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Contents

Database Engineering Bulletin is a quarterly publication of the IEEE Computer Society Technical Committee on Database Engineering. Its scope of interest includes: data structures and models, access strategies, access control techniques, database architecture, database machines, intelligent front ends, mass storage for very large databases, distributed database systems and techniques, database software design and implementation, database utilities, database security and related areas.

Contribution to the Bulletin is hereby solicited. News items, letters, technical papers, book reviews, meeting previews, summaries, case studies, etc., should be sent to the Editor. All letters to the Editor will be considered for publication unless accompanied by a request to the contrary. Technical papers are unrefereed.

Opinions expressed in contributions are those of the individual author rather than the official position of the TC on Database Engineering, the IEEE Computer Society, or organizations with which the author may be affiliated.

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Letter from the Editor

This issue of Database Engineering focuses on highly available systems. The first five articles are from commercial vendors who market fault-tolerant computer systems. The next three articles describe specific systems that were built for applications which required a high degree of availability. The final article on this topic presents some new research directions for maintaining system availability. This issue also includes one general interest paper from Germany on database programming languages.

More and more end users of automatic teller windows, on-line reservation systems, and word processors are becoming dependent on the continuous availability of interactive computer systems. System failures, which can shut down these or other applications, thus have an increasing impact on the day to day operations of both companies and individuals. Tandem Computers Incorporated recognizing the serious impact of such failures has been a pioneer in the development of fault-tolerant systems. (An overview of the Tandem's approach to fault-tolerance can be found in the December 1983 issue of Database Engineering and is not repreated in this issue.)

Since Tandem's success, numerous other companies are developing fault-tolerant hardware and software systems. This issue contains overviews of the systems provided by Auragen, Computer Consoles, Stratus, Synapse, and Syntrex. Each article describes a different architecture and operating system approach to maintaining high availability. The articles also describe how specific types of failures are handled.

The next three papers describe how high availability is maintained for specific distributed applications. A paper from Bell Labs describes the redundancy and transaction processing of a system to support the Direct Services Dialing Capability. A paper from Bank of America describes a large bank teller support system and presents some impressive availability statistics. A paper from Philips Data Systems then describes the transaction mechanisms they support to allow continuous processing even though some of the updates have to be delayed.

The final paper, from UCLA, describes how the reliability and thus availability of systems can be increased through direct operating system management of distributed and replicated name spaces and general distributed transaction mechanisms.

I would like to thank the contributors to this issue. It is clear that there are many approaches to increasing system availability. I suspect that sometime in the not too distant future continous operations in the presence of a small number of failures will become the norm of what is expected from computer systems. I trust that the readers will find the overviews of the different approaches as interesting and informative as I have.

Future Issues

Database Engineering will continue to devote each issue to a special topic. The topics of the next four issues are described below:

1. Expert Systems. Dr. Adrian Walker (IBM Research, San Jose) is the Guest Editor for the September issue.

2. Automated Office Systems. Prof. Fred Lochovsky (visitor at IBM Research, San Jose from the University of Toronto) is the Guest Editor of the December issue. Submission Deadline is August 1.

3. Statistical Database Management. Prof. Don Batory will be the editor of the March, 1984 issue. Submission deadline is November 1.

4. Engineering Design Databases. Prof. Randy Katz will be the editor in charge of the June, 1984 issue on this topic. Submission deadline is February 1.

Papers relevant to these special topics should be submitted to the editor in charge of that issue and to Dr. Won Kim, our Editor-in-Chief. As space is available we will also accept a few general interest papers for each issue. These papers should be sent directly to Dr. Kim.

Daniel R. Ries

The Auragen System 4000

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The Auragen System 4000 is an expandable, fault-tolerant multi-micro-processor designed to provide a foundation for a wide variety of high availability applications in the transaction processing, comunications and office automation arenas. The wide applicability of the system is due to a combination of a novel architecture, the implementation of a highly enhanced version of the UNIX ~ operating system, the addition of a full-function relational database management system and the inclusion of a rich complement of productivity tools and user-oriented application development aids.

Detailed discussions of each of these features can be found in [1]. Our purpose in this note is to briefly describe the most important aspects of the Auragen approach to fault-tolerance.

I. Fault-Tolerant Design Goals

The essential ingredient of all fault-tolerance is redundancy -- in both hardware and software. The amount of redundancy, and where to employ the redundancy, is largely determined by the number and the types of failures to which the system is designed to be immune.

In general, failures come in three flavors:

a) permanent physical failures such as shorted connectors, burnt out chips, etc.
b) transient component failures due chiefly to temporary environmental disturbances, and
c) operational mishaps such as data entry errors, the use of erroneous software, etc.

Failures of type c) are the hardest to deal with and are best handled by software. The easiest case is when mishaps occur in connection with the storage and retrieval of information from large files. Here there are a number of well-known recovery techniques, involving the use of redo and undo logs, which have proved to be quite robust, and require no special hardware to implement. Variations on such techniques have been incorporated into AURALATE, the Auragen relational DBMS and will be discussed later. Unfortunatly, however, the general problem of providing automatic recovery from operational mishaps is very difficult to deal with in a systematic manner, and really falls outside the realm of fault-tolerant computing as practised today.

Instead, designers of fault-tolerant computer architectures have

~ UNIX is a trademark of Bell Laboratories

sought largely to cope with physical failures. In the case of the Auragen system, the main goal has been to produce a machine with continuous, or nearly continuous, availibility despite the inevitable occurances of physical failures. This goal has been achieved by designing an architecture which

1) provides survivability through any single hardware failure,
2) enables users to repair failures (i.e. change faulty boards) while the system is running and
3) enables users or field engineers to expand and reconfigure a system without having to shutdown and subsequently sysgen again.

Except for possibly the requirement that users be able to repair and reconfigure systems themselves, none of these features are new; what is new is the ways in which they have been implemented.

II. Hardware Organization

An Auragen system is a loosely coupled configuration of between 2 and 32 clusters, interconnected by two 16 megabyte/sec shared buses. Under normal circumstances, in the absence of a bus failure, the two buses behave as a single 32 megabyte/sec bus.

The clusters themselves are tightly coupled multiprocessors consisting of their own memory, power supply, battery backup, several different kinds of intelligent I/O controllers and 3 MC68000's. One of the 68000's is used exclusively for performing operating system functions, while the other two are used to process user tasks. All peripherals are dual ported and are always attached to two separate clusters -- although peripherals need not be attached to each cluster. Discs, which have higher survivability requirements than other peripherals, may optionally be configured to operate in mirrored pairs.

This organization has enough hardware redundancy within a two cluster system so as to be able to continue operating after any single hardware failure. Systems with three or more clusters can survive some types of multiple hardware failures.

III. Operating System Support

The Auragen operating system, AUROS, is a significant enhancement of UNIX System III. From the outside, it looks exactly like a superset of System III, in that it supports all the standard UNIX facilities and interfaces, in addition to some new and very user friendly capabilities at the command level.

Internally however it is entirely different from System III. Among the many enhancements are

a) a demand paged virtual memory system allowing virtual addressing up to 32 Mbytes per process,

b) extensive interprocess communication facilities employing both messages and shared memory,
c) a distributed process structure in which all I/O services have been split off from the kernel and placed into separate server processes for mulitprocessing efficency,
d) automatic load balancing among clusters, and
e) a fault-tolerant mode of operation based on the automatic creation of backup processes in foreign clusters.

This last feature, which is described more fully in the next section is what gives the Auragen system its unique character in the fault-tolerant marketplace. Indeed, because fault-tolerance is implemented at a very low level , i.e. entirely within the AUROS kernel, any program which will run under UNIX System III, will run on the Auragen system in a completely fault tolerant fashion -- without any special action on the part of the user.

