the mechanism for retrieving a case relevant to a given design task, (5) the mechanism for adapting a retrieved design to satisfy the constraints of the design task, (6) the mechanism for evaluating a design against the specification of the design task, (7) the mechanism for redesigning a failed design, (8) the mechanism for acquiring new design knowledge, (9) the mechanism for chunking information about a design into a new case, and (10) the mechanism for storing a new case in memory for potential reuse in the future. It then proposes that decisions about these issues might lie in the designer's comprehension of the designs of artifacts he/she has encountered in the past, that is, in his/her mental models of how the designs achieve the functions and satisfy the constraints of the artifacts.

To elaborate and evaluate this proposal, the dissertation analyzes the design of physical devices such as simple electric circuits, heat exchangers, and angular momentum controllers. It develops a theory of designers' comprehension of device designs in terms of functional models of how devices work. The functional model of a device provides a causal explanation of how the structure of the device produces its functions. The dissertation then describes how the theory of functional models gives rise to principled answers to many basic issues in case-based design. It also describes the KRITIK system, which instantiates and simulates this computational model.[2]

Physical Devices

A *physical device* is a physical artifact with (output) intrinsic functions and (internal) causal behaviors that result in the functions. My dissertation focuses on the design of physical devices whose intrinsic function is to transform a given behavioral state into another given behavioral state when a stimulus is supplied from the environment. The design task in this domain takes as input a specification of the transformation function that is desired of a device. It has the goal of giving as output a specification of a structure for the device that can deliver the desired function. The dissertation focuses on the conceptual (or preliminary) phase of this task. The conceptual phase of the design process pertains to the generation (and evaluation) of a high-level qualitative design for the device.

Functional Models

The theory of functional models is developed in two steps. The first step focuses on the content of functional models. The *functional model* of a device explicitly represents the intrinsic functions and the causal behaviors of the device. This explicit representation of the functions and behaviors is necessary for indexing design cases in memory and retrieving cases relevant to a given task, assigning blame when a design fails to deliver the function desired of it, and guiding the simulation of the modified design in the evaluation phase. Based on Bylander and Chandrasekaran (1985), the dissertation adopts a component-substance ontology of physical devices. In this ontology, the device-independent functions of primitive components of the domain are viewed in terms of their interactions with abstract substances. The structure of a device is viewed as constituted of components, substances, and relations among them; the behavioral states of the device are viewed in terms of the properties of substances and components at specific points in the device space and time; the intrinsic functions are viewed as transformations from one behavioral state to another; and the causal behaviors are viewed as a sequence of behavioral state transitions that compose the interactions among the components and the substances in the device structure into the functions of the device as a whole.

The second step in the development of the functional model focuses on its organization. The dissertation presents a behavioral representation language for organizing the functional model of a device. Based on Sembugamoorthy and Chandrasekaran (1986), the device functions in this representation act as indexes to the causal behaviors responsible for them. A state transition in a behavior acts as an index to the causes responsible for it (for example, a function of a component, another device behavior), enabling conditions (for example, a structural relation), and deeper domain knowledge governing the transition (for example, physics principles, qualitative equations). Because the device functions act as indexes to causal behaviors, and the behaviors act as indexes to the functions of device components, this representation provides a hierarchical decomposition of the

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device. This decomposition is needed to focus the processes of credit assignment and qualitative simulation.

Case Memory

A design case in KRITIK specifies (1) a previously encountered problem in terms of the functions desired of the device, (2) a solution to the problem in terms of the structure for the device, and (3) a pointer to the functional model for the design. Thus, design cases act as indexes to design-specific functional models and the models provide a functional decomposition of the cases. The cases themselves are indexed by the functions delivered by the stored designs. The behavioral representation language provides the vocabulary for representing a design function. Given the specification of the functions desired of a device, this language enables KRITIK to compare the content of the desired functions with the content of the functions delivered by the stored design cases and, thereby, to retrieve design cases that can deliver functions similar to the desired ones.

Credit Assignment

KRITIK views design adaptation as a kind of credit-assignment task. That is, it views the known design as having failed to deliver the desired functions, assigns blame for this failure by identifying the structural faults responsible for it, and generates proposals for repairing the faults. It uses four types of knowledge for solving this credit-assignment task: (1) the functional model of the known design, (2) a taxonomy of design failures, (3) a taxonomy of design repairs, and (4) a family of design-modification plans. The taxonomy of design failures corresponds to the types of differences that can occur between the function delivered by a design and the function desired of it. The taxonomy of design repairs corresponds to the types of modifications that can be made to the structure of a design. Both taxonomies arise from the component-substance ontology. A *modification plan* is a specialized search procedure that specifies an ordered sequence of abstract operations. The modification plans are indexed by the type of differences between the desired and delivered functions they can help to reduce, and each plan knows of the (abstract) types of structural modifications that can help to reduce the functional difference to which it is applicable. Given a functional difference, KRITIK retrieves the modification plan applicable to it and instantiates the plan in the context of the functional model of the known design. The instantiated plan traces the causal behaviors of the model to identify specific structural modifications that can reduce the given functional difference. The explicit representation and the hierarchical organization of the model help to focus the process of credit assignment.

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Model Revision

KRITIK evaluates the proposed modifications by a variation on the method of qualitative simulation. Because KRITIK cannot assume a representation of the modified design, it acquires the causal behaviors of the modified design by revising the behaviors of the original design instead of deriving them from lower-level representations. It uses a family of model-revision plans for this task, where the revision plans correspond to KRITIK's taxonomy of design repairs and are indexed by (abstract) types of structural modifications. Given a proposed structural modification, KRITIK retrieves the model-revision plan applicable to it and instantiates the plan in the context of the known functional model of the original design. The instantiated plan determines the behavioral constraints that the given modification generates and propagates them through the model of the original design to obtain the causal behaviors of the modified design. Again, the explicit representation and the hierarchical organization of the model help to focus the process of constraint propagation. Thus, a method for incremental learning of qualitative models is provided.

