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A KNOWLEDGE-BASED APPROACH FOR TIMBER CONNECTION DESIGN

by

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SUMMARY

The complexity of the current timber connection design process is one of the major reasons preventing the wider use of wood products in low-rise non-residential and innovative residential construction. Connections of members in structures, particularly in timber buildings, require the combination of both quantitative and qualitative aspects of design to produce a safe and aesthetically pleasing structure. Knowledge-based expert systems offer designers access to the full range of design methods, allowing the connection design task to be completed with ease and confidence. This study investigates the expert system approach by constructing a framework for such a design aid — a framework that incorporates techniques from artificial intelligence, architecture, and engineering. The design aid has potential for industrial application, and could be developed into an educational tool for timber and wood product design courses at the university level.

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1.0 OBJECTIVE

The objective of the work carried out in this project is to develop an expert system that integrates architectural and structural design issues for timber connections and thus provides design alternatives for user-prescribed design requirements.

2.0 INTRODUCTION

Professionals in the building industry acknowledge that one of the biggest challenges in structural timber design today is the task of joining structural members made of wood or engineered wood products. The problems that arise in designing these connections demand an approach that incorporates knowledge from the fields of architecture, engineering, and materials science.

In response to this need, a unique research program into the design of timber connections has been jointly initiated by Forintek Canada Corp., the University of British Columbia (UBC) Department of Civil Engineering, and the UBC School of Architecture. This research program began in 1989, when a Forintek Canada Fellowship in Timber Engineering was established at UBC. In 1993, the Canadian Forest Service, the Natural Sciences and Engineering Research Council of Canada, and UBC entered into a three-year partnership program with Forintek Canada Corp. to further the research effort. The research was carried out jointly at the UBC Department of Civil Engineering and the Western Laboratory of Forintek Canada Corp. The research partner from UBC was Professor S.F. Stiemer, and the investigation became the subject of a doctoral thesis undertaken in the Department of Civil Engineering, in collaboration with Dr. E. Varoglu at Forintek as research co-adviser. The Ph.D. candidate working under Professor Stiemer was Taylor. This research program has also provided research projects for two other graduate students in the Department.

3.0 BACKGROUND

In a timber frame building, the structural components include beams, girders, columns, floor, roof, and wall systems. Each component must be connected with the others in a way that suits the expected function of the structure and often the aesthetic theme of the building, as well as providing structural safety. In many cases, the performance of the building is governed not only by the characteristics of structural components, but also by the way these components are connected together. Hence, connections in timber buildings are critical within the total building design process.

Market studies have identified that one of the major impediments to expanded use of wood products in low-rise non-residential construction is the complexity and cost of the current practice in timber connection design (Crowley 1993). A computer-automated, knowledge-based approach for timber connection design presents an excellent opportunity to formalize knowledge in this area, as well as to facilitate architectural and engineering design with a traditional building material from a renewable resource.

Dym and Levitt (1991) provide an overview of several knowledge-based approaches to engineering design. Described below are three of these approaches and their suitability for timber connection design: configuration model; case-based design; and pure selection approach.

The Configuration Model. The configuration model approach for design involves the hierarchical generation, testing, evaluation, and elimination of design solutions. It has been successfully used to configure VAX computers at the Digital Equipment Corporation (Barker and O'Connor 1989; McDermott 1982). The advantage of this approach is that the new design problem need not be specified completely. Heuristics in the form of good engineering practice can be readily incorporated into the evaluation process of candidate solutions. The configuration approach can also be adapted with ease to take advantage of new engineered wood products, hardware, and fasteners in timber connection designs.