IV. Fault-Tolerant Implementation

Prior to the mid 1970's, virtually all fault-tolerant computers employed duplicate components, either as standby spare parts, or in a majority voting type of configuration, whereby the duplicate components would simultaneously replicate each other's actions. The types of machines built using these early approaches were invariably special purpose systems intended mostly for military, space and telephone switching applications. The major disadvantage of such designs was one of cost; at least three or four times the number of components needed to build an equivalent non-fault-tolerant machine were required to build one of these systems -- but unfortunately no extra computing power could be derived from the duplicate components.

In the mid 70's, Tandem Computers [2] pioneered an approach to fault-tolerance which partially solved the problem of wasted duplicate resources. The Tandem design, which was aimed specifically at the commercial transaction processing market, involved creating an inactive process, P-bak, for each active process P. P and P-bak would live in different processors, so that if a failure should occur in P's processor, P-bak would immediately be activated in its processor. Since, in the absence of failures, P-bak does not execute, this scheme allows all the duplicate hardware to be used for non-redundant work most of the time.

The Auragen design began with the conviction that the Tandem approch was the most cost effective of all approaches to fault-tolerance, but that the Tandem implementation was less than optimal in at least two ways.

First, the data portion of P-bak had to be kept almost exactly up to date with P's data space. This was done by having P send a "checkpoint" message to P-bak everytime P did an I/O. Although P-bak did no processing upon receipt of the checkpoint message, a

very significant amount of message traffic, and thus processor activity, was generated in the process of handling the checkpointing mechanism.

The second shortcoming of the Tandem approach was that the creation and awareness of P-bak, as well as the sending of the checkpointing messages, was entirely the responsibility of the programmer. This made the writing and testing of fault-tolerant programs significantly more difficult than the development of non-fault-tolerant applications. Tandem recently remedied this situation somewhat by providing tools which would automatically do the checkpointing for the programmer. Those tools however, are quite disappointing in that they only handle a limited class of applicatons, and their use generates significantly more checkpointing overhead than the amount which would be generated by a clever programmer doing his own checkpointing.

To remove these two shortcomings, Auragen developed a technique strongly analogous to the rollforward type of recovery employed by many database management systems. A full description of the method is given in [3], but the basic ideas are as follows. Instead of having P checkpoint its data space at the occurance of every I/O, AUROS arranges to have all messages received by P simultaneously deposited in a message queue at P-bak. Only after P has processed some system defined number of messages will P-bak's data space be synchronized with that of P. After the synchronization is complete, all the messages queued at P-bak are discarded and the whole process is repeated.

If a failure should occur which causes the activation of P-bak, then P-bak will begin execution at the point of its last synchronization. Since the message queue at P-bak contains all the messages sent to P -- between the time of the last synchronization and the failure -- P-bak can easily redo all the work done by P within that interval, and continue on from there. Of course some care has to be taken during the rollforward phase to insure that P-bak does not redo any work which P has done that is already reflected somewhere else in the system. A clever technique to handle this has been devised, and is fully described in [3].

The whole procedure of queuing messages, synchronizing the P-bak's with the P's and initiating recovery upon fault detection is entirely handled by AUROS. Fault detection itself is implemented by a variety of hardware and software methods. These include parity checking, power level monitors, watchdog timers, background diagnostics and very careful checking of system call parameters.

The scheme of having a completely inactive P-bak, infrequently synchronized with P, clearly trades off a somewhat longer recovery time -- 5 to 10 secoonds on a system-wide basis -- for significantly higher system performance during normal processing times. Since permanent failures which bring down clusters are relatively rare events -- maybe 5 or 6 times a year -- and since transient failures will generally require recovery for only single processes, this

tradeoff seems highly desirable.

V. Database Management

As UNIX itself offers little in the way of sophisticated data management services, it was necessary for Auragen to build a number of such facilities on top of AUROS. Among the facilities provided are a multiuser B-tree-based ISAM -- intended for use with the Auragen supplied COBOL -- and, more significantly, a full function relational database management system, AURALATE. As an upward compatable extention of IBM's relational product SDL/DS, AURALATE supports an impressive list of functional capabilities.

For a full description of AURALATE, the reader should refer to [1] and the references contained therein. Our interest in AURALATE here is concerned solely with AURALATE's recovery mechanisms, which as we shall see, have interesting performance consequences.

As with most sophisticated DBMS's, AURALATE employs an optional redo log of after images (intended for rollforward recovery from an old copy of a database after a media failure) and a mandatory undo log of before images (used to support both transaction backout, and warm restart after any non-media failure). The proper maintainance of such logs on most systems requires expensive commit processing.

In general, various write-ahead-log and buffer flushing protocols are needed to insure that sufficent information for recovery is contained in the appropriate disc files, rather than in system buffers, which after a failure, must be assumed to be corrupt. Specifically, these protocols have the effect of degrading performance by causing disc writes at every commit point, rather than buffering the writes for defferal to a later time.

On a system such as the Auragen, where fault tolerance has already been implemented at a level much lower than the DBMS, it turns out that commit processing need not require write-ahead-log and buffer flushing. This is because there are only two ways for a transaction (or AURALATE itself) to abort; either because of some external cause (hardware failure), or through some fault of its own (operator abort, illegal memory access etc). In the first case the transaction's backup will take over in a foreign cluster and continue as if nothing had happened, so in effect the transaction does not abort at all. In the second case, the abort signal will be trapped and the apppriate transactions backed out before closedown. Thus only in the second case is a restart necessary, but no special action need be taken by the restart procedure.

In this scenario, the undo log is used only to support transaction backout -- and in a very inexpensive manner. Skeptics who believe that failures may cause the loss of main memory, can if they wish, enable the expensive type of commit processing. Hopefully, after some experience with the system, they will regard it as unnecessary.

Another unnecessary luxury is the redo log, if the mirrored disc option is used. Since the redo log requires additional disc writes, whereas writes to a mirrored disc are essentially free, once again we see that a low level implementation of fault-tolerance can provide some performance benefits at higher levels.

VI. Performance

A single 8 Megahertz 68000 costs about $60 and has about 25% of the raw computing power of a VAX 11/780 [4,5]. If you put 7 or 8 68000's together in the proper way, an impressive amount of performance is potentially achievable. Part of the significance of the Auragen accomplishment is a demonstration of precisely this fact.

At the time of this writing (May 1983), the System 4000 is about 3 months away from being subjected to detailed performance testing. All preliminary indications, however, very conservatively suggest that a two cluster Auragen system will run about one and a half times as fast as a VAX 11/780 within a transaction processing environment. (Comparatively configured, the Auragen will cost about one half as much as the VAX.) Similarily, we expect a 10-15 cluster system to provide the transaction processing power of a large IBM mainframe at a fraction of the cost.

Some of this impressive price/performance capability is due to the availability of cheap LSI components. Much of it, however, is due to the distributed multiprocessor architecture of the system coupled together with the way the operating system has been split into a large number of small processes.

It should be emphasised however, that although an Auragen system is completely distributed -- and that, for example, clusters can be configured to serve as front or back ends to other clusters, and that programs can be downloaded into terminals -- at the user level all that is seen is a single system running a single copy of AUROS.

VI. References

[1] Auragen Systems Corporation, System 4000 Overview, Fort Lee, NJ, 1983.

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Transaction Processing in the PERPOS Operating System

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1.0 INTRODUCTION

PERPOS is an operating system developed by Computer Consoles, Inc. (CCI) for a new family of general-purpose computer systems based upon the Perpetual Processing architecture. These are expandable, fault-tolerant systems designed for on-line transaction processing. The basic architecture has been in use since 1976 in special purpose telephone industry applications. These new systems combine many of the architecture concepts from those previous systems with a set of new general purpose features. They feature, in addition to fault-tolerance, UNIX™-compatible transaction processing supported by a shared global file system.

