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WORKSHOP REPORT

The First Workshop on Blackboard Systems

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The emergence of the blackboard architecture as a widely used paradigm for problem solving led us and other members of the blackboard research community to organize a workshop. The workshop was held during the 1987 American Association for Artificial Intelligence Conference in Seattle. The main purpose of the workshop was to highlight the advances in blackboard architectures since the introduction of the paradigm in Hearsay-II and identify issues relevant to future blackboard system research. This article describes the issues raised and the discussions in each of the five workshop panels.

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The First Workshop on Blackboard Systems, sponsored jointly by the American Association for Artificial Intelligence (AAAI) and the Boeing Advanced Technology Center, was held 13 July 1987 during AAAI-87 in Seattle. A group of researchers from industry and academia gathered at the University of Washington to discuss issues and research directions in blackboard systems. It was the first blackboard workshop open for participation to the general AI audience.

Since its inception with the Hearsay-II project in the early 1970s, the blackboard architecture has undergone major changes, as discussed in Nii (1987). Because interest in this technology is growing rapidly and blackboard systems differ significantly in their implementation, the organizers determined a need for a workshop in order to improve communication between the various researchers in this field, achieve a consensus on the defining characteristics of blackboards, and describe ongoing research. With these motivations in mind, the workshop was organized as a series of five panel discussions, each concerned with one of the most relevant areas of interest: (1) blackboard architecture and organization; (2) control issues; (3) parallelism, concurrency, and distributed systems; (4) performance and real-time issues; and (5) development environments.

The format of each panel was determined by the moderator. In general, the moderator laid out the issues pertaining to the area and encouraged the panel members to present their perspectives. The panel members discussed the issues in the context of their own work. Their presentations were followed by discussion with the workshop participants. Highlights of the discussions follow.

Blackboard Architecture and Organization

The first panel was primarily concerned with identifying the architectural and organizational attributes that distinguish blackboard systems. As more and more systems appear claiming to use the blackboard paradigm, it is increasingly necessary to determine a set of criteria that define the essential elements of blackboard systems. This panel was also concerned with the question of how far systems can deviate from the basic blackboard architecture and still rightly be classified as a blackboard system. Penny Nii moderated this panel.

The consensus was that the essential components of a blackboard system are the blackboard database and the knowledge sources. The *blackboard database* is the repository of information, and the *knowledge sources* represent the procedural knowledge that uses and manipulates the blackboard data structures. Also inherent in a blackboard architecture is the knowledge-oriented selection mechanism, or metalevel control, for choosing the next knowledge source to be executed. These criteria can be used to determine whether a system can indeed be called a blackboard system. However, differences in implementation, especially where control mechanisms are concerned, are to be expected because of the influence of special problem-solving requirements of particular applications.

Appropriately, this panel began with Robert Engelmore's presentation of the history and evolution of black-