Case-based Design. The case-based design approach is used for landscape design (Navinchandra 1988) and for the design of small mechanical and electrical devices (Goel and Chandrasekaran 1989). In this approach, a library of connection prototypes can be the starting point for solving a timber connection design problem. Heuristics can be used for selecting one of the prototype solutions as a candidate for providing a framework for the design problem under consideration. A series of attributes of the candidate solution are tested and those attributes that fail to satisfy the constraints of the new design problem are modified. This approach is especially feasible for designing standard or semi-custom timber connections. It has similar advantages to that of the configuration model approach in that it can handle incomplete specification of a new design problem and can incorporate good engineering practice in the form of heuristics. A disadvantage, however, is that the case-based design approach is not easily adaptable to cases using new connections that incorporate new engineered wood products, fasteners and connection hardware as they are introduced into the construction market.

Pure Selection. The pure selection approach for timber connection design requires that a set of standard connection designs be available in a library with a set of algorithms for verifying that connection selections from the library meet the requirements of the new design. For a new design problem, one of the designs from the library is selected as a candidate. The selection is generally done by the user. If a candidate design fails meeting the new requirements, it is modified and a verification is attempted again. However, modifications of the standard designs are limited only to the size and number of fasteners. The configurations and the hardware used in the connection cannot be modified. If a candidate design cannot meet the requirements of the new design after all the limited modifications are tried, then the user may change the candidate standard design and repeat the verification process. This approach automates the design process when all the new designs can be classified as very limited variations of previous designs stored in the library. The advantage of pure selection is that designs that were used in the past form the basis of new designs, and therefore a higher confidence level is built into the new designs. However, new designs are only a limited variation of previous designs, and therefore must be specified in detail so that a suitable candidate solution can be selected.

4.0 STAFF

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5.0 A CONFIGURATION MODEL FOR CONNECTION DESIGN

Timber connection design is conceptualized as an arrangement of parts consisting of: structural members to be connected; hardware (metal plates, hangers, etc.) to be used in the connection; and fasteners (nails, bolts, rivets, etc.) to be used between the hardware and the structural members. Accordingly, connection design is formulated as a configuration problem (Stefik 1993). Much of the design effort in this approach goes into defining and characterizing the set of possible hardware and fasteners for given structural members to be connected. Hardware and fasteners are constrained by having to come from their corresponding predefined sets. Similarly, structural members to be connected are members of another predefined set. The computational model of configuration ensures that the compatibility requirements between structural members, hardware, and fasteners, are handled most efficiently. To achieve this, a catalogue of parts is used, which specifies what requirements one part has for another to be used correctly. The search performed to characterize the possible hardware and fastener options is guided by the prescribed design requirements for the connection, requirements that pertain to the function of the connection, as well as to its safety, aesthetic quality, and cost.

The configuration model is well suited for timber connection design because hardware, fasteners, and structural members making up any connection can be selected from three predefined sets. At any given time and location, the sizes of sets corresponding to possible structural members, hardware, and fasteners are determined by the timber and engineered wood products manufactured, by the hardware and fasteners commonly available in the market, and by the preferences and prejudices of the designer. However, it is important that new structural members, hardware, and fasteners introduced from time to time into the market can be inserted with ease into their current predefined sets for use in future connection designs.

The model has four elements (Stefik 1993): a specification language, a sub-model for parts, a sub-model for spatial arrangements, and a sub-model for sharing. A detailed description of each of the elements of the model is presented by Varoglu *et al.* (1995). A summary of the four elements of the model follows.

5.1 Specification Language

A specification language for connection design describes the requirements that a connection configuration must satisfy. For each major function of the connection, there is a key component as illustrated in Figure 1.