This architecture consists of three basic types of components having distinct functional roles as application processors, coordination processors, and front-end processors* which are interconnected through a local network. A system may be configured with a variable number of components operating as distributed front-end processors and a pool of application processors that dynamically share the work load and provide fault tolerance.

The multiple components of these systems are logically coupled by a specialized communications interface to operate as a single functional entity, yet each is a separate, independently running computer.

This paper focuses on the system features which provide the multi-processor, fault-tolerant, transaction processing environment. The system is not limited to these features; it can support many other application models including typical dialogue-oriented interactive sessions and loosely coupled distributed processing. Different combinations of the same system features determine these other models; they are, therefore, indirectly described, but not otherwise elaborated upon.

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* These names for the system components are used to clarify issues central to this paper. They are not intended to supplant the names used in other literature from CCI concerning the Perpetual Processing system.

2.0 SYSTEM ARCHITECTURE

The system architecture consists of a high-bandwidth local network (Data Highway) which interconnects a pool of application processors, distributed front-end processors, and redundant coordination processors, as shown in Figure 1. Each application

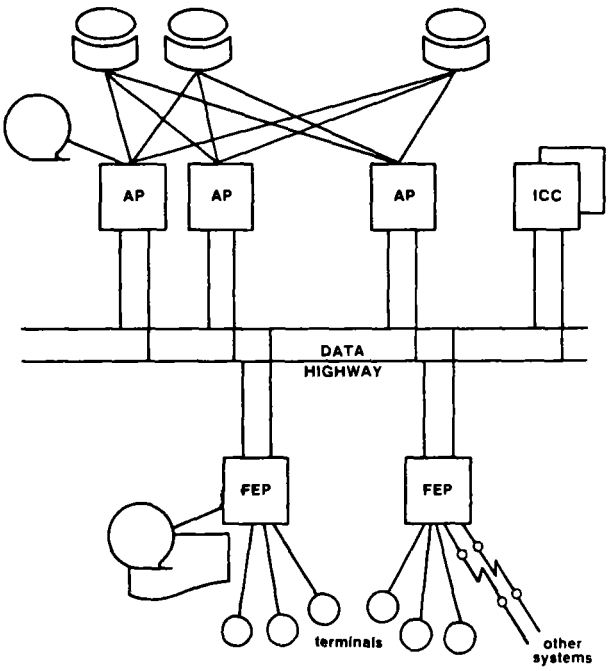

Figure 1
SYSTEM ARCHITECTURE

processor is directly connected to each of the mass storage units. This arrangement allows the application processors to be functionally interchangeable and independent of each other and to run in parallel, sharing the single global file system. Except for this multi-ported disk interface, no unique hardware requirements are dictated by the architecture.

The application processors (AP) normally execute the main body of the user's application. The front-end processors (FEP) provide a variety of functions, including terminal device handling, transaction generation, and foreign network interfaces. The interprocessor coordination controller (ICC) serves as a central coordination and synchronization point for the system.

2.1 Multi-Ported Disk Subsystem

The disk subsystem is conceptually the center of the architecture. The primary function of the other components when running a typical transaction application is moving data between disks and terminals, doing a surprisingly small amount of processing in between.

Perhaps the most unique attribute of the mass storage subsystem is the handling of replicated disk areas. To gain flexibility and save disk space, the redundancy of stored data is handled on a partition basis, rather than on a volume basis. The number of copies and their physical placement may be determined by the level of performance and fault tolerance required by each application. Read accesses are optimized by using the first available copy while data consistency is guaranteed by handling write accesses as write-to-all copies.

The use of more than two replications of a data area is primarily a performance feature for data inquiry oriented applications. Sufficient data replications can allow each application processor independent and simultaneous access.

2.2 Application Processors

Application processors are autonomous, each functioning independently of (but in cooperation with) the other system components. Even though these processors operate independently, they function as parallel processors running the same application. Load balancing is provided by a feature of the protocol used as part of the transaction interface between the front-end processors and the application processors. The front-end processors distribute transactions to the application processors based on application configuration and flow control information.

2.3 Coordination Processors

The system includes two coordination processors. At any given time one is the active coordination processor and the other is a warm standby. This standby is the only system component not actively sharing in the application tasks.

The active coordination processor is the central point for synchronizing global operations in the system. Global operations are typically resource requests which cannot be arbitrated within a local component, or system status changes which must be coordinated between multiple components. The largest percentage of these operations are data base locks used to synchronize concurrent access of a file by two or more application processors.

2.4 Front-end Processors

The system architecture permits a variety of front-end processors. Ranging in functionality from simple terminal concentrators to distributed application processors, they differ from application processors primarily in that FEPs have no direct access to the global data base, whereas APs have no direct access to terminals. In other words, front-end processors are functionally distinguished from the application processors in that they generally perform tasks which are not penalized by being separated from the global file service.

In a typical transaction application, front-end processors support such functions as screen formatting, sending transaction messages to the application processors, receiving the replies, and assisting in recovery process from some system faults. This separation of "front-end" and "back-end" processing (the back end is the pool of application processors) improves system modularity, reliability, and dynamic load balancing.

2.5 Data Highway

The application, coordination, and front-end processors are interconnected by a duplex communications network. These dual cables are in simultaneous use to enhance both the performance and the reliability of the system. Based on a distributed packet switching scheme using a CSMA/CD protocol adapted from Ethernet [1], the network implementation, which uses off-the-shelf technology, is well suited to the architecture because of its distributed control properties and high bandwidth.

2.6 Comparison with other Architectures

The Perpetual Processing architecture is a hybrid of centralized server and distributed processing approaches. It provides direct access to the file system with a central point of concurrency control and recovery as in a centralized server environment. On the other hand, it has the modularity and flexibility of a distributed architecture; in addition, it provides reliability features typically lacking in either centralized or distributed systems.

This architecture also differs from most other fault-tolerant systems. General-purpose fault-tolerant systems often consist of a series of interconnected pairs of computer components where the primary is used for application tasks and the backup comes into use only if the primary fails. In such systems, operations run redundantly on the backup or alternatively the primary may "checkpoint" information needed to assume control to the backup after each non-retryable step in the transaction execution [2].

The checkpointing approach allows the backup to do other tasks, but generates a high level of communication overhead. The redundant execution approach requires specially designed non-productive hardware.

These other fault-tolerant systems generally utilize fully distributed architectures since they already rely on distributed processing concepts to implement primary and backup computers. This architecture leads to performance limitations, especially for large data base oriented applications.

The PERPOS approach to processor fault handling is to use standard transaction recovery techniques [3] [4] to backout partially complete transactions (when needed) and to restart them on another processor. Recovery is simplified by the central data base and central lock server architecture (see the section on concurrency control and recovery) and automated by the front-end processors. This design causes minimal system complexity and overhead while providing fault-tolerant execution.

3.0 TRANSACTION PROCESSING FEATURES

Traditional definitions of transaction management include scheduling, resource management, concurrency control, and error recovery functions [4]. The last two are associated with maintaining data consistency and usually are closely related to the data base management features of the system. These will be treated separately below.

3.1 Process Control

Transaction management has often been implemented in the form of entirely new facilities built on top of a general-purpose operating system, duplicating the operating system functions of process control and recovery management. We have combined process management and transaction management to avoid this duplication and provide some generalized new features of distributed process control that effectively exploit the system architecture.

The PERPOS transaction execution environment consists of a network of sender and server processes distributed across the front-end and application processors. This approach is conceptually similar to a number of distributed data base proposals [4] [5] [6] [7]. The transaction senders are typically responsible for the human interface functions and the servers for data base update or inquiry functions. In PERPOS these processes are not constrained from utilizing any of the other features available on the system. They become senders and/or servers primarily by how they are invoked and the communication scheme that ties them together, not by following special programming rules.

