I. INTRODUCTION

The University of Calgary's initiative to develop a local computing network for research in distributed programming environments grew out of collaborative efforts among faculty members and graduate students in the Computer Science department. Several research proposals were prepared during 1982 resulting in four NSERC grants: Major Equipment and Infrastructure grants awarded in June 1982 and Strategic Equipment and Operating grants awarded in November 1982.

The overall project's primary goals were to pursue research in distributed systems and to construct a programming environment that supports the development of distributed software. The result - The Jade Environment - integrates a set of multilingual software development tools for specifying, implementing, testing, and evaluating the performance of distributed computer systems. This environment provides extensible monitoring and protocol verification, interactive graphical animation, and prototyping facilities that are unique in North America.

A third version of this environment, Jade/3, was released in the Fall, 1985, along with a five volume, 582 page User's Manual [Jade 85]. This Jade/3 environment represents the achievement of nearly all of the original project objectives. There are now over 45 research and 60 undergraduate users of Jade/3 and its tools. Jade/3 is a fundamental component in the software development environment at the University of Calgary; the Naval Research Laboratories (NRL), Washington D.C.; Willowglen Corp., Calgary; and is being installed at the University of Saskatchewan. Other users of the environment include the Alberta Research Council and we are discussing licensing agreements with a number of organizations.

Graduate students currently being supervised by the grantee and co-investigators include sixteen M.Sc. and eight Ph.D. candidates. Nineteen M.Sc. and one Ph.D. theses have been completed during the project. These are listed in Appendix A. The Jade research group has published over forty five journal papers: twenty three on concepts and tools directly related to the project, five on aspects of the environment itself, eight on applications of Jade/3, and nine in other research areas. Seventy six full conference papers have been published: forty on topics related to Jade, seventeen describing parts of the Jade environment, and five on applications of Jade. Thirty four technical reports and submitted papers: eighteen related to the environment, eleven on the environment, and three on applications; and ten books and films have also been written during the project. These publications are listed in Appendix B.

Jade/3 is currently being maintained with support from a three year $42,000 NSERC Infrastructure grant, $36,000 from the Department of Computer Science, and other funds from industrial affiliates. NRL has provided $140,000 to support the development of distributed simulation research based on Jade. Esso Resources has provided $30,000 to support disabled user interface tools built using Jade/3. The Alberta Microelectronics Center (AMC) is also providing substantial support for the development of Jade applications in the area of VLSI design tools. An example Jade workstation screen involving a chip test facility with hardware, software, and simulation components is shown in Appendix C.

The body of this final project report contains: II Achievements, III Rationale for changes in the original objectives, IV The significance of achievements, V The accessibility of Jade/3 and research results, and VI The training and experience provided to research staff and students, and socio-economic benefits that have resulted from the project.

II. ACHIEVEMENT OF PROJECT OBJECTIVES

The primary objectives of Project Jade were to construct: (A) a network of workstations with a Vax Unix host; (B) interactive graphical user interface tools, (C) distributed system simulation and prototyping tools; (D) information management tools; and (E) a programming environment that integrates the tools of (B) through (D) on the network of (A). All of these areas, except (A), involved significant research problems.

These objectives are briefly outlined in the following paragraphs along with the major achievements in each area. Deviations from the original objectives are also described. Additional goals and achievements not defined in the original proposals are presented in (F). The rationale for changes in the original project objectives is discussed in III which includes recommendations made by two external project review teams.

(A) A network of workstations with Unix host to support the environment

An Ethernet connecting three classes of terminals to a Unix host was originally proposed. The Corvus Concept was selected as the medium performance Jade workstation. This M68000 based diskless workstation has 1/2 Mbytes of memory, a bit mapped display, and an Omninet interface. A Vax 11/780 with 16Mbytes of memory and about 1 Gbyte of disk space running Berkeley Unix 4.2 is the primary research host machine. This Vax is connected via Pronet to three other departmental Vax 11/780s that are used primarily for undergraduate teaching.

A significant achievement was the design and construction of an Omninet/Unibus interface and associated networking software. This gateway between Omninet and the other Vax/Unix networks (i.e. Ethernet and Pronet) provided a more cost effective network to support distributed system development than the originally proposed Ethernet. Another change from the original proposals was to focus on a single, medium performance, diskless Jade workstation that could be acquired in sufficient number to create a user community. Simpler terminals were not supported directly as a bit-mapped display was deemed essential, and color workstations were too expensive to acquire in sufficient number.

The less expensive Omninet and single Jade terminal type network, plus approximately $250,000 in University funds and $300,000 in discounts from Digital Equipment enabled us to build a hardware infrastructure consisting of four large Vax/Unix hosts and two subnetworks of 25 Corvus workstations. This equipment infrastructure made it possible to provide access to the Jade Environment by a much larger number of students, research staff, and faculty than originally envisioned, a factor which had a highly positive affect on project research and achievements. **(Faculty: Graham Birtwistle, John Cleary, David Hill, Tom Keenan, Brian Unger, Ian Witten, and Brian Wyvill)** [1]

(B) Interactive Graphical User Interface Tools

The user interface proposed consisted of graphics and animation tools with the potential for supporting multimedia dialogs via both graphics and speech processing. Although experiments with multimedia user interfaces were performed no support for speech processing is included in the current release of Jade/3. With this exception, all of the original user interface goals have been achieved.

The Jade/3 interactive graphical user interface consists of three major components: the Jaggies graphics system, the Jagged graphics editor, and the workstation Window System. The objectives of Jaggies was to support: the construction of document illustrations; simple displays of process states with real-time animation; and a clean, orthogonal and easy to use interface for the graphics programmer.

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[1] People listed in bold are the principle faculty contributors to the work described above, i.e. up to the previous bold subtitle.

Jaggies provides all the features of a "standard" graphics package, such as GKS or CORE, plus hierarchical, recursive object modelling based on a novel approach. In traditional graphics systems the program driving the graphics must issue commands to display pictures on the screen and to erase them. Jaggies describes the desired state of the screen by manipulating a hierarchical data structure while ensuring that the actual state of the screen reflects this structure. Achieving this is complicated by the need to incorporate colour (or a simulation of colour), and clipping, each of which is available through transforms at every level of the hierarchy. Jaggies has been described in [Wyvill 84B & C] [1]. Jagged is an interactive program, built on top of Jaggies, that assists users in building static pictures. The user designs pictures with the workstation mouse by pointing, sketching, and selecting from menus. The Jaggies pictures thus created can then be animated, if desired, by distributed programs that send messages to Jaggies. Jagged is described in [Unger 86A & B].