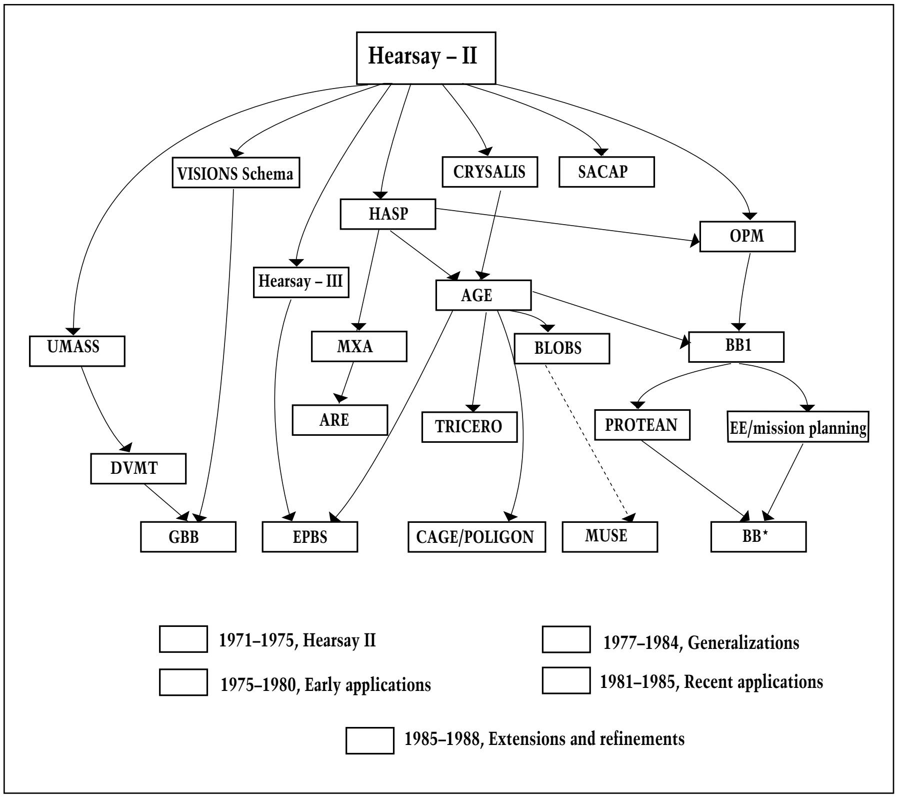

Figure 1. Evolution of Blackboard Systems.

Adapted from *Blackboard Systems,* eds. R. Engelmore and T. Morgan, Wokingham: Addison-Wesley.

board systems. As figure 1 shows, Hearsay-II was the first blackboard system from which all current blackboard systems have evolved, with AGE playing a major role in this evolution. Mark Williams outlined features in terms of capabilities for data and knowledge organization, knowledge-application strategy, and problem-solving strategies. Roberto Bisiani raised issues of knowledge source granularity; asynchronous versus synchronous knowledge sources; objects, frames, or databases with query languages for blackboard data structures; and architectures for research and development versus production blackboard systems.

Mitchell Potter discussed the characteristics that make a problem a good blackboard application. Well-known characteristics include reasoning with incomplete and inconsistent information and a requirement for different reasoning methodologies or the communication between heterogeneous problem-solving components. This last characteristic has influenced the use of blackboards as software engineering tools. Vasudevan Jagannathan added to this list and indicated that blackboard systems facilitate the control of problem solving by using control heuristics, exploring multiple hypotheses in parallel, and reasoning at multiple levels of abstraction. Sarosh Talukdar discussed his experiments in organization using the Distributed Problem-Solving Kernel (DPSK) at Carnegie-Mellon University.

Control Issues

An integral component of a blackboard system architecture is the notion of *opportunistic problem solving*—the capability of applying the right expertise at the most opportune moment. Controlling the problem-solving activity to make sensible progress toward the system goals and focusing attention on the most credible paths are crucial to system coherence as well as system performance. Coherence is critical if blackboard applications are to explain their actions satisfactorily. Strong evidence exists that achieving these goals more than offsets the overhead associated with control (Hayes-Roth 1985).

The different representations of control knowledge depend on the nature of the implementation. Implementation of control can be goal directed, data directed, operator directed, or plan directed. Alternative control architectures range from pattern-directed control as in OPS, event prioritization as in AGE, procedures as in Hearsay-II, metalevel plans as in the Distributed Vehicle Monitoring Testbed (DVMT), and an explicit and layered control blackboard as in BB1. Some issues raised by this panel were control in a parallel environment and the cost associated with control in a real-time environment.

Following the introduction of these issues by Barbara Hayes-Roth, who moderated this panel, Victor Lesser described his experiments using approximate processing for metalevel control based on an explicit understanding of the state of the problem solver. Philip Johnson discussed the implementation of the BB1 control regime on top of the Generic Blackboard System (GBB) kernel. Vaughan Johnson discussed experiences with BB1-style control. Gerard Mayer presented a signal-understanding system which uses knowledge clusters to organize domain and control knowledge for greater execution autonomy and which has the ability to adapt to a distributed environment. Duvvuru Sriram discussed a Smalltalk-based blackboard system developed at the Massachusetts Institute of Technology. Terry Weymouth discussed an image-understanding system that requires intelligent control in a dynamic environment.