Transaction server processes are allocated by a transaction initializer (daemon) in each application processor. They may be allocated when a message is received for that particular server or may be pre-allocated and execute many transaction instances to reduce allocation and deallocation overhead.

Transaction program allocation, message distribution, and many transaction management functions are controlled by a central transaction description table. This table describes how applications are to be distributed among the application processors (they can be unbalanced if desired), how messages are to be parsed and distributed to each program, and how the processes are to be allocated (pre-allocation, concurrency level, recovery class, etc.). An administrative utility allows on-line modification of this table.

The program interface to transmit or receive a transaction message consists of standard 'read' and 'write' system calls. Library sub-routines permit both sender and server programs to structure transaction messages to include text and data areas, screen format descriptions, field attributes, and other application-specific information. Filters are also available to strip all but the text from a message, so that UNIX commands which expect a stream of characters may be used directly as transaction server programs. This interface design allows standard UNIX language compilers, program development tools, debuggers, and even off-the-shelf programs to be used for application development, yet provides the special process control, performance and recovery attributes needed for on-line application processing.

The key feature developed for this sender/server separation is the communications scheme which connects the two components. This scheme is also fundamental to achieving the load balancing and fault tolerance objectives. It reliably delivers messages from any terminal in the network to one of the appropriate server processes on any of the application processors. This many-to-many terminal-to-process interface for transactions is distinctly different from the one-to-one interface of a UNIX "login" session (which is also supported). The layered protocol which accomplishes this communications scheme automatically compensates for newly added components, components lost due to a fault, or changes in work load on the running components.

3.1 Concurrency Control and Recovery

In addition to the process control functions described above, transaction management is typically responsible for concurrency control and error recovery. These are closely integrated with the data base management facility to provide deadlock resolution and to prevent system crashes or aborted transactions from violating data base consistency.

We agree with Stonebraker [8] that the most desirable approach to achieve internal parallelism of data base access and yet avoid duplication of operating system facilities for scheduling and multi-tasking is to use a process-per-user instead of the single-run-time-server DBMS model. For the DBMS to be distributed into user processes requires improved management of the operating system buffer pool, an efficient central lock table, and efficient task switching. Actually, providing these facilities in PERPOS was the only practical solution to supporting a general DBMS since the single-server DBMS approach has inherent conflicts with the multiple application processor architecture.

The notion of "atomic" transactions [4] [6] has so far been the key to ensuring the consistency of a database in the face of concurrent operations. A transaction is a series of data base actions (e.g., read or write a record) which corresponds to a single change in the real world. The "atomic" property of transactions is provided by keeping track of all data base changes and undoing or redoing changes after a fault so that the effect of the transaction is all-or-nothing. Accomplishing this all-or-nothing execution requires atomicity at both logical and physical levels. The physical level consists of managing writes to all copies of a replicated data area and updating the file system's internal data structures to maintain consistency; the PERPOS kernel handles these tasks transparently to the application. Logical level atomicity ensures that multiple physical requests (e.g. 'read' and 'write' system calls) are treated as a single atomic operation; it is provided by the DBMS, file-access method libraries, or directly by application programs.

Implementing atomicity at the logical level is much easier in this system architecture than in other distributed processing systems. Neither the data base nor the locks are distributed, which means most complex deadlock and "commit" protocol issues can be avoided. The single global data base allows most applications to use single-process transactions. A single process need not use two-phase commit protocols or other schemes to get all processing sites to agree unanimously on committing the transaction. Moreover, a centralized lock scheme using the coordination processor prevents "global deadlocks," where transactions in different nodes are waiting on each other to free separate local locks.

Perpetual Processing applications can, therefore, use single-machine concurrency control and recovery schemes. Also, since the front-end and coordination processors are not affected by an application processor failure, they are available to facilitate simplified, automated recovery. In effect, an application processor failure is handled in the same manner as a transaction abort. The data base locks remain set in the coordination processor (one of the requirements for atomicity) so that the data are unchanged by other transactions. When the front-end processor

is informed by the network control logic that an application processor has failed (or that a transaction has aborted), it initiates the recovery procedure.

This recovery procedure differs for different types of transactions. Transactions fall into three general classes: repeatable, automatically recoverable, and manually recoverable. In strict atomicity theory a transaction is "repeatable" if it will reproduce the original output if rerun [4]. A transaction which does not update any stored data is repeatable without recovery. A transaction is "recoverable" if it holds exclusive use locks on any data it changes and share locks on any data it reads until the commit point. In practice, transactions can be made recoverable or repeatable using many techniques.

Recovery is automatically provided for transactions that use the system DBMS or file-access methods. The front-end processor is responsible for initiating recovery transactions, when necessary, and for resending lost transactions after a transaction abort or application processor fault. These recovered or resubmitted transactions will naturally migrate to other application processors due to the communication interface design.

Strictly following these atomicity rules is not always necessary. Transactions which are not atomic can also be very useful for certain applications. For example, in an application where transaction sequence is not important, the use of share locks on read data could be dropped. Concurrency can be increased and locking overhead reduced by not holding read locks until the commit point or by not using read locks at all. In some applications (e.g., word processing) the data is less sensitive, and small inconsistencies can be corrected manually. In this case, delaying the updates until a commit point is reached is not necessary. This approach is usually used only on a copy of the data, so the original is still available as a fallback. Note that regardless of the degree of logical level atomicity used, physical level atomicity is always mandatory because inconsistencies in the file system structure would generally cause a system outage.

3.3 Performance Features

PERPOS supports a number of features geared toward allowing critical applications to obtain their needed system resources. Basic time-sharing "fair" scheduling algorithms may not be sufficient for some transaction processing applications. In order to allow a wide range of transaction processes with different response requirements to execute concurrently, memory-residency options and extended user-process priorities are provided. Key processes can be locked in memory and run before any time-sharing-type process if the system administrator desires.

Data base access performance can be optimized using contiguous pre-allocated files and features which control kernel buffer pool management. Execution speed can be further increased by using an initial stack-size designation to prevent run-time stack growth handling. With proper use of these and other features, high priority transactions can avoid most common causes of operating system overhead and contention with lower priority tasks.

4.0 USER VIEW

PERPOS provides a UNIX-compatible user interface and program execution environment. The popular UNIX operating system is widely known and needs no further description here [9]. It is a flexible, adaptable system. Achieving UNIX compatibility within our distributed architecture did present some interesting challenges. The key design tasks were in providing user transparency for transaction management, data replication, multiple concurrent application processors, and distributed front-end processors.

The user view of the system is a single machine environment. That the system consists of a network of many application processors and front-end processors instead of a single machine is made transparent by the transaction and virtual terminal interfaces. Transaction sender and server programs communicate through a facility much like a UNIX pipe, while a login session interface reads and writes a stream of characters just as in a single processor UNIX.

Data replication is another feature made transparent to user programs. Reference to a logical disk partition through the file system automatically will allow a read-from-any- or a write-to-all-physical-copies. Transparent device access logic uses standard file system path names for peripherals, just like a single machine. Moreover, peripherals on any front-end or application processor are accessed with the same path name from any component. In addition to simplifying the user view, this virtual device interface provides system reconfiguration flexibility and makes process migration much easier as a component failure recovery technique.

Of course the actual system architecture is not hidden from system administration programs. An interactive extent (i.e., disk partition) maintenance utility is provided to print or modify logical/physical extent control information (extent name, location, online/offline/error state, etc). Another utility may be used to introduce new extents or bring them up-to-date and online. Similar interactive utilities are available for network maintenance (examining and modifying component state information) and transaction processing application maintenance (transaction description table modification).

5.0 CONCLUSION

The development of PERPOS started in June 1980 and has included from 6 to 15 implementers. The PERPOS system has been running in the development lab on PDP 11/44 application processors since mid-1982. It was then ported to Motorola 68000-based processors and has been operational as a full system since December 1982. Future plans include incorporating many additional hardware developments, including higher performance processors, additional networking interfaces, and collapsing the same system functionality into fewer components.