The Jade Window System enables a user to interact with a number of different tasks, where each task has its own "window" for output, and shares the keyboard and mouse input devices. Multiple views can be provided into an executing distributed system. A uniform menu interface with a unique context sensitive help facility is made available to application programs by the Window System whose novel implementation is also a distributed system itself. The Window System is described in [Unger 86A & B], [Hill 84]. **(Faculty: Brian Wyvill and David Hill)**

Identifying structural models from user behaviour sequences and using the resulting models for prediction, have been been applied to a variety of problems. One application is the automatic personalization of a user interface described in a journal paper [Witten 84] and in [Greenberg 83C, 84 & 85] which is also the topic of one completed M.Sc.(Greenberg) and one Ph.D.(Greenberg) in progress. Another application is modeling users' typing behavior to expedite text entry [Witten 82A & B, 83A] and [Darragh 83] and a report [Witten 84A]. A third is text compression; extremely impressive compression ratios have been achieved (2.2 bit/char on English text drawn from a 94-character alphabet, with no prior knowledge) described in a journal paper [Cleary 84A] and in [Witten 83B]. **(Faculty: John Cleary and Ian Witten)**

The Multimedia Adaptive Workstation for the Disabled (Mawd) project, report [Hill 85C], is intended to improve access to computer power for disabled university students and represents a major Jade/3 application. It provides highly usable and innovative interfaces based on touch, speech and graphics that have been built upon Jade/3. One M.Sc. has been completed (Dohrn). Three M.Sc. (Dignum, DuWors, Jansonius) and one Ph.D (Esau) projects are in progress in related areas. Current work includes speech and touch as a substitute for conventional direct manipulation for disabled students [Hill 84A]. A grant from Esso Resources for $30,000 was received to develop this Jade application. **(Faculty: David Hill)**

High performance graphics research includes the design and implementation of a 3D hierarchical graphics system using Jade/3. This work is described in four journal papers [Wyvill 85A, B, C, & 86] and in [Wyvill 84A & B, 85A, B, & C]. At each level objects are defined as geometrical transformations of sub-objects, and may include recursive references. Objects are not limited to a single data type and may refer to a variety of different leaf nodes representing primitives (polygons, particles, fractals). The objects are rendered in one pass facilitating the manufacture of animated film.

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[1] Publication references refer to "conference" papers unless otherwise specified, e.g. journal or technical report, in Appendix B.

The project also involves research into distributed rendering algorithms implemented on Jade/3 using Jipc (Warnocks, Z-Buffer and ray tracing) [Cleary 83A & B]. This work has lead to the development of Graphicsland - an integrated set of 3D modelling and animation tools. We have received requests for Graphicsland from Germany, and by the summer of 1986 there will be installations of Graphicsland in England and New Zealand. So far about 200 seconds of film have been made demonstrating these techniques. Recently a technique for automatic animation of talking faces, with synchronised speech, has been described [Pearce 86]. Another modelling technique resulting from this research called Soft Objects shows great promise for the entertainment industry and appears to offer significant benefits to the geophysical industry as well. The research on Soft Objects has already been successfully applied to produce slides of an ISO surface in a heavy oil reservoir, journal paper [Wyvill 85C] and in [Wyvill 86A & B]. **(Faculty: Brian Wyvill)**

(C) Software Simulation and Prototyping Tools

The original proposals specified tools that support the development of "target" software systems via: the simulation of target system components, the interactive monitoring and control of prototype target software, and the embedding of prototype software within an actual target system. Prototyping is accomplished by supporting the implementation, testing, and evaluation of distributed programs whose components interact solely via the Jade Inter-Process Communication protocol (Jipc) [Neal 84]. An application can be developed within Jade/3 and then ported to a target network of computers. This target may be an embedded system for which a tailored Jipc implementation exists.

Simulation models are developed for devices which exist in the target network but not in Jade/3. An application distributed program can be implemented and then its performance evaluated via simulation. Alternative peripheral devices and the target computer network architecture can also be evaluated. An initial design and implementation of this prototyping tool is described in a journal paper [Lomow 85], a conference paper [Lomow 85] and in Lomow's M.Sc. thesis. This work builds on previous computer system and software simulation approaches presented in [Unger 82A & B]. Although this tool has been built and tested it was considered too experimental to be released as part of Jade/3. **(Faculty: Brian Unger)**

Techniques for monitoring distributed systems addresses the problems of non-determinism in distributed systems and the corresponding impact on system behaviour caused by monitoring. An extensible monitoring scheme has been defined which collects process interaction information from a multilingual distributed application program. This information is sent via unmonitored Jipc messages to one or more "consoles" which interact with the "user", ie. the developer of the application program. Different consoles provide different interpretations, or views, of an executing distributed application program.

A number of different kinds of consoles have been explored including: a basic one line of text per inter-process event view; an animation sequence with icons representing processes and messages moving among these processes; a deadlock detector; a representation of traffic density among processes; and a protocol verifier which reports only deviations from a protocol specification. The basic monitor also provides a breakpoint facility and enables collecting interaction histories which can be replayed to produce repeatable executions during debugging by controlling non-deterministic choices. The user can also control non-determinism to force improbable execution paths. These ideas have been described in three conference papers [Dewar 84], [Joyce 84 & 85], and a research report [Joyce 85]. The extensible monitoring scheme has been implemented in Jade/3 along with several consoles. One visiting scientist (Dong Zhixin) is working in this area, one M.Sc.(West) and one Ph.D. project (Lomow) are in progress. **(Faculty: Brian Unger)**

Virtual Time is a new research area that involves an optimistic synchronization scheme for a set of cooperating processes where each process maintains its own local virtual time. Applications include distributed simulation and distributed data bases, as well as, general synchronization problems. Messages are time stamped and "rollback" occurs when a process receives a message with a time stamp in its past. This novel scheme was first described by Jefferson and Sowizral at Rand. A joint 2 year project to implement a Virtual Time system on Hypercube that involves 6 full-time technical staff at UCLA and JPL is now nearing completion.

We have been working with this research group at UCLA where several Ph.D.s have already been completed in the distributed simulation and database areas (e.g. Orna Berry spent two months here in Fall'85 completing her Ph.D. dissertation research). At Calgary we have developed a unique design based on Jade that supports multilingual, transparent synchronisation accomplished via backtracking in Prolog and via process state snapshots for procedural languages [Cleary 85A], [Unger 85]. NRL has provided $140,000 to support this research and to implement our design which is now being tested. Currently two Ph.D. students (Lomow and Li), one M.Sc. student (Schack), and a visiting scientist (Xiao Zhong-e) are working with several research staff. **(Faculty: John Cleary and Brian Unger)**

Process style simulation has been another closely related research area involving Demos, simulation environments, and animated simulations (Andes). This work has been described in four journal papers [Birtwistle 84A & B, 85, 86], five conference papers [Birtwistle 82B, 84B & C, 85C, 86A] and one book [Unger 84]. **(Faculty: Graham Birtwistle and Brian Unger)**

(D) Information Management Tools

Innovative systems have been created for browsing through on-line documents that involve text, graphics and animated interactive displays. An online Unix browser, which was implemented as part of Bramwell's M.Sc. thesis, is part of Jade/3 providing access to all Jade software, software documentation, and project information. This system was described in a recent CACM paper [Witten 85] and in [Bramwell 84]. An interactive documentation tool which provides a highly flexible interface to an on-line reader/browser has also been implemented as a distributed system within Jade/3 [Bonham 82, 84, 85]. This system supports linked streams of text (footnotes, figures, and annotations as well as the main text) which can be entered and manipulated by several people working together. Two M.Sc. theses have been completed (Bramwell, Bonham). **(Faculty: Ian Witten)**

(E) The Jade/3 Software Development Environment

This third version of the Jade Environment integrates the distributed system prototyping, simulation, and monitoring tools described in (C), the on-line browser of (D) and provides a uniform user interface via the tools of (B). This Jade/3 Environment supports the development and execution of programs whose individual components can be implemented in Ada, C, Lisp, Xlisp, Prolog, or Simula. Processes written in these languages communicate via the Jipc (pronounced gypsy) message-passing kernel.