Redesign Cycle

Next, KRITIK qualitatively simulates the modified design by tracing the revised causal behaviors. If the simulation determines that the proposed design results in the functions desired of it, then KRITIK chunks the modified design and the revised model into a new case, indexes it by the functions delivered by the design, and stores it in its memory for potential reuse in the future. Otherwise, KRITIK enters a propose-evaluate-redesign cycle in which it abandons failed structural modifications, generates new ones, evaluates them, and so on. If KRITIK cannot generate alternative structural modifications, then it abandons the old design case altogether, retrieves another one, and attempts to adapt it.

Experimental Evaluation

The dissertation reports the results of a small set of experiments that evaluate KRITIK for the design of simple physical devices. KRITIK takes as input the specification of a transformation function that is desired of a device in the form of the behavioral states the function takes as input and gives as output. The system gives as output the specification of the structure for the device in the form of modifications to the structure of a known device and the functional model for the modified design. KRITIK contains 10 design cases and corresponding functional models in 2 domains: electrical circuits and heat exchangers.[3] It started with six design cases and corresponding models and automatically acquired the other four cases and models as it solved new design problems in the two domains. The four experiments with KRITIK show that it can retrieve and adapt design cases even when the desired function differs from the functions delivered by known designs in several features. They also show that KRITIK can revise functional models and evaluate new designs even when the structure of the new design differs from the structures of known designs in several features. In addition, the experiments show that KRITIK can reuse newly acquired design cases and functional models for solving still newer problems. The validation of KRITIK for the design of both electrical circuits and heat exchangers helps to ensure that its knowledge representations and reasoning methods have some generality.

Related Research

The dissertation also discusses the relationship between my work and previous research in three areas: design problem solving, case-based reasoning, and model-based reasoning. In the context of design problem solving, it compares KRITIK's approach with other approaches such as heuristic association (McDermott 1982) and plan selection, instantiation, and refinement (Brown and Chandrasekaran 1989). It argues that although other approaches are useful for solving small routine design problems, the case-based approach offers significant computational advantages for complex innovative design. In the context of case-based reasoning, it compares KRITIK with other case-based AI systems such as MEDIATOR (Kolodner and Simpson 1989) and CHEF (Hammond 1989). It argues that integrating case-based and model-based reasoning can significantly enhance the capabilities of case-based AI systems. Finally, in the context of model-based reasoning, it compares KRITIK's method with other methods for qualitative simulation, for example, solving simultaneous qualitative differential equations (deKleer 1984; deKleer and Brown 1984). It argues that explicit representation of functions and causal behaviors of a device can provide indexes to lower-level representations of the device in the form of equations. It further argues that revising known models to acquire new models is an attractive alternative to run-time derivation of the new models from lower-level representations.

Conclusions

My dissertation shows that case-based reasoning is a productive approach for conceptual design problem solving. By reusing old designs that solve similar problems, the case-based approach can often transform apparently innovative and complex conceptual design tasks into relatively routine and simple parametric modification tasks. It develops a theory of functional models of physical devices, which gives rise to a theory of the content, organization, indexing, and modification of design cases. Finally, it shows that model-based reasoning provides powerful mechanisms for retrieving, adapting, and evaluating design cases and that case-based reasoning provides a powerful mechanism for incremental learning of functional models.

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Notes

1. Copies of this dissertation can be obtained from the librarian, Laboratory for Artificial Intelligence Research, The Ohio State University, Columbus, OH 43210.

2. *Kritik* is a Sanskrit word that roughly translates to "the designer."

3. KRITIK2, a more recent version of KRITIK, contains about twice as many cases and models from the domains of electric circuits, electromagnetic devices, heat exchangers, and angular momentum controllers.

References

Brown, D., and Chandrasekaran, B. 1989. *Design Problem Solving: Knowledge Structures and Control Strategies*. London: Pitman.

Bylander, T., and Chandrasekaran, B. 1985. Understanding Behavior Using Consolidation. In Proceedings of the Ninth International Joint Conference on Artificial Intelligence, 450–454. Menlo Park, Calif.: International Joint Conferences on Artificial Intelligence.

deKleer, J. 1984. A Qualitative Physics Based on Confluences. *Artificial Intelligence* 24:205–280.

deKleer, J., and Brown, J. 1984. A Qualitative Physics Based on Confluences. *Artificial Intelligence* 24:7–83.

Goel, A. 1989. Integration of Case-Based Reasoning and Model-Based Reasoning for Adaptive Design Problem Solving. Ph.D. diss., Dept. of Computer and Information Science, The Ohio State Univ.

Hammond, K. 1989. *Case-Based Planning: Viewing Planning as a Memory Task*. Boston: Academic.

Kolodner, J., and Simpson, R. 1989. The MEDIATOR: Analysis of an Early Case-Based Reasoning System. Cognitive Science 13(4): 507–549.

McDermott, J. 1982. R1: A Rule-Based Configurer of Computer Systems. *Artifi-*

cial Intelligence 19:39–88.

Sembugamoorthy, V., and Chandrasekaran, B. 1986. Functional Representation of Devices and Compilation of Diagnostic Problem-Solving Systems. In *Experience, Memory, and Reasoning*, eds. J. Kolodner and C. Riesbeck, 47–73. Hillsdale, N.J.: Lawrence Erlbaum.

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