This system is unique in that it has fault-tolerant features that do not rely on special hardware and which actually improve, rather than distract from, system performance for certain applications. The architecture provides productive redundancy where every processor is handling an active processor load (no checkpointing or process pairs) and the read-from-any logic makes use of all copies of a replicated database.

Perhaps the most outstanding feature is the user transparency of many aspects of the architecture and operation. To users this system appears the same as a typical single process UNIX computer. The Perpetual Processing features are hidden under standard program interfaces and administrative utilities. Even new features, like transaction processing, have very few semantical differences from a standard UNIX environment.

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A FAULT-TOLERANT TRANSACTION PROCESSING ENVIRONMENT

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Stratus Computer, Inc.

The Stratus/32 multiprocessor, fault-tolerant system for commercial applications supports on-line transaction processing, batch processing, word processing and interactive program development. It uses a combination or hardware and software that provides continuous processing or user programs during computer failure without checkpoint/restart programming at the user or system level. Central to the system's fail-safe operation are processing modules, each of which has redundant logic and communication paths, logic and CPU boards and main and disk memory. Twin components operate in parallel with each other; when one fails, its partner carries on.

Architectural Overview

The Stratus/32 processing modules are connected via the StrataLINK high-speed coaxial link. Each processing module consists of memory, two Motorola Corp. 68000 CPUs, at least one disk and various peripheral controllers and devices (Fig. 1). Both 68000 CPUs are visible to the operating system, and each executes its own instruction stream using a shared memory.

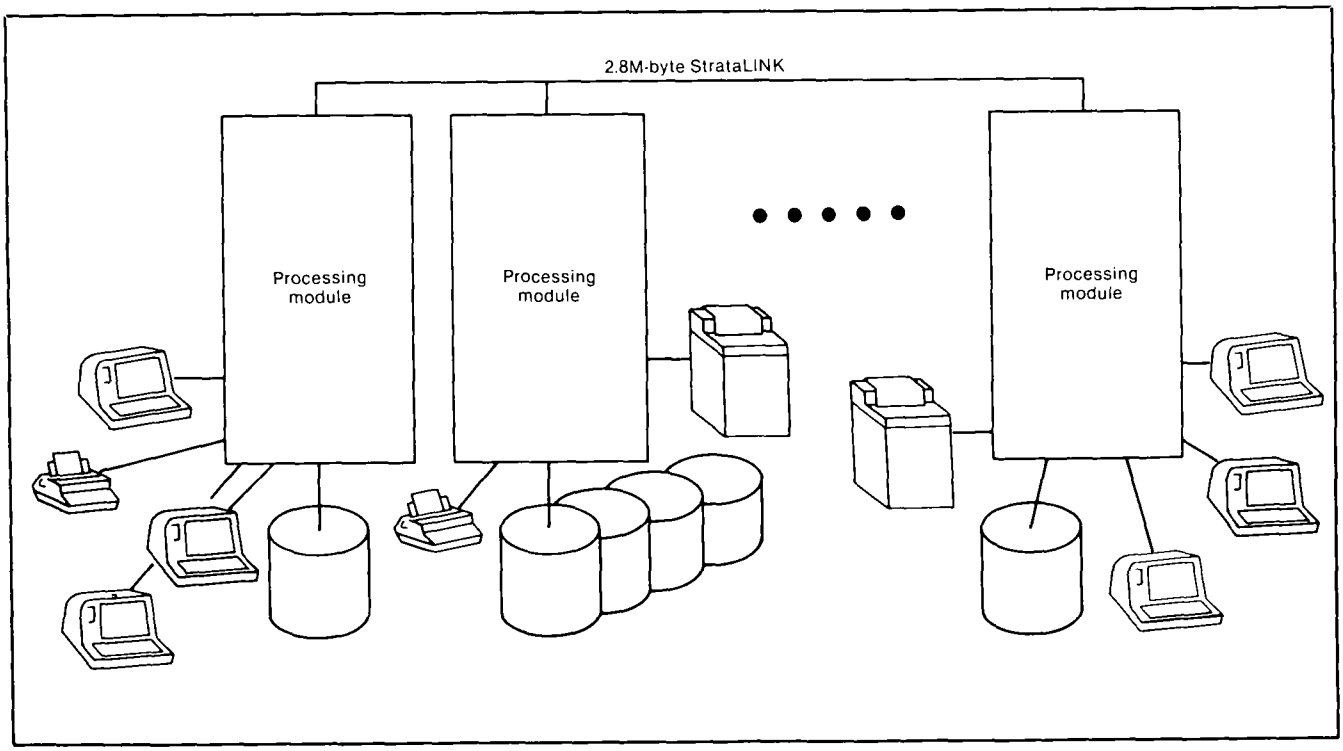

Fig. 1. A Stratus/32 system consists of as many as 32 processing modules *connected by a high-speed coaxial link. The modules can be located anywhere within an office building or can be adjacent to each other.*

Each processing module can be configured as fully redundant, partially redundant or non-redundant. The degree of a module's redundancy determines the module's resistance to hardware failure. A fully redundant module can withstand failure of essentially any component in the module without performance or data loss and without user program interruption. Multiple modules are used only to achieve greater system capacity; they never serve as backup for other modules.

Stratus's distributed virtual operating system (VOS) runs in each of the processing modules. All modules are equal and can operate independently, but through the use of transparent local networking software, VOS makes the entire set of processing modules appear as a single computer system to programs, programmers and application users.

Although each peripheral device is attached to a processing module, VOS makes all devices available to programs running in any module. Similarly, a program running in a module creates processes to run in the same module or in others. An interactive terminal user can create processes to execute commands or to run programs in any module. The users need not be aware of the module they are using. Likewise, batch jobs can run anywhere in the system.

All VOS service requests have a uniform interface that is independent of the processing module on which the work will be performed. For example, a request to open a file has the same form and arguments regardless of where the file resides. VOS examines the file name, looks in a device table to determine the module that owns the device and performs the requested operation or makes a network request over the StrataLINK to the VOS running the owning module. The requesting program does not see the network request. Consequently, user programs are unaware of the location of files or devices and see the multiple-module network as a single virtual-computer system (Fig. 2).