Processes implemented in C and Xlisp can reside on any of the workstations or Vaxes, while processes implemented in the other languages are currently restricted to the four Vaxes. Cross compilation and downloading of Ada, Prolog, and Simula components to the workstations is currently under development. The Jipc kernel has also been ported to Cadlink Sun, SMI Sun and MTU workstations. Porting of the kernel to a 3*3 array of M68000 based computing nodes, called the "Mesh Computer" is also partially implemented, completion requires additional funding. The environment and its major components are described in a journal paper [Lomow & Unger 85] and [Unger 84A, 86A & B], a research report [Witten 83], and the User's Manual [Jade 85]. **(Faculty: John Cleary, David Hill, Brian Unger, and Brian Wyvill)**

(F) Additional Goals and Achievements

Distributed Prolog research has resulted in the design and implementation of a distributed version of the and-parallel portion of Shapiro's Concurrent Prolog (CP). This implementation manages the distribution of logical variable bindings among local implementations of CP and is based on Jipc. A discrete event simulation system has been implemented in Concurrent Prolog [Cleary 85C] and report [Cleary 84]. Previous work on discrete event simulation in Concurrent Prolog was reported in [Cleary 84]. This work builds on Ivan Futo's seminal work in the field of simulation and logic programming.

The integration of Prolog into Jade/3 has enabled the implementation of a number of novel systems. These include a logic programming language for 2D graphics (GROWL) described in report [Cleary 85] and a distributed implementation of it. GROWL has been implemented using the Jade graphics system [Wyvill 84C] and has been used to construct a graphical debugging system for Prolog programs. In it GROWL is used to draw an and/or representation of the executing program and its data structures. This interactive tool provides a very powerful environment for debugging standard Prolog programs. The distributed implementation of GROWL includes a novel and powerful scheme for reducing the communication between the logic intensive Prolog and remote graphics processors. Cleary and Kornfein have developed a set of rules for proving partial and, more significantly, complete correctness of Horn clause programs. Three M.Sc. theses (Dewar, Kramer and Kornfein) have been completed. **(Faculty: John Cleary)**

A Mesh Computer project was begun in 1983 to construct a multiprocessor system that could be used as a test-bed for distributed programs developed using Jade. Since then the system has been designed from scratch including inter-processor communication and board design. Since late 1984 a four processor system using M68000 processors has been running. The system is easily scaled to much larger sizes because of the two dimensional layout of processors where only neighboring processors can communicate. This enables a very simple and regular layout of processors and backplane wiring while permitting very high speed interprocessor communication.

The communication between processes is via nearest neighbour shared memories which enable transfer rates of 2Mbs per communication link without involving the receiving processor in any overhead. The Jade/3 Jipc kernel has been ported to the system and used to develop programs for it. The technique is to develop and simulate algorithms on Jade/3 and when debugged to cross-compile and run them on the mesh computer. This has been used for a number of test programs and for a distributed version of a ray-tracing program for high quality graphics.

This research has been described in a journal paper [Cleary 86], in [Cleary 83A & B], and in a report [Cleary 83]. One M.Sc. thesis has been completed (Vatti) and one other is in process (Pearce). Work is currently proceeding on a 9 processor configuration and on a design for a successor system with increased memory and integral access to a graphics frame buffer. A technician and programmer (Asaph and Vance) are currently involved in the mesh computer implementation. **(Faculty: John Cleary and Brian Unger)**

VLSI Specification & Proof research has been targetted at hardware verification, composition algorithms and a cell library. This work has been accomplished using Jade/3. Jade has been essential for our prototyping work enabling processes to be written in the language of one's choice (C for dialogs, Lisp for design capture, Prolog for AI, Simula for architectural simulations and graphics) with the knowledge that they would all interact problem free.

A recent development has been a VLSI chip test environment consisting of a software front end to an existing specialised chip test hardware controller. The chip test hardware was designed and built by Schediwy and provides an interface between serial RS232 communication line and the chip under test. The user can not only drive a set of test vectors to the chip and read the results, but also carry out a switch level simulation at the same time. This provides a quick and effective way of verifying chip operation. The dialog permits many Jade views to be open at the same time. Jade windows may used to show the chip floorplan, which lines are active, which sections are communicating with each other, etc., see Appendix C for an example Jade workstation screen snapshot. Testing may be carried out in batch mode or by single stepping. The dialog was conceived and implemented in only 3 days - a feat which would not have been possible without Jade.

Research in hardware verification has been explored to ensure that a design will meet its specification. One very large practical design (37 bipolar chips) has been (almost) verified [Birtwistle 86B]. The HOL proof of a small computer was reported in [Joyce 85B & C]. The design was fabricated in 1985 as an 8-bit computer. Composition rules enable the automatic construction of correct large systems from validated sub-systems. Work has been completed on composing behaviours, layout, structure, and constraints and incorporated them into the SHIFT prototype [Liblong 83]. The SHIFT prototype included a small library of flexible CMOS and NMOS leaf cells. Schediwy's M.Sc. thesis details a library of rigid fixed height double metal CMOS cells that have been fully characterized in the electrical domain. Both use a composition algorithm based upon constraints and implemented in [Liblong 83].