Parallel, Concurrent, and Distributed Blackboard System Issues

The interest in parallel and distributed computation that is evident in other AI fields is shared by researchers of blackboard systems. The Hearsay-II architecture was originally conceived as a parallel architecture. Early experiments by Fennell and Lesser and the development of DVMT at the University of Massachusetts by Lesser and Corkill raised various issues related to parallelism and organization in distributed blackboard systems. Significant advances in multiprocessor architectures have provided new impetus for work in this area, and a flurry of activity has taken place in parallel and distributed blackboard systems.

This panel, moderated by Harold Brown, addressed justifying the implementation of a blackboard system in a distributed or parallel environment and determining the appropriate blackboard architecture for such an implementation. Because most of this work is in its preliminary stage, the panelists discussed specific research projects. Anthony Stentz discussed the CODGER system, which is used for outdoor mobile robot navigation, at Carnegie-Mellon University. The blackboard integrates the various subsystems and expert systems and is mainly responsible for dispatching messages and synchronizing in a heterogeneous environment. A robot cell control system, presented by Hugo Velthuijsen from Neher Labs, the Netherlands, uses a simulated multiprocessor environment. In addition to selecting appropriate knowledge sources, the control blackboard matches the processor to the knowledge source as part of its activity.

Issues raised by Edwin Addison in describing a distributed sensor net system at Westinghouse Electric Corporation include appropriate partitionings for the blackboard database, communication bottlenecks across processors, measurement of effectiveness, and exploratory development versus structured design of the blackboard system. The Advanced Architectures Project at the Stanford Knowledge Systems Laboratory is investigating the applicability of parallel architectures to achieve speedups of orders of magnitude in expert system applications. The project's work, presented by James Rice, involves investigating the issues using blackboard system applications running in a simulated parallel architecture.

Calvin Ling gave an overview of the AI Chipset Project at Boeing Electronics High Technology Center, which is investigating the feasibility of implementing some of the blackboard functions in hardware. Ling presented a preliminary hardware design and discussed the issues that influenced the design. These issues included (1) blackboard access and triggering and the need to perform knowledge source execution on dedicated processors, (2) agenda maintenance, (3) scheduling in a pipelined fashion with possible replication, and (4) the need for using the architecture in embedded applications. Tom Skillman, with the same project, described an intelligent control application as a test bed for the AI chipset.

Performance and Real-Time Issues

Dan Corkill, the moderator of this session, began by examining the range of criticisms of blackboard systems. Some critics claim blackboard systems are too slow for real-time and time-critical AI applications, others claim they are too slow for anything other than prototyping applications, and still others go so far as to say they are too slow to be useful at all. The rejoinder to these criticisms is that today's blackboard architectures are, in fact, fast enough. Also, the performance of applications can be made acceptable by using more sophisticated blackboard database and pattern-matching machinery, control knowledge, incorporating concurrent activity by way of multiprocessor or distributed networks and employing specialized hardware (for example, a blackboard machine). Dan Corkill urged the panelists to examine these criticisms and observations in the context of their own work. Of particular interest were the system enhancements required to achieve improved performance.

In general, the panel discussion focused on what the alternative performance criteria are, such as fastest solution time, best answer within available time, least inappropriate problem-solving activity, and how these criteria can be measured. Most panelists described performance improvements and efficiency considerations attempted at the blackboard-tool level to support particular applications. It was agreed that the lack of accepted performance metrics must be rectified.

The presentation by Michael Wilber on the Heuristic Control Virtual Machine (HCVM) indicated how execution efficiency could be improved at the blackboard-tool implementation level for improved performance at the application level. Rajendra Dodhiawala discussed the performance benefits derived from Erasmus' ability to be configured to the needs of the application. Peter Raulefs addressed the relevance of real-time and time-critical performance and how it influenced the design of HCVM. John DeLaney discussed performance issues related to a signal-mode understanding application as part of the Advanced Architectures Project at Stanford University. Alan Garvey presented results of BB1 experiments showing conclusively that the benefits of control reasoning outweigh its overhead in the PROTEAN system, leading to improvements in system performance. Ching-Huei Wang presented a framework for object recognition that includes a formalism for estimating the utility of knowledge sources. He discussed the results of performance analysis of an address-block recognition system for mail sorting using the framework.