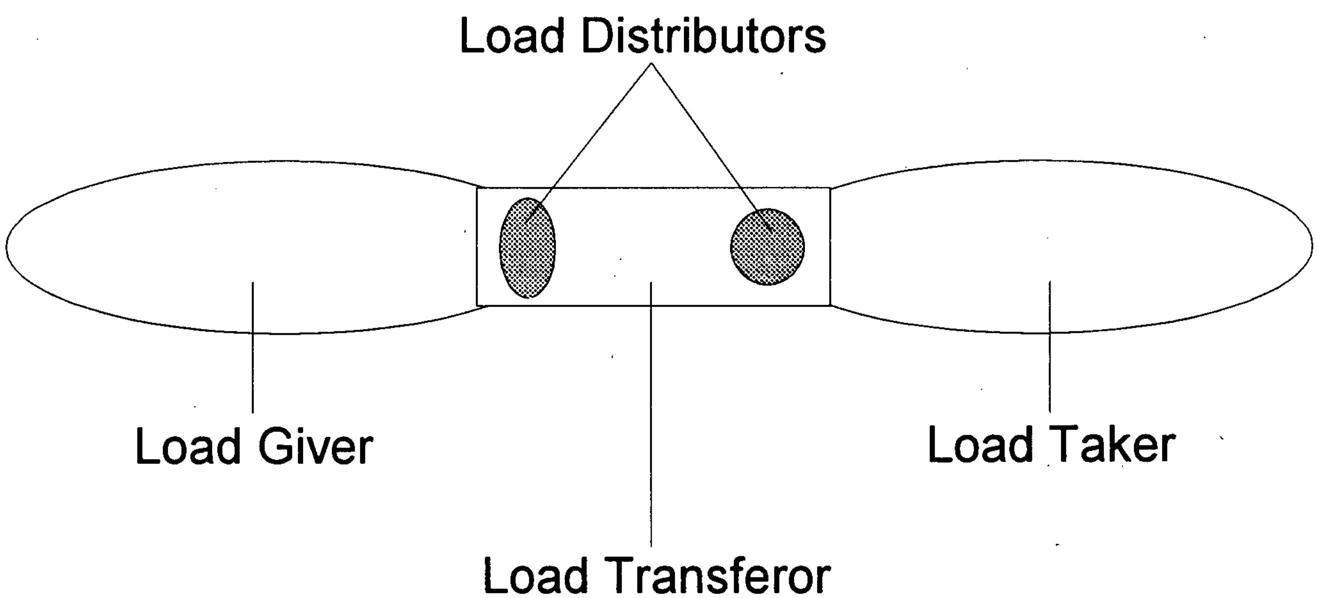

Figure 1. An abstraction of a timber connection according to the function of components.

For example, structural wood members provide the function of giving and taking the load from the connection. Hardware in the form of metal plates, hangers, and other forms provide the transfer of load from load givers to load takers. Fasteners are used to distribute the load coming from the load givers to transferors, and also to distribute the load from transferors to the load takers. As shown in Figure 2, the key components in a functional hierarchy are load giver, load taker, load transferor, and load distributor.