Early context and random logic chips were jdesigned using our own tools. More recent (and much larger chips) have been built using SPAR's Electric and Xerox PARC tools. Work continues on a 150,000 transistor instruction stream memory chip (Coates M.Sc. thesis). A serial multi-ported static smart memory chip (34,000 transistors) was fabricated and tested in 1986. Software from Kroeker's M.Sc. thesis, Liu's Ph.D. thesis, and Schediwy's M.Sc. thesis have been incorporated into Schlumberger's Electric VLSI design system. [Lyon 86] describes a patent application for a 4 transistor CMOS static memory cell. Three M.Sc. theses (Coates, Kroeker and Liblong) are finished, eight more M.Sc. projects (Brinsmead, Graham, Keefe, Ling, O'Byrne, Schediwy, Stone, and Williams), and three Ph.D. dissertations (Joyce, Liu, Renert) are underway in VLSI. **(Faculty: Graham Birtwistle)**

Interval Algorithm research involving the centered forms originally defined by Moore were generalized and implemented. The original definition was for one function in one variable. This definition was generalized to complex functions in one [Rokne 82A & 83A], and more variables [Rokne 85A]. A completely new and efficient generalization was described in [Rokne 86B]. These generalizations were implemented using Jade/3. A package for drawing complex centered forms was written using Jaggies. A Prolog program is now being written to manipulate multivariate polynomials which is being applied to the new centered form. Other work by Cleary and Rokne has provided a natural integration of real arithmetic into Prolog. Two M.Sc (Bao, Wolters) and one Ph.D. projects are in progress. **(Faculty: Jon Rokne)**

III. RATIONALE FOR CHANGES IN OBJECTIVES

Two external technical reviews were held during the project to evaluate our progress, current goals, and to decide on changes in goals and research directions. The first was held in June, 1983 and involved three visitors: Eric Manning, University of Waterloo; Renee Elio, Alberta Research Council; and John Lugsdin, Orcatech Ltd. An intensive day was spent in presenting Jade progress and discussing alternative directions. The feedback received from the visitors was very supportive. This review was very helpful in defining and confirming the detailed objectives for the first version of Jade, i.e. Jade/1.

The second technical review was held on December 14th and 15th, 1983. Five visitors were invited to evaluate our progress and objectives: Peter Cashin, Bell Northern Research; David Cheriton, Stanford University; Renee Elio, Alberta Research Council; Peter Hibbard, Carnegie Mellon University; and Jean Vaucher, University of Montreal. The pre-release Jade/1 environment was demonstrated. The visitors were impressed by the magnitude of work accomplished but also expressed concern that we were attempting to do too much.

Their specific recommendations are summarized in the following: 1) Attempt to clearly distinguish: development of software that supports research; maintenance of that software; and research. Then allocate staff and equipment resources to these three areas more consciously. 2) Attempt to identify research goals that are unique and which we have the resources to pursure successfully. 3) In deciding where research effort is to be focussed, be wary of influencing individual researchers to work in areas that do not take advantage of their experience. 4) Tackle at least one application of Jade to completion - including the specification, simulation and prototyping for performance evaluation, debugging, testing, and maintenance of a distributed system. 5) Explore the advantages of distributed simulation over single processor simulation. 6) Explore the impact of Jade's graphical, simulation, and prototyping tools on productivity and software quality.

These suggestions were discussed extensively during the review and subsequently during two weekend workshops by faculty, students and staff. Although we did not respond to all of these suggestions, substantial changes in emphasis were made. These included our subsequent focus on one workstation type, monitoring and simulation, completing numerous applications such as the Xtree evaluation [Unger 86C], MAWD via the Esso grant, the 3D distributed graphics, the interactive documentation tool [Bonham 85], Virtual Time [Cleary 85A] and [Unger 85] via the Naval Research Labs grant, the VLSI design tools, Interval Algorithms, and the Mesh test-bed. This diversity in Jade applications was partially due to the 3rd suggestion above.

IV. SIGNIFICANCE OF ACHIEVEMENTS

The significance of project achievements is reflected in our refereed publications. The Jade research group has published over 45 journal papers, 76 full conference papers, 34 technical reports and submitted papers, and 10 books and films. These publications are listed in Appendix B.

The integrated support for the development of distributed programs implemented in a mixture of procedural and applicative languages is unique in North America. The "Port" project (University of Waterloo), "Eden" (University of Washington), as well as, the earlier Unix, Interlisp, and Ada Programming support environments are primarily built around a single language. Although uni-lingual environments offer many advantages, we have found the integrated support of multiple languages to be crucial in a computer science research environment.

The ability to mix procedural and applicative languages has a number of advantages in designing and building general purpose distributed systems. Often certain components of an application program can be specified in an applicative/interpreted language, such as Lisp or Prolog. These executable specifications can be evaluated and tested, and appropriate components re-implemented in a procedural language during the development process. The development process is greatly simplified if execution can be suspended, changes made to interpreted components, and then execution continued. This facility is particularly relevant for interactive user interface components, and for distributed embedded systems where linking, and down loading are often time consuming.

The Jade/3 monitoring facilities are also unique. The ability to create tailored, multiple animated pictorial views of an executing distributed program, e.g. views relevant at the application level, and all implementation levels down to the Jipc layer, is extremely powerful. Further, the ability to control execution, e.g. single stepping and replay, and control non-determinism greatly aides debugging and testing. Finally, run-time error detection via protocol specifications offers a middle ground between correctness verification and testing.

An outline of the significance of Jade/3 applications and other research that is supported by the environment is beyond the space available for this report. Research by about half of the faculty of the Computer Science Department is being supported including work on human machine interfaces, high performance graphics, simulation, computer communication systems, distributed logic programming, distributed systems, document preparation and browsing systems, robotics, and VLSI design systems.

V. ACCESSIBILITY OF RESULTS

One of the primary goals of the project has been to communicate research results to both academic and industrial scientists with interests in distributed software research and development. This objective is carried out on four levels:

1) **Research Papers & Reports** totalling over one hundred fifty publications have been written.

2) **Workshops, Conferences, and Industry Presentations** during the project include: a weekend workshop on Jade in Banf, March'84 for faculty, staff, students, and invited visitors; a day of demonstrations and presentations to industry in April and June'84, and June'85; a conference on "Distributed Computing and Jade", Calgary, September'84 including Eric Manning, Univ. of Waterloo, and Kristin Nygaard, Oslo; and a project debriefing workshop in Banf, November'85.

3) **Computer Science Educational** support in senior undergraduate and graduate courses in distributed computing and human-computer interfaces via a widely available programming environment that is fully documented and maintained.

4) **Distribution of the Jade/3 Environment** via the University of Calgary's Software Research and Development Group (SRDG), a group within the University of Calgary created to support communication and collaboration among university and industry researchers in applied computer science. Since November the SRDG has negotiated with several external organizations interested in using Jade/3. This list includes:

- The Naval Research Laboratory (NRL), Washington D.C. USA, has acquired internal licenses from the University of Calgary for use of parts of Jade/3. Both the Information Technology Division (ITD) and the Navy Center for Applied Research in Artificial Intelligence are using Jade/3. A current collaborative project involves porting Jade/3 to SMI Sun workstations and building Virtual Time on Jipc.
- Willowglen Systems Ltd., a Calgary based company with an international reputation in Supervisory Control And Data Acquisition systems (SCADA systems) is licensing Jade/3 for use as a distributed software development environment. Willowglen will be using Jade/3 to develop and prototype proprietary SCADA software.
- The Alberta Research Council has been using Jade/3 since Fall'85.
- The University of Saskatchewan has recently acquired Jade/3 on a collaborative basis to support further work underway in their Computational Science Laboratory.
- Others include: Novatel Communications Ltd., Calgary; the Analytical Sciences Corporation, Reading, Mass., USA; the Department of National Defense, Ottawa, Ontario, Canada; EG&G, Manassas, Virginia, USA; and MARI International, Newcastle, G.B.