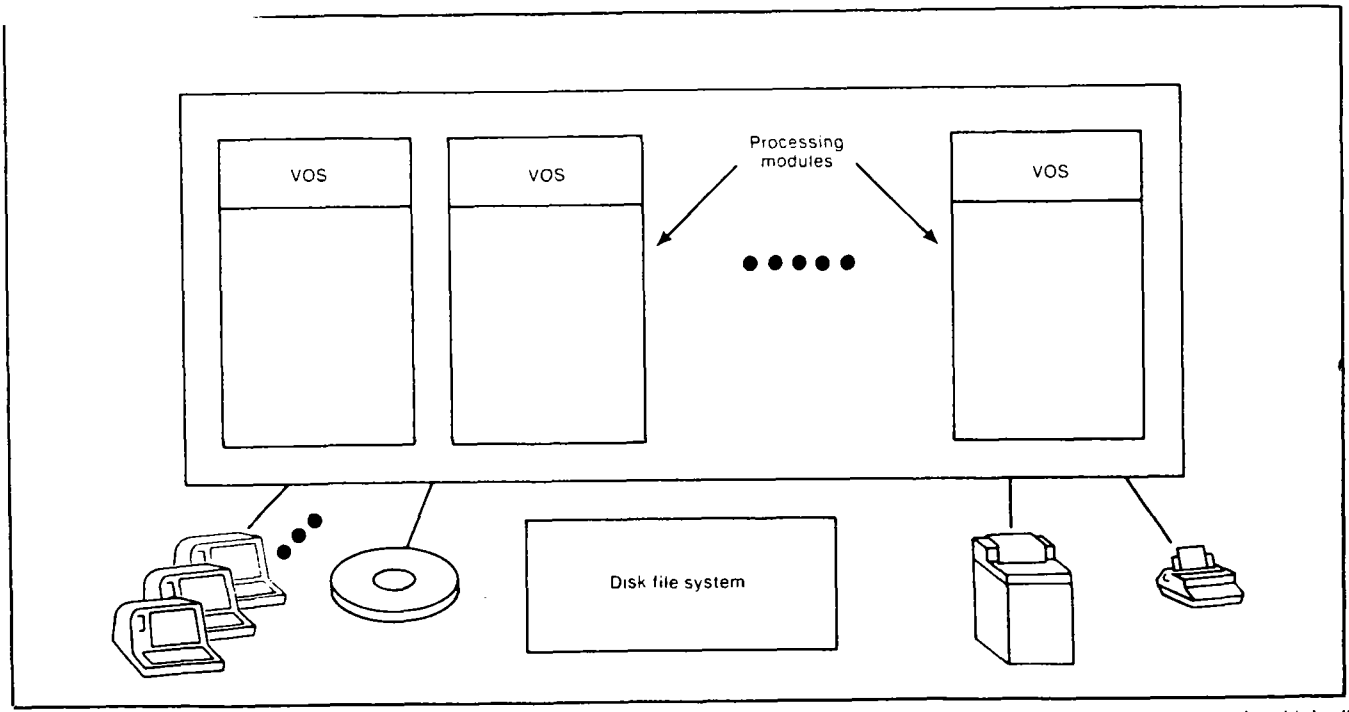

Fig. 2. The Stratus/32 virtual operating system (VOS) *makes all processing modules appear as part of a single virtual system in which all devices, files and system resources are accessible as if it were a single computer.*

Examining the Hardware

A processing module includes one or more cabinets that contain a complete computer with a logic-board chassis, dual power supplies, peripheral devices and terminal port. A single cabinet holds a fully redundant module consisting of two 143M-byte disk drives, a magnetic tape, 16M bytes of memory, redundant CPU boards and a set of redundant peripheral controllers (Fig. 3).

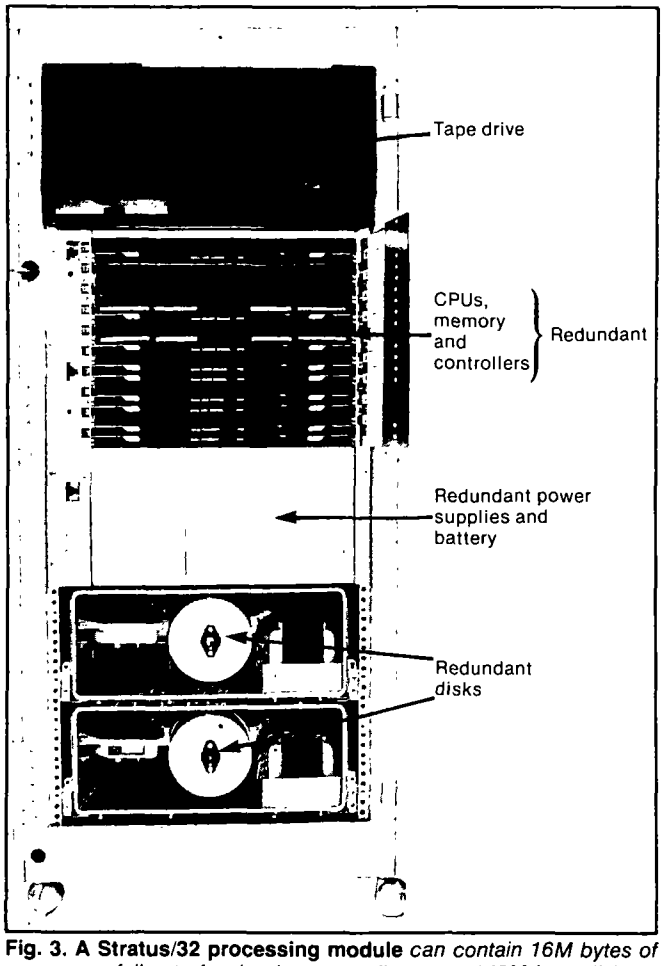

Fig. 3. A Stratus/32 processing module *can contain 16M bytes of memory, a full set of redundant controllers, two 143M-byte disks, a tape drive and two software-visible CPUs. (Additional disks and tapes are held in adjacent cabinets.)*

A high-speed bus with a 125-nsec. cycle time is central to processing-module organization. The bus -- virtually two buses operating in parallel -- has two sets of data and control-logic paths. Each logic board that can be attached to the bus can detect its own failure and shut itself down. It can also run with a redundant board that continues to operate in the event of its partner's failure. Neither logic board is primary, and neither is aware of the other. The pair of boards appears collectively to other system components as a fail-safe entity.

The self-checking technique used by each type of board differs slightly, but generally involves the uses of two sets of logic on a board. Each set performs every operation in parallel with the other. When data are to be sent to the bus or to a device, the results produced by the two sets of logic are compared. If identical, the result is sent onto the bus or to the device. Dissimilar results indicate a board failure, and no data are sent. In this case, a red LED on the board is lit, and an interrupt signal is sent on the bus. Until the board is tested and logically reconnected by maintenance software, it remains off-line. The board's redundant partner continues to operate, and no other component of the system is aware of the failure (Fig. 4).

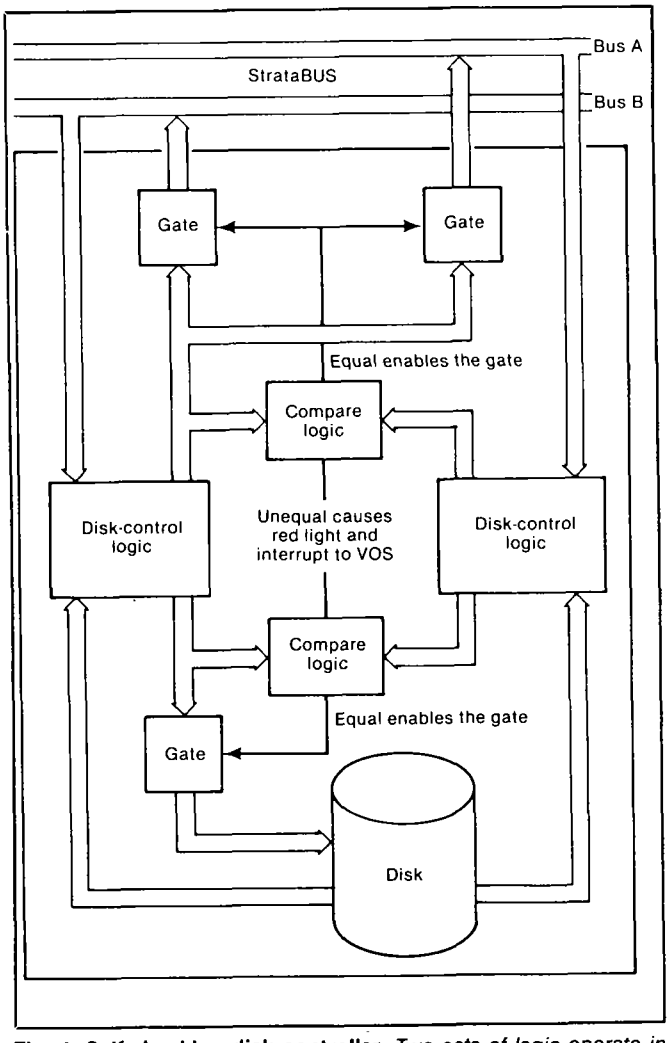

Fig. 4. Self-checking disk controller. *Two sets of logic operate in parallel with each other. If their results differ, a warning light goes on, and no data are sent until the situation is corrected.*

The CPU board contains two complete sets of logic and is self-checking. Four Motorola 68000 processors provide each board with two processors visible to the operating system (Fig. 5). A redundant partner CPU board ensures continuous processing in the event of a failure of a CPU board. At a component price of approximately $100 for each 68000, this is a cost-effective solution to continuous processing that was not practical until the availability of VLSI technology.