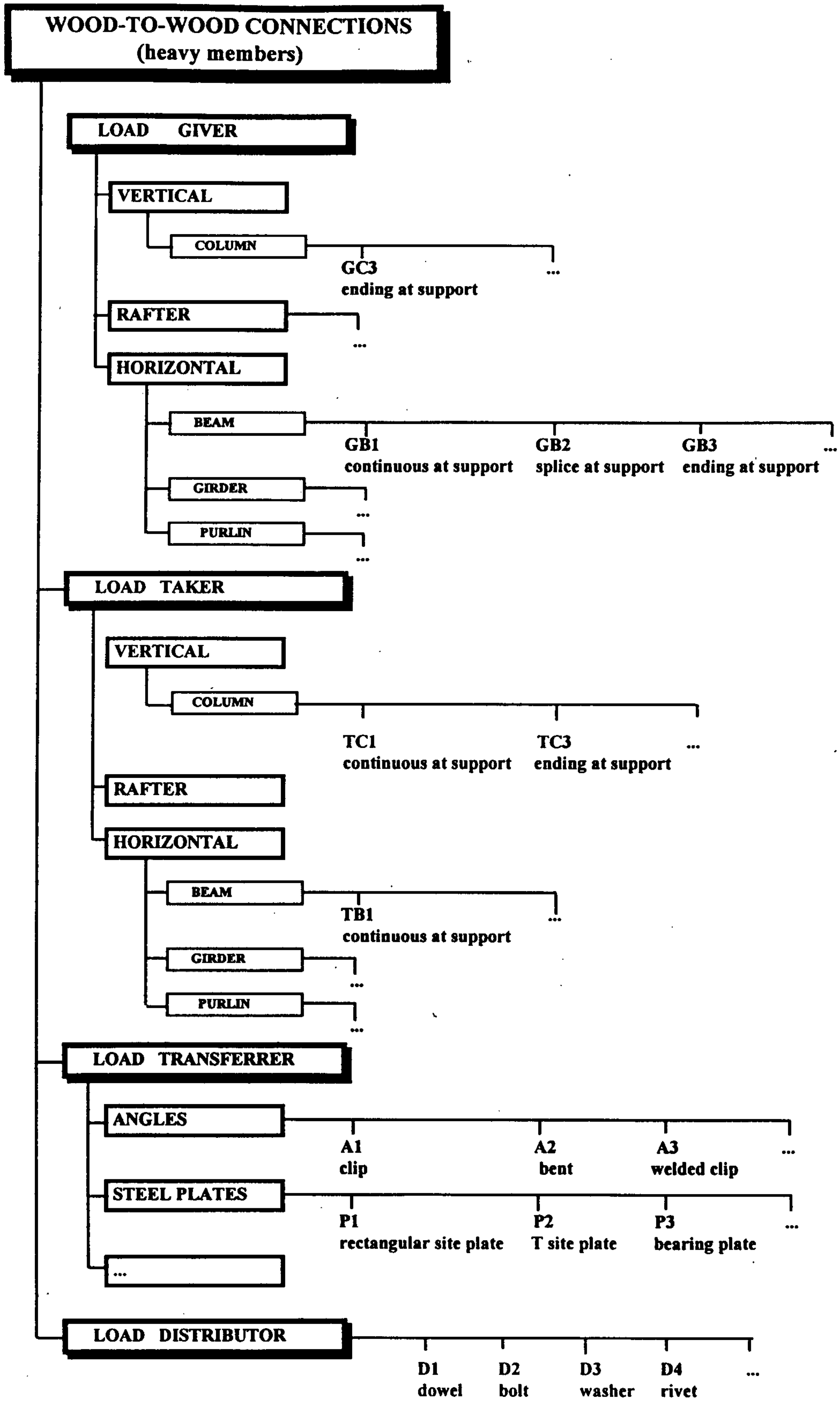

Figure 2. Key components in functional hierarchy (Varoglu *et al.* 1995).

5.2 Parts Sub-model

The sub-model for parts specifies the kinds of parts that can be selected for a design configuration and the requirements that parts have for other parts. This information can be organized as a catalogue, which also indicates which parts are compatible with each other and which can be substituted for each other under particular circumstances. This information is available either in product information sheets from manufacturers of new wood products, hardware, and fasteners, or in the *Wood Reference Handbook* (1991) for current hardware and fasteners.

5.3 Arrangement Sub-model

This sub-model describes acceptability and preferences for spatial arrangements. If the load giver and taker are prismatic structural members with rectangular cross-sections, then the common boundary between the load giver and taker is known to be made up of several line segments. These line segments can be used to arrange the configuration of the load transferors in the connection. In particular, transferors should be arranged spatially in such a way that the line segments common to load giver and load taker overlap the common line segments between the surfaces of the transferors shared by load giver and taker.

Several criteria should be considered in the arrangement sub-model. Many of them address issues related to good engineering practice, such as avoiding the possibility of causing tension perpendicular to grain in wood, limiting stresses due to shrinkage, avoiding the crushing of wood members as a result of the unconstrained displacements of parts, and maintaining a certain level of ductility of joint.

5.4 Sharing Sub-model

Load transfer in a connection is through the surfaces of load giver, load taker, and transferors. The total load carried by the surfaces of a part is distributed with the use of distributors (fasteners). Each distributor consumes a certain amount of each transferor's surface, as well as a certain amount of the load giver's or taker's surface. As shown in Figure 3 for a metal angle, some surfaces of distributors (AB) are used by the load giver; other surfaces (BC) are used by the load taker.