The SRDG has also established an Industry Affiliates Program to provide interested organizations with direct access to the research expertise which has evolved from this project. This includes the scheduling of seminars & conferences to serve as a forum to present more detailed information on research achievements.

VI. TRAINING OF RESEARCH PERSONNEL and SOCIO-ECONOMIC BENEFITS

A large community of researchers and students within the Computer Science Department have, and are, benefiting from access to the Jade/3 environment. These include over 60 undergraduate students, 20 graduate students, 10 faculty, and 33 full-time, part-time, and summer technical staff that have worked on the project during the past three years. Graduate students involved in the project, including 19 M.Sc. and 1 Ph.D. completed and 16 M.Sc. and 8 Ph.D. projects in progress, are listed in Appendix A.

Research staff that have worked full-time for at least six months on the project include: Jeff Allan, Bob Bramwell, Alan Dewar, Dong Zhixin, Richard Esau, Jeff Joyce, Danny Levinson, Li Xining, Dave Maulsby, Craig McPheeters, Radford Neal, Murray Peterson, Konrad Slind, Xiao Zhong-e, and Zhou Heying. Part-time technical staff include: Keith Andrews, Mike Bonham, Laurie Kramer, James Inkster, Wallace Kroeker, Breen Liblong, Greg Lomow, Rick Schediwy, and Dave Vance. Students employed over summers include: Saul Greenberg, Victor Francaschin, Dan Freedman, Dave Laidlaw, Ringo Ling, Dennis Pelletier, Brian Schack, Darrin West, and Yen Yung-Hsiew.

We have been fortunate to have a number of visiting scientists from China. Significant research contributions to the project have been made by Dong, Zhou, Li, and particularly Xiao on the Virtual Time project. The research staff have also made substantial research contributions to project achievements. These include Radford Neal who acted as system architect responsible for creating an integrated environment from diverse faculty research group interests, software components, and conflicting requirements. Other key individuals were Bob Bramwell and Danny Levinson who made substantial contributions to the Jade graphics systems and user interfaces, and Murray Peterson on the workstation kernel and Jipc. Jeff Joyce and Konrad Slind made significant contributions to the animated monitoring system.

Jade has also had a dramatic impact on the computer science graduate program. The Jade equipment and research projects have made it possible for us to double the size of our M.Sc. program and establish a PhD program (now 8 students). A request for funding for a further increase in size is now under review by the Province of Alberta As evidenced by the attached letters from ARC and AMC, the upsurge in our research profile has been one of the reasons for attracting provincial research centres to expand into Calgary, to take advantage of our trained graduates, and to embark on joint research and development projects.

Socio-economic benefits for Canada can be identified in several areas: direct industrial application of Jade/3; indirect industrial application of Jade techniques and experience; socially supportive developments dependent on Jade; and further research arising from Jade that also has significant socio-economic impact. Direct industrial applications are outlined in V (4). The commitment of NRL to use of the environment exports Canadian technology and is also of direct economic benefit. Indirect industrial benefits acrue from the disemination of research results described in V (1 & 2). It is particularly noteworthy that the Alberta Research Council have established an industrial software group in Calgary with close links to Jade. The MAWD workstation for the disabled represents one socially supportive development highly dependent on the rapid prototyping capabilities of Jade.

The research programs arising out of Jade are particularly significant in that they follow the pattern of multi-disciplinary research targeted on tools and applications which also have clear socio-economic benefits. The project has established a highly collaborative research environment in the Department of Computer Science at the University Calgary. This has already attracted further high-quality faculty and researchers. It has also attracted industry to participate in an affiliates program that will ensure continuing technology transfer between the University and Canadian industry.

☐ Biotechnology / Biotechnologie
☐ Food-Agriculture / Alimentation-Agriculture
☒ Communications and Computers / Télécommunications et informatique
☐ Industrial Materials and Processes / Matériaux et procédés industriels
☐ Energy / Énergie
☐ Oceans / Océans
☐ Environmental Toxicology / Toxicologie de l'environnement
☐ Open / Ouvert

Name/Nom: DR BRIAN W. UNGER
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Title of Project/Titre du projet:

Project Jade: An Environment for the Development of Distributed Software

The University of Calgary's initiative to develop a local computing network for research in distributed programming environments was funded by four NSERC grants: Major Equipment and Infrastructure grants awarded in June 1982 and Strategic Equipment and Operating grants awarded in November 1982. The project's primary goals were to pursue research in distributed systems and to construct a programming environment that supports the development of distributed software. The result - The Jade Environment - integrates a set of software development tools for specifying, implementing, testing, and evaluating the performance of distributed computer systems.

A third version of this environment, Jade/3, was released in the Fall 1985, along with a five volume, 582 page User's Manual. There are now over 45 research and 60 undergraduate users of Jade/3 and its tools. Jade/3 is a fundamental component in the software development environment at the University of Calgary; the Naval Research Laboratories (NRL), Washington D.C.; and Willowglen Corporation, Calgary. Licensing agreements are under discussion with a number of other organizations. Continued development and maintenance of Jade is being funded by industrial affiliates, and by Canadian and USA research funding agencies.

Components of a distributed program can be implemented within Jade/3 in Ada, C, Lisp, Xlisp, Prolog, and Simula. This unique environment provides extensible monitoring and protocol verification, interactive graphical animation, and software prototyping and simulation facilities for developing multilingual distributed programs. Publications on the environment, related research, and applications include 45 journal papers, 76 conference papers, 34 research reports, and several books and films.

Applications of the Jade/3 Environment that have been developed include: distributed document preparation systems; a distributed implementation of Concurrent Prolog; a multiprocessor array test-bed for distributed graphics, simulation, and Prolog; a distributed simulation system based on Virtual Time; Interval Algorithms; and VLSI Specification & Proof Tools.

The project has resulted in an expansion of the University of Calgary's graduate program in Computer Science, and has substantially contributed to the creation of a Ph.D. program. Project faculty have supervised 19 M.Sc and 1 Ph.D. projects that have been completed and 16 M.Sc. and 8 Ph.D projects are in progress.

Key Publications on the Jade Environment and its Components

Bonham, M. and Witten, I.H. (1985) "Distributed document preparation with interactive and noninteractive viewing" *INFOR, 23* (4) 365-388, November.

Jade (1985) "Jade User's Manual" Research Report J84/1/1, Department of Computer Science, University of Calgary, September.

Lomow, G.A. and Unger, B.W. (1985) "Distributed Software Prototyping and Simulation in Jade" *Canadian INFOR Journal, 23* (1) 69-89, February.

Unger, B.W., Dewar, A., Cleary, J., and Birtwistle, G.M. (1986) "A distributed software prototyping and simulation environment: JADE" *Proc. SCS Conference on Intelligent Simulation Environment*, 63-71, San Diego, January.

Witten, I.H. and Bramwell, B. (1985) "A system for interactive viewing of structured documents" *Communications ACM, 28* (3) 280-288, March.