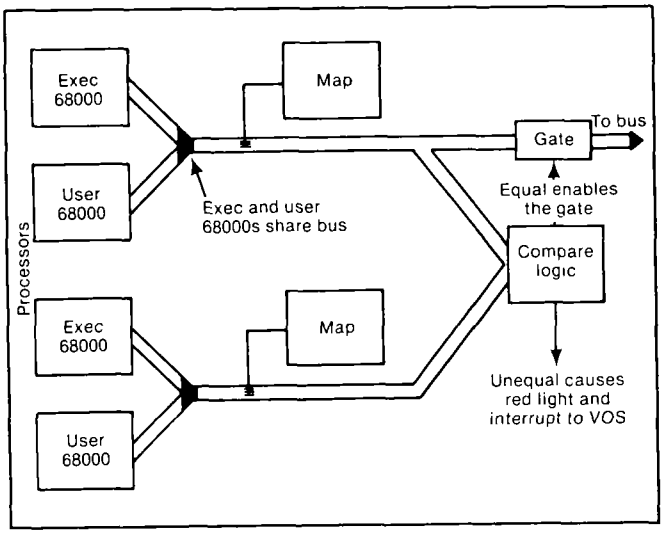

Fig. 5. A single Stratus/32 CPU board contains four Motorola 68000 processors *that provide two software-visible processors. The board is fully self-checking and contains redundant virtual/physical address-translation maps.*

Redundancy is achieved by using a pair of logic boards of each logical entity in the system. Each board is attached to both halves of the bus, and both boards operate in parallel, performing identical operations. The output of both boards is placed on the bus at the same instant and is guaranteed to be identical.

Memory is duplicated in a redundant system so that N megabytes of program-visible memory is implemented using 2N megabytes of physical memory with N megabytes attached to each of two memory controllers. When data are written to a given memory location, both memory controllers respond and write the data into their memory. When data are read from memory, both controllers respond and read from their memory.

The controllers and the memory are synchronized and appear to the rest of the system as a single logical entity. Memory subsystems are not paired with CPUs, bus halves or other system components. Memory is implemented from 64K RAMs and is packaged on 2M-byte boards. It has a 375-nsec. read-cycle time and is four-way interleaved.

The memory system can be dynamically reconfigured to be redundant or non-redundant. This allows a module to use all available memory when full redundancy is not needed. Reconfiguration can occur on-line without affecting running programs.

Disks cannot run completely synchronized with each other; they require help from the operating system to provide continuous processing. Each disk can be configured to have a duplicate. The mirror disk is attached to a separate controller to protect from controller failure. When a program writes a record to a redundant disk, the operating system writes records to the disk and to its mirror. When a program reads from the disk, the operating system reads from the disk that is not busy or whose heads are best positioned to read the record. If a read error occurs, the record is read from the other disk.

StrataLINKS, like disks, cannot run synchronized. However, the operating system has sufficient software error detection to run dual StrataLINKS as separate parallel links until one fails. Failure of a link is detected, and data are retransmitted over the other link without affecting users of the link.

A failure scenario

When a logic board or an attached peripheral device fails, it puts itself off-line, lights a red light on the board and transmits an interrupt to the operating system. Maintenance software in the system tests the failed board to determine if the failure was transient or hard. In either case, the failure is noted in a hardware-failure log file, and selected terminals are notified of the failure. If the board passes the maintenance-software check, it is resynchronized with its redundant partner and put back on-line, and its red light is turned off. If the board fails the software check, it remains off-line, and a red light on the system control panel is lit.

A maintenance software process automatically calls the Stratus national service center and passes a data packet containing site and failure information when hard failures occur. Stratus service people know within a minute of customer failures.

A failed board can be replaced in a running system by a nontechnical person without special tools and without affecting any user's program. VOS dynamically reconfigures itself when a board is added or removed from the system.

Transaction Processing

The Stratus/32 transaction processing encompasses several products. Included are:

VOS File System
StrataNET
Transaction Processing Facility
Forms Management Facility

The Virtual Operating System (VOS) File System manages all the input, storage, and output of users' data. Its flexible file organizations make access easy and efficient from any processing module in any system within a geographically distributed Stratus network.

Data are accessed without regard to physical location or storage device. Files are organized in a directory structure by disk within processing module. Data objects can be located from anywhere in a network or systems by explicitly using the module/directory pathname, or by using a user-defined link to the explicit pathname. There are also a number of features which locate objects implicitly. VOS manages the global file system and controls the allocation, placement, and recovery of disk space. The input and output mechanisms are designed to provide maximum efficiency for interactive transaction applications.

Data security is very important in a distributed application and Stratus provides data security as an integral part of VOS. Each file has an access control list consisting of pairs of user IDs and associated access rights (execute, read or read/write). Access rights can be specified by user or group of users and are enforced by the VOS File System. Access-control lists provide file security without embedding passwords into programs. The lists operate on the basis of people or groups who access the file; consequently, they are easy to administer and use. Security is provided regardless of what program or system commands are used to access files.

StrataNET

StrataNET, the Stratus networking software, permits two or more Stratus nodes to run as if they were a single system. Just as users or individual processing modules of a system have access to their entire system, users of a networked system have access to the entire network without any network-oriented requests or commands. Normal file operations and inter-process communication operate transparently to the user's program. File and directory access control apply to requests across the network. StrataNET has its own security options that allow the system administrator to permit, permit after network password check, or deny incoming requests on each system node.

Transaction Processing Facility

The Stratus Transaction Processing Facility (TPF) simplifies application development and provides fast response in a high volume on-line transaction processing environment. Development is simplified because TPF provides all the system tools and structures required to develop transaction processing applications. The application programmer is free to concentrate on application programs. Application programs can be writen in COBOL, PL/1, BASIC, FORTRAN, or Pascal. All language features can be used, including I/O statements. Fast response is achieved with multi-tasking, multiple transaction servers, and the use of a large program address space.

TPF offers functions specialized to meet the demands of on-line transaction processing. It coordinates the receipt and delivery of messages for an application communicating with hundreds of termi-

nals, and initiates a user processing routine upon receipt of a message rrom a terminal or device. TPF monitors the progress of each user routine, and provides for the parallel execution of multiple transactions.

Terminal handling requester processes and application server processes can reside anywhere within a system or anywhere within a network of systems. An application developed to run on a single processing module can easily be run on several modules with no change to the programs. (Figure 6). TPF provides for the orderly growth of applications -- without the need to reprogram or even to recompile -- by flexibility in the use of message queues. There are message queues for communication between a server and the requesters. A single queue can connect any number of servers with any number of requesters. Queues can be redirected dynamically by changing the pathname of the queue to point to another module on the same or different system.

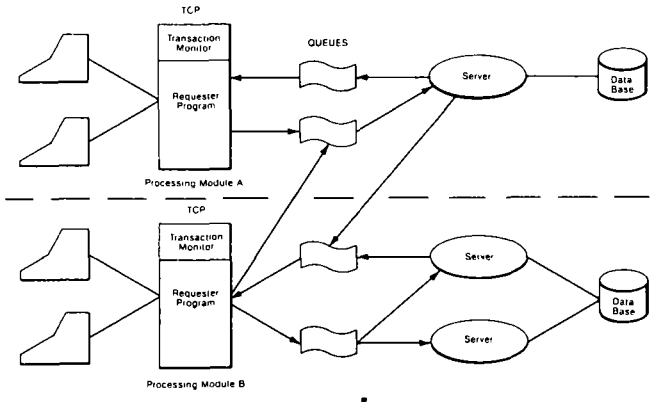

Figure 6

TPF ON MULTIPLE MODULES

TPF provides complete file protection for transactions, including transactions that involve updating data on multiple computer systems within a network. This protection ensures data integrity regardless of extended power failures, communication line failures, system software failures, application program errors, and operator errors.