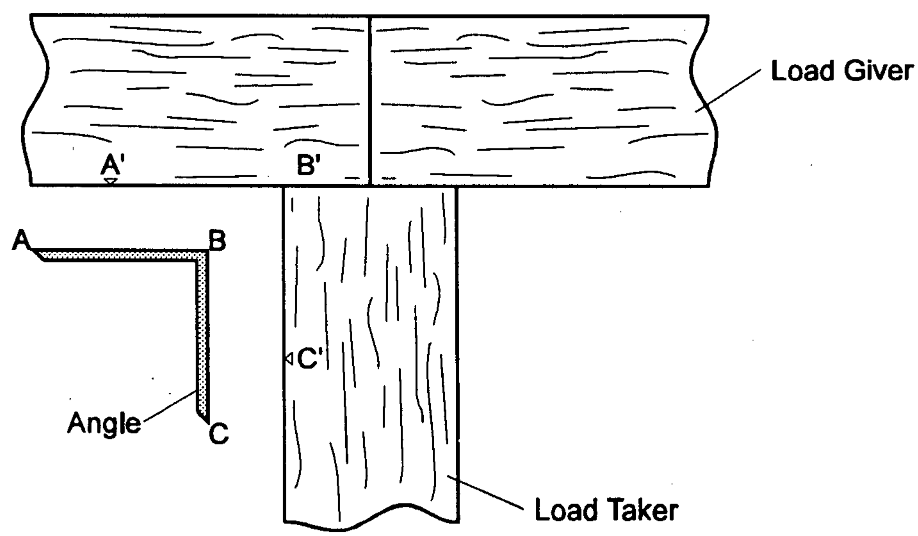

Figure 3. Shared surfaces of an angle between load giver and taker (Varoglu *et al.* 1995).

Similarly, corresponding matching surfaces of the giver (A'B') and taker (B'C') are used by the distributors. Each surface — whether belonging to a load transferor, taker, or giver — has its own specific load carrying capacity per unit area. The load carrying capacity of wood members per unit area must be compatible with the load distribution capacity of the specific distributors to be used per unit area. For all the parts to be compatible, the sum of the surface areas of the transferor must be shared with the load giver and the load taker, must not exceed the total surface area of the transferor. Similarly, each use of a transferor consumes one of the line segments common to the load giver and the load taker.

6.0 INITIAL SPECIFICATIONS OF A DESIGN

The initial partial configuration specifying a connection design includes the key components, load giver, and load taker. At first, however, the level of abstraction for each key component can be quite different. For example, the load giver might be specified in detail as a spliced beam at the connection, with a prescribed member size and required load capacity. The load taker might be specified as a column in a more abstract level in the functional hierarchy.

The connection design as a configuration problem requires that the detailed specifications of load taker, load transferor, and distributors be determined for the initially prescribed load giver. In the final design, a suitable arrangement of all included parts of the connection is then determined.

7.0 AESTHETIC CONSIDERATIONS FOR TIMBER CONNECTIONS

Aesthetic issues in the design of the timber connections are investigated by Taylor (1995) in his doctoral thesis, which forms a part of this research project. Here a brief summary of aesthetic considerations from that work is presented.

The visual elements of design that typically influence viewers are color, texture, shape, pattern, and scale. Within certain ranges, a designer can adjust any of these visual elements of the structural parts of the connection to diminish or increase the aesthetic effectiveness of the overall design. Since structural members of a timber connection are normally specified by shape and scale, only color, texture, and pattern of the member surfaces remain as visual element variables. However, architects will change shape and scale of members to suit the overall visual design if connection aesthetics prove inappropriate. Edel (1967) lists the following seven traits that give designed objects an attractive appearance:

- Rhythm - a regular occurrence or alteration in design elements;
- Dominance - a part that is most easily perceived through some outstanding difference with the rest of the design and intended to attract attention;
- Balance - a visual equilibrium in design features that may be either symmetrical or asymmetrical;
- Transition - a gradation from one feature to another that may be abrupt or gradual;
- Variety - a diversity of difference in design elements in varying degrees; and
- Unity - a harmonious relationship of all design elements woven together.