Wyvill, B.L.M., Neal, R., Levinson, D., and Bramwell, R. (1984) "JAGGIES — a distributed hierarchical graphics system" *Proc. CIPS Session '84*, 214-217, Calgary, Alberta, May.

Appendix A:

Graduate Student Theses During The Project

THESES COMPLETED

Name	Full Titles	Supervisor	Completion Date
Levinson, D.	The Well-Tempered Speech Recogniser (Ph.D.)	D. Hill	1982
Ang, T.	Local Area Communications	G. Birtwistle	1983
Brookwell, B.	Representation and Display of Selected Surfaces Using Texture Mapping	D. Hill	1983
Girling, D.	Well-Tempered Speech Synthesizer	D. Hill	1983
Barker, K.	Local Area Network Security	T. Keenan	1984
Dohrn, C.	Speech Pad: Direct Manipulation Computer Access for the Visually Disabled Based on Speech and Touch	D. Hill	1984
Greenberg, S.	User Modeling in Interactive Computer Systems	I. Witten	1984
Liblong, B.	A Structured Hierarchical Intermediate Form for VLSI Design	G. Birtwistle	1984
Lomow, G.	Distributed Software Prototyping and Simulation	B. Unger	1984
Vatti, R.	Multiprocessor Ray-Tracing	D. Hill	1984
Bonham, M.	Viewing and Formatting Documents On-line	I. Witten	1985
Dewar, A.	A Graphical Prolog Debugger	J. Cleary	1985
Kramer, L.	Knowledge Representation in Expert Systems	J. Cleary	1985
Kornfein, R.	Mechanization of Reasoning	J. Cleary	1985
Lukey, T.	Program Comprehension and Debugging	D. Hill	1985
Masrani, R.	Natural Language Processing in Object Oriented Prolog	I. Witten	1985
Novacek, M.	Particle Graphic Systems	B. Wyvill	198
Zissos, A.	An Expert System for Analyzing Editor Interaction Traces	I. Witten	1985
Coates, B.	A Fast Instruction Memory	G. Birtwistle	1985
Kroeker, W.	EFIDO a silicon compiler for digital filters	G. Birtwistle	1986

THESES IN PROGRESS

Name	Full Titles	Supervisor	Expected Completion Date
Bao, P.	Numerical Analysis	J. Rokne	1987
Brinsmead, M.	VLSI	G. Birtwistle	1987
Dignum, J.	Specification of Human Interface	D. Hill	1986
Du Wors, R.	Human Computer Interaction and Expert Systems	D. Hill	1985
Esau, R.	Speech Interaction(Ph.D.)	D. Hill	1988
Greenberg, S.	Intelligent Adaptive Interfaces (Ph.D.)	I. Witten	1986
Harris, S.	Expert Systems for Oil Well Logging	J. Cleary	1986
Inkster, J.	Distributed Simulation	B. Unger	1985
Irving, G.	Interactive Dialog Design Tools (Ph.D.)	D. Hill	1985
Jansonius, C.	Intelligent Tutoring Systems	D. Hill	1986
Joyce, J.	Specification Directed VLSI design (Ph.D.)	G. Birtwistle	1987
Liu, E.	An Expert System for Gate Matrix Layout(Ph.D)	G. Birtwistle	1986
Li, X.	Software (Ph.D.)	B. Unger	1988
Lomow, G.	Distributed Systems (Ph.D.)	B. Unger	1986
Pearce, A.	Multiprocess Ray-Tracing	J. Cleary	1986
Schack, B.	Human Memory Simulation	B. Unger	1986
Schediwy, R.	A CMOS cell architecture and library	G. Birtwistle	1986
Singh, R.	Algorithms	B. Wyvill	1987
Stone, G.	VLSI	G. Birtwistle	1987
West, D.	Artificial Intelligence	B. Unger	1987
Wolters, M.	Numerical Analysis	J. Rokne	1989
Wu, X.	A Digital Image: Processing & Coding(Ph.D)	J. Rokne	1986
Yen, Y.	Parallel Algorithms for an Integer Programming Problem	B. Unger	1986
Yow, C.	VLSI	G. Birtwistle	1989

Appendix B: Publications During The Project Period

REFEREED JOURNAL PAPERS

Birtwistle, G.M., Lomow, G.A., Unger, B.W., and Luker, P. (1984A) "Process Style Packages For Discrete Event Modelling: Using Simula's class Simulation" *Transactions on Simulation, 1* (2) 175-195.

Birtwistle, G.M., Lomow, G.A., Unger, B.W., and Luker, P. (1984B) "Process Style Packages For Discrete Event Modelling: Data Structures and Packages in Simula" *Transactions on Simulation, 1* (1) 61-82.

Birtwistle, G.M., Lomow, G.A., Unger, B.W., and Luker, P. (1985) "Process Style Packages For Discrete Event Modelling: Transaction, event, and activity approaches" *Transactions on Simulation, 2* (1) 27-56.

Birtwistle, G.M., Luker, P., Lomow, G.A., and Unger, B.W. (1986) "Design and implementation of Demos" *in press Transactions on Simulation.*

Bonham, M. and Witten, I.H. (1985A) "Re: A large font virtual terminal interface: a software prosthesis for the visually impaired" *Communications of the Association for Computing Machinery, 28* (11) 1236-1237, November.

Bonham, M. and Witten, I.H. (1985B) "Distributed document preparation with interactive and noninteractive viewing" *INFOR, 23* (4) 365-388, November.

Cleary, J.G. and Witten, I.H. (1984A) "Data compression using adaptive coding and partial string matching" *IEEE Transactions on Communications, COM-32* (4) 396-402, April.

Cleary, J.G. and Witten, I.H. (1984B) "A comparison of enumerative and adaptive codes" *IEEE Transactions on Information Theory, IT-30* (2) 306-315, March.

Cleary, J.G. (1984C) "Compact hash tables using bidirectional linear probing" *IEEE Transactions on Computers, C-33* (9) 828-834, September.

Cleary, J.G. and Darragh, J.J. (1985) "A fast compact representation of trees using hash tables" *IEEE Transactions on Computers.*

Cleary, J.G., Wyvill, B., Birtwistle, G.M., and Vatti, R. (1986A) "Multiprocessor ray tracing" *in press Eurographics.*

Corbett, C. and Witten, I.H. (1982A) "On the inclusion and placement of documentation graphics in computer typesetting" *Computer Journal, 25* (2) 272-277, February.

Corbett, C. and Witten, I.H. (1982B) "Host-satellite software tools for microcomputer systems" *IEEE Journal on Software and Microsystems,* 35-40, February.

Greenberg, S and Witten, I.H. (1985) "Adaptive personalized interfaces - a question of viability" *Behaviour and Information Technology, 4* (1) 31-45, March.

Hutchinson, N., Patten, T., and Unger, B.W. (1985) "The Flooding Sink: A New Approach to Local Area Networking" *in press Computer Networks, 10* (2).