Development Environment Issues

The primary concern of the final panel was the identification of the development tools that are desirable for building blackboard applications; that is, what features a robust blackboard development shell should provide. Because most of the blackboard shells discussed are built on sophisticated workstations and utilize frame-based or object-oriented technology, they provide capabilities found in more general-purpose shells, such as incremental development facilities and graphic display of knowledge bases. Beyond these generic features, however, blackboard application development is greatly enhanced by capabilities tailored to the special nature of the architecture. The different shells discussed vary considerably in the sophistication of the environments provided and emphasize different aspects of the user interface. For example, BB* reflects a heavy emphasis on explanation capabilities; Erasmus provides sophisticated trace and debugging capabilities, as well as reconfigurability; and ATOME provides support for temporal reasoning. Other capabilities that enhance development are support for frame-based representations, truth maintenance systems, mechanisms for enforcing consistency, and performance-metering tools.

Richard Fikes described OPUS, a set of building blocks for developing a blackboard shell. Joshua Levy described BBC, a flexible tool written in C on Unix for generating a blackboard system tailored to a set of specifications. Stefan Roth presented the Generic Expert System Tool (GEST), a blackboard tool with features such as truth maintenance, temporal reasoning, and knowledge base consistency checking. Hassan Laasri presented ATOME, a blackboard tool with capabilities for temporal reasoning. Michael Hewett discussed BB1 from a software-engineering viewpoint. He explained the various features of BB1, such as explanation, user interface, and uniform data representation. Larry Baum presented Erasmus' development environment, which is built on top of an object-oriented language. The features of this environment include multiple representation schemes such as Knowledge Engineering Environment (KEE), the Boeing Frame System, and KnowledgeCraft; incremental development; and extensive trace and postrun diagnostic capabilities. This panel was moderated by Lee Erman.

Conclusions

The intent of this first blackboard workshop was to come to terms with the major issues relevant to further research and development of blackboard systems. The popularity of blackboard systems is increasing rapidly, and a demand exists for capabilities that lay the groundwork for innovative ideas. The blackboard community must recognize these demands and anticipate the evolution of other technologies, such as parallel computers and heterogeneous environments for knowledge processing systems. Each of the panels dealt with an area of considerable activity, and the implications of work in all the areas need to be considered in assessing progress in this field.

Based on feedback received from the workshop attendees, the following assessment of the workshop emerges: The workshop provided an excellent opportunity to gain a clearer understanding of the volume and diversity of ongoing blackboard research and to become better acquainted with fellow researchers. However, many attendees wished that more time had been set aside for discussion. It was felt that having fewer panels would facilitate this discussion. Some suggestions were also made that presentations by the panelists be abbreviated somewhat.

The second workshop, held during AAAI '88, incorporated the feedback we received from the participants of the first workshop. We planned to have fewer panels to allow more time for discussions. This format was consistent with the intent of the workshop: to focus on the exchange of interesting ideas.

Some of the papers presented at the workshop are included in a forthcoming, edited volume describing recent work in blackboard architectures and applications. For more information about this book, or a list of workshop attendees and papers presented, contact Rajendra Dodhiawala at FMC Central Engineering Labs, 1205 Coleman Avenue, Santa Clara, CA 95052.

Acknowledgments

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Thomas L. Skillman, Jr. is a research scientist in the Symbolic Processing Laboratory at Boeing Electronics High Technology Center in Seattle, WA. He is currently developing a blackboard-based hierarchical control system for mobile robots and works with a team designing a custom hardware multiprocessor system for real-time blackboards. Skillman's research interests include intelligent control system architecture, adaptive declarative control, mobile robotics, artificial neural network-based processing, and custom hardware design to support intelligent system implementation.