Using all of these traits is not necessary in all designs. Satisfying two or three of them together is usually sufficient to ensure the aesthetic success of the design.

To judge a whole connection's aesthetic merits, Taylor (1995) proposed a rating system based on applying the above aesthetic traits to the visual design elements of all the parts in the connection. The reader interested in details of this qualitative approach to addressing architectural issues in connection design is referred to Taylor (1995).

8.0 IMPLEMENTATION

The configuration model described above is implemented for proof of concept purposes by Taylor (1995) and Gedig[1] using a general purpose expert system development tool, KAPPA-PC, available from IntelliCorp. (1992). KAPPA-PC is a hybrid environment that provides a number of problem-solving techniques in symbol level. These include the use of objects, rules, a powerful programming language, KAL, and an inference engine that reasons by the backward or forward chaining of rules.

The key components of the domain as illustrated in Figure 1 are represented by objects. Functional relationships of the key components are organized in hierarchy with inheritance properties. Each object has a number of slots to describe the characteristics of the objects as well as their behavior. For instance, two of the slots of a beam object are used for storing the height and the species of the beam. Each action that an object can do is represented by a method. In turn, methods are activated by messages received by objects. For example, sending a message to a horizontal load giver object will activate it to search for the required parts for itself. Search for the design options are pruned by rules representing the criteria for good engineering practice, as well as by the geometrical constraints derived for meeting acceptability requirements for the arrangement of parts. Finally, all surviving solutions are evaluated to select the ones that meet the load carrying requirements. This is done by assessing the relationships between the surface characteristics of objects forming parts of each candidate solution.

The user interface for the connection design tool employs graphic images based on design idioms (Taylor 1995; Zhou[2]). Several test cases selected from a range of currently used heavy timber connections are presented by Taylor (1995) to validate this development.

9.0 RESULTS AND DISCUSSION

Our research into this specific area of automated design with wood achieved the following:

- It advanced an approach to the aesthetic assessment of connection designs.
- It advanced a method that can generate design alternatives for timber connections based on qualitative (architectural) and quantitative (engineering) design requirements.
- It formalized as design criteria heuristics derived from the linguistically based rules of thumbs and referred to by designers as "good engineering practices."
- It showed that the proposed model of timber connections is capable of handling incomplete initial design specifications, which is generally the case at the early stages of the design process.
- It showed that the proposed model can also incorporate new wood products, hardware, and fasteners with ease, as well as the style and preferences of designers.

10.0 CONCLUSIONS AND RECOMMENDATIONS

The goal of this research is to provide better communication between architects and engineers, integrating engineering and architectural knowledge in connection design through the techniques of artificial intelligence. It

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[1]Gedig, M. 1995. Automatic generation of hardware configurations for heavy timber connections. Draft research report. University of British Columbia, Vancouver, B.C.

[2]Zhou, Y. 1995. Automatic configuration module for heavy timber connection. Draft research report. University of British Columbia, Vancouver, B.C.

is expected that the ease of design of timber connections, as well as improved communication between design professionals, will contribute to the expanded use of timber, a valuable renewable resource, in construction.

Aside from its potential for industrial application, this work has promoted wood construction as a high-technology area in engineering and architectural studies. It has also focused interest in the general area of design with wood, as demonstrated by the research projects conducted by two M.A.Sc. students, Gedig[3] and Zhou[4].

It is recommended that the results of this research be pursued further for the development of educational tools in wood design and that it become part of new methodologies to be introduced in graduate courses on architectural and engineering design in wood.

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[3]Gedig, 1995.

[4]Zhou, 1995.

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