Jassem, W., Hill, D.R., and Witten, I.H. (1984) "Isochrony in English Speech: its statistical validity and linguistic relevance" *Pattern Process & Function in Discourse Phonology, Berlin: De Gruyter,* 203-225.

Keenan, T. (1982) "The Computer Media" *Journal of the Alberta Association for Continuing Education, 10* (1) 39-44, May.

Liblong, B., Melham, T., Birtwistle, G.M., and Kendall, J. (1985) "Towards a VLSI Design Tool System" *Canadian INFOR Journal, 23* (4) 389-402, May.

Lomow, G.A. and Unger, B.W. (1985) "Distributed Software Prototyping and Simulation in Jade" *Canadian INFOR Journal, 23* (1) 69-89, February.

Pooley, R. and Birtwistle, G.M. (1986) "X25 prototyping in Demos" *accepted by Advances in simulation modelling.*

Rokne, J. and Wu, T. (1982A) "The circular complex centered form" *Computing, 28,* 17-30.

Rokne, J. (1982B) "Optimal computation of the Bernstein algorithm for the bound of an interval polynomial" *Computing, 28,* 239-246.

Rokne, J. and Wu, T. (1983A) "A note on the circular complex centered form" *Computing, 30,* 201-211.

Rokne, J., Singh, B.M., and Dhaliwal, R.S. (1983B) "Diffraction of torsional waves by a circular rigid disc at the interface of two bounded dissimilar elastic solids" *Acta Mechanica, 40,* 139-146.

Rokne, J. and Alefeld, G. (1984) "On the iteractive improvement of approximate triangular factorization" *Beitraege zur Numerische Mathematik, 12,* 7-19.

Rokne, J. (1985A) "A low complexity explicit rational centered form" *Computing, 34,* 261-263.

Rokne, J. (1985B) "Including Iterations for the Lambda-Matrix Eigenproblem" *Computing, 35,* 207-218.

Rokne, J., Singh, B.M., and Dhaliwal, R.S. (1985C) "Diffraction of torsional waves by a penny-shaped crack in an infinitely long cylinder bonded to an infinite medium" *in press Journal of Engineering Fracture Mechanics.*

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Rokne, J. (1986B) "A Simple Method for Computing the Values of the Derivative of a Rational Function" *in press Journal of Computational and Applied Mathematics.*

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Witten, I.H., Bonham, M., and Strong, E. (1982A) "On the power of traps and diversions in a document preparation language" *Software Practice and Experience, 12,* 1119-1131.

Witten, I.H. and Neal, R. (1982B) "Using Peano curves for bilevel display of continuous-tone images" *IEEE Computer Graphics, 2* (3) 47-52, May.

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Witten, I.H. and Wyvill, B. (1983B) "On the generation and use of space-filling curves" *Software Practice and Experience, 13,* 519-525.

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Witten, I.H. and Bramwell, B. (1985A) "A system for interactive viewing of structured documents" *Communications ACM, 28* (3) 280-288, March.

Witten, I.H. (1985B) "Elements of computer typography" *International Journal of Man-Machine Studies, 23* (6) 623-687, December.

Wyvill, B.L.M., McPheeters, C., and Garbutt, R. (1985A) "A practical 3D computer animation system" *in press Journal of the British Kinematographic, Sound and Television Society.*

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Zissos, A.Y. and Witten, I.H. (1985) "User modelling for a computer coach: a case study" *International Journal of Man-Machine Studies, 23* (6) 729-750, December.

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Bonham, M. and Witten, I.H. (1985) "Shape - a unifying concept in document layout" *Proc. PROTEXT II* , 126-132, Dublin, Ireland, October.

Bramwell, B. (1984) "Browsing around a manual" *Proc. Canadian Information Processing Society Session '84*, 438-442, Calgary, Alberta, May.

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Cleary, J.G., Lomow, G.A., Unger, B.W., and Xiao, Z. (1985A) "Jade's IPC Kernel for Distributed Simulation" *Proc. Association of Simula Users*, Calgary, Alberta, August.

Cleary, J.G. (1985B) "A Distributed Implementation of And-parallel Concurrent Prolog" *Proc. IEEE International Conference on Parallel and Distributed Systems*, Calgary, Alberta.

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Esau, R., Kroeker, W., and Birtwistle, G.M. (1984) "The RLC Silicon Compiler" *VLSI'84 Conference*, Edmonton, Alberta, September.

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Hill, D.R., Dohrn, C., Darragh, J., Esau, R., Levinson, D., Unger, B.W., and Witten, I.H. (1984A) "Using speech output as a medium for human-computer dialogue" *Proc. Canadian Information Processing Society Session '84*, 470-476, Calgary, Alberta, May.

Hill, D.R. and Irving, G. (1984B) "The Interactive Dialog Driver: a UNIX Tool" *Proc. Canadian Information Processing Society Session '84*, 307-313, Calgary, Alberta, May.

Hill, D.R., Witten, I.H., Neal, R., and Lomow, G.A. (1984C) "Jecl and Hide: practical questions for the Jade user interface" *Proc. Canadian Information Processing Society Session '84*, 373-380, Calgary, Alberta, May.

Hill, D.R. (1986A) "Interacting with future computers" *Proc. Int. Future Advances in Computers*, Christchurch, New Zealand, February.

Hill, D.R. (1986B) "Voice as a computer input and output medium in the health care context" *Human-Computer Communications in Health Care*, 131-146, Stockholm, Amsterdam, June.

Hill, D.R. (1986C) "AI: in the beginning" *invited paper at Int. Future Advances in Computing Conference*, Christchurch, New Zealand.

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Inkster, J., Lomow, G.A., and Unger, B.W. (1984) "Combined Continuous and Discrete-Event Simulation in Ada" *Proc. SCS Conference on Simulation in Strongly Typed Languages*, San Diego, California, February.

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Keenan, T (1982) "Strategic Issues in Distributed Data Processing" *Proc. CIPS National Conference*, Toronto, Ontario, November.

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Lomow, G.A. and Unger, B.W. (1982) "The Process View of Simulation in Ada" *Proc. SCS Winter Simulation Conference*, 77-86, San Diego, California, December.

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Masrani, R. and Keenan, T.P. (1984) "Security and privacy in cellular telephone systems" *Proc. AFIPS Conference on Computer Security*, 397-410, Toronto, Ontario, September.

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Unger, B.W., Dewar, A., Cleary, J, and Birtwistle, G.M. (1986B) "The JADE approach to distributed software development" *Proc. SCS Conference the 2nd European Simulation Congress*, Antwerp, Belgium, September.

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Appendix C: A Jade VLSI Application

The VLSI Research group used Jade software to prototype a facility for testing fabricated IC chips. The test facility employs both the Jade Interprocess Communication system (Jipc) and the user-interface prototyping features of the Jade workstation. We have used this facility to test a chip called "TAMARACK" which is a simple microprocessor recently designed by one of our group members.

Figure 1 is a snapshot of the graphical monitoring tool called Mona showing a system of three communicating processes involved in testing the TAMARACK chip. The process labeled 'tamarack' generates "read pin" and "write pin" requests to the chip through a hardware interface. A variety of test interfaces allows the chip to be tested at varying levels of user interaction. These test interfaces are implemented as separate processes which communicate "read pin" and "write pin" requests to the hardware interface through the 'tamarack' process.

The other two processes, shown in Figure 1, 'pins' and 'download', are examples of test interfaces. 'pins' is an interactive graphical interface (see Figure 2) that allows individual input pins of the test chip to be toggled between +5v and 0v by 'clicking' on/off buttons of the graphical user interface. A solidly filled button represents +5v at the corresponding pin whereas an unfilled button represents 0v. A half-sized square inside a button represents an undefined voltage. For example, to cycle the TAMARACK chip through a complete microcycle, the "phiA" button must be clicked on and then off, followed by clicking "phiB" on and then off. [1] Each time an input pin is toggled, all of the output pins of the chip are read and the graphical interface is updated to show the resulting state. The 'pins' test interface facilitates fine-grained testing of the TAMARACK chip. At a more advanced stage of testing, the 'download' interface is used to download test programs to the TAMARACK chip. This interface also communicates "read pin" and "write pins" requests to the hardware interface through the 'tamarack' process.

A variety of other test interfaces are envisioned and each of these would be similarly integrated into the test facility as Jipc processes. One advantage of implementing this test facility as a system of communicating processes is that more than one test facility can be used at once. For example, a specialized test interface may generate a sequence of "write pin" requests to perform a complex test on the chip. In this case, the graphical display of the 'pins' interface can be used to monitor the test.

Separating the task of generating requests to the hardware from the human interface task allows several test interfaces to be used simultaneously. This division also allows the hardware to be replaced by a functionally equivalent simulation. We have used both the 'pins' and 'download' test interfaces to drive a switch-level simulation of the TAMARACK chip. In this case, the simulation process is run instead of the hardware interface process. The simulation process follows the identical protocol and thus, whether the actual chip or a simulation of the chip is used remains transparent to the test interfaces.

In short, we believe that the organization of this test facility as a system of communicating processes offers several advantages in terms of functionality and re-configurability. This facility was easily prototyped in approximately three days using Jade software.

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1 A two phase non-overlapping clocking scheme is used. Clock signals can be generated manually because TAMARACK is based entirely on static logic.

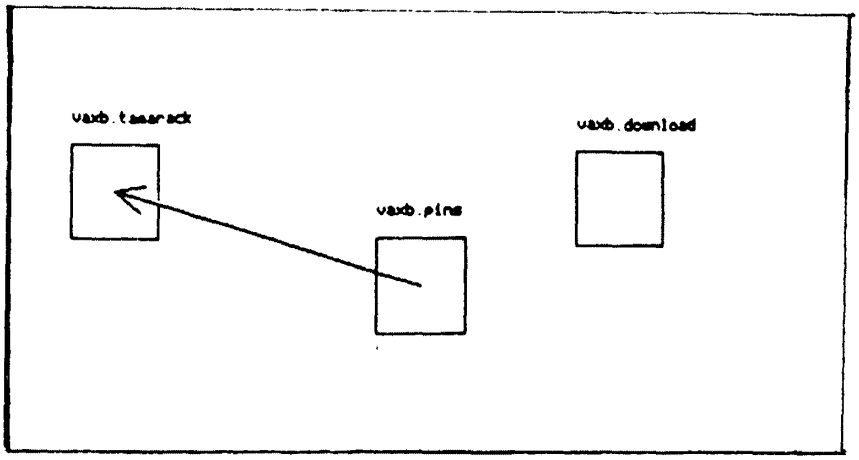

Figure 1. Distributed system Implementing VLSI chip testing facility.

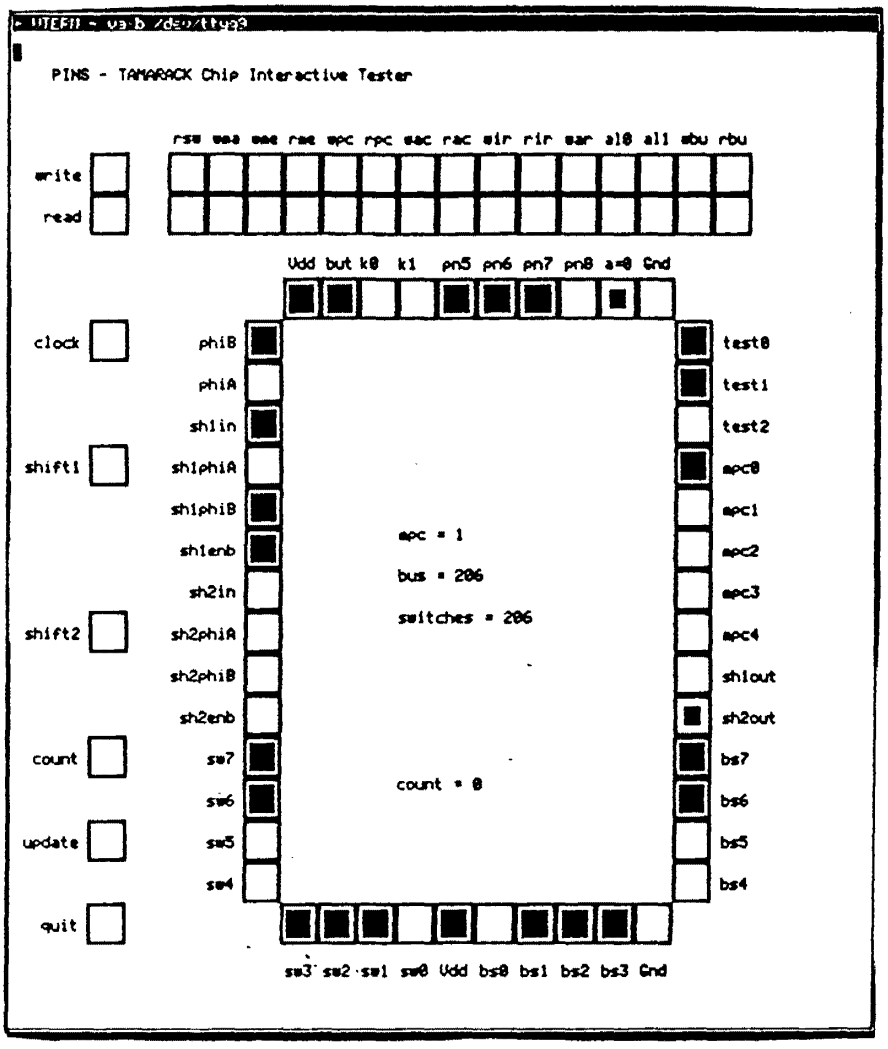

Figure 2. Interactive graphical chip test interface.