The file protection features of TPF simplify the server program design by providing the functions that maintain data consistency and integrity during transaction processing. START, COMMIT and ABORT transaction commands ensure data consistency and integrity. START marks the beginning of a transaction, and COMMIT marks the end. When COMMIT is issued, the file updates are guaranteed to be completed by VOS regardless of failures due to any cause. The ABORT transaction results in all files being restored to their pre-START state. Since data can reside on a single processing module or can be distributed over many processing modules and systems, these commands provide data integrity independent of its physical location. TPF and VOS ensure that the data remain consistent in the unlikely event of a failure.

A two-stage commit process first writes all updated records to disk and sets a "Phase I Commit" flag in the file header. The original disk image is also preserved in the file. All nodes involved in the commit must report a successful completion of phase I before VOS authorizes the second phase, which actually commits the updates. Should a hardware or software failure occur during the two phases, the restart salvage disk process will detect the "Phase I Commit" flag and take the necessary recovery steps. Because two, mirrored disks are used, even a disk failure can be sustained.

Conclusion

Stratus Computer uses hardware to detect failures before incorrect data can corrupt processing and databases. Redundant hardware allows the Stratus/32 to continue processing without performance loss in spite of a component failure. System software in VOS, TPF and StrataNET ensures that transaction processing in a networked environment occurs with an assurance of data integrity.

The synergy of hardware-based fault tolerance and high data integrity system software creates an efficient and friendly transaction processing environment.

THE SYNAPSE APPROACH TO HIGH SYSTEM AND DATABASE AVAILABILITY

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INTRODUCTION

The Synapse N+1 (TM) is a computer system oriented to online transaction processing which emphasizes database integrity and functionality, system availability, and modular growth across a wide performance range. This paper gives a brief overview of the hardware and software, then highlights the approach to achieving high availability. This approach involves five key concepts:

* Redundant Hardware Components - There is a least one more of each component than is required for satisfactory operation, hence the name N+1. These components are not 'extra', but in full use at all times.

* Automatic Failure Detection and Reconfiguration - The hardware and software can detect a failed component, reconfigure the system without it, and continue without operator intervention.

* Fail-safe Database Storage - The DBMS assures that the database will always be consistent following a failure and that committed data will not be lost.

* Application State In Database - This fail-safe storage is used by the system itself to maintain the state of the online application systems.

* Online Database Maintenance - The application does not need to be taken offline in order to do database backup or reorganization.

THE HARDWARE

The hardware architecture is designed to optimize performance, expandability, availability and concurrency.

Multiple Hardware Components

Basic to the N+1 approach is that there is at least one more of each hardware component than is necessary for acceptable system operation. The system has multiple processors, buses, memory boards, power supplies, disk controllers, disks, etc. so that no single hardware failure will render the system inoperative. Secondary storage may be mirrored on a logical volume basis, which may be all or part of a physical volume. Disk drives are sealed Winchester-type units for higher reliability. Systems are configured with multiple paths to disks or tapes and will automatically use a secondary path

in the event of a failure.

Tightly Coupled Architecture

The basic architecture is tightly coupled, centered around the Synapse Expansion Bus (TM). The Expansion Bus is actually two independent buses with an aggregate data transfer rate of 64 megabytes/second. Up to 28 processors may be attached to the bus. They may be either General Purpose Processors (GPP's) or Input/Output Processors (IOP's), each of which is Motorola 68000 based. GPP's execute user programs and the majority of the Synthesis (TM) operating software from shared memory. IOP's each manage up to 16 device controllers or communications subsystems. Unlike the GPP, the IOP executes operating system software from its own 128 Kbyte local memory. IOP's have DMA capability to shared main memory.

One problem that multi-processor systems have had in the past is bus or memory contention. Synapse has solved this problem with a sophisticated memory caching scheme. Each GPP has a two set associative cache of 16K bytes. Modifications to the cache are not written through and requests for memory owned by another cache are satisfied between processors without going to memory. This mechanism allows a full complement of GPP's to be added to a system without degradation.

The tightly coupled architecture provides high performance due to superior sharing of resources such as memory and processors. Basic queuing behavior in the system is single queue, multiple server whereas behavior in loosely coupled systems is more correctly modeled by serveral single queue, single server systems. The tightly coupled architecture also provides simpler hardware redundancy. Removing a failed GPP, for example, from the system is trivial since all GPP's can uniformly access all memory and all peripherals.

Configurable and Expandable

Since GPP's, IOP's, and memory modules are very independent, systems may be configured to the optimal mix of processor, I/O, and memory capacity. Each processor, controller, and megabyte of memory is physically a 15" x 17" board. There are a total of 64 slots in a single N+1 system cabinet. The system may be grown simply by adding boards. Additional processors are totally transparent to user software. They are simply added to the resource pool managed by the operating system.

THE SOFTWARE

In this section we briefly describe the levels of system software, termed System Domains, from the hardware out to the user.

System Levels (Domains)

Monitor - At the lowest level is the Monitor which is stored in ROM. This code controls hardware self-test and system booting.

Kernel Operating System (KOS) - The KOS is the next layer. Its major functions are memory management, physical I/O, process/processor scheduling, and system reconfiguration.

Database (DB) - Directly above the KOS is the Database domain. This software implements the transaction model, provides fail-safe storage through logging and recovery code, supports the relational data model, and provides a B*-tree access method.

Extended Operating System (EOS) - Above the DB code is the Extended Operating System. This layer uses the DB mechanisms to provide a named object system. This is a hierarchical directory name space for all system objects, e.g. files, tables, devices, forms, etc. The EOS also provides device independent I/O.

Transaction Processing (TP) - Above the EOS, is the Transaction Processing domain. This includes a screen access method and menu system, transaction thread management, and application restart.

User - Above TP is the user domain. This is where the Command Language Interpreter and application programs execute.

The Process Model

The process model was designed to optimize the production Transaction Processing application which is very overhead intensive. Much of its time is spent satisfying requests for system services, such as I/O or database accesses. Thus special emphasis was placed during design on minimizing the overhead required to change context in order to get such a service. The processor has 16 Mbytes of direct addressability in a segmented addressing scheme. Each of the system domains has a one megabyte segment of addressability for its code and another one (or two) for data. Thus requesting a system service is a jump to a different virtual address within the same process. The Cross Domain Call and its associated return take a total of 100 MICROseconds. This compares with six to ten MILLIseconds for an interprocess call, a technique used in many minicomputer operating systems.

The Application Model

Synapse has integrated software into the basic system which is normally associated with add-on transaction processing monitors. The purpose is to improve the system performance and to simplify the writing of transaction processing applications. Application systems are built of program units which are small, separately compiled program modules. Each typically receives a screen of input, processes it, and displays another screen while terminating. Thus while terminal operators are viewing screens, there is very little process state and no program state. The TP subsystem provides the mechanisms to combine multiple Program Units into a single Application Unit and to provide control of process flow from one Program Unit to the next. The TP subsystem optionally checkpoints the process state and screen contents between these units. Thus in the case of a failure, terminals are returned to their latest screen. In a small percentage of cases, one screen may need to be reentered.

DATABASE ORIENTATION

The Synapse DBMS plays a central role in the system, including its high availability requirement. The basic approach is to keep critical information in database which provides a fail-safe storage. The database functionality was a necessary component of the Synapse system for the customer. However, Synapse's DBMS is unique in that it resides at a very low level within the operating system and is used extensively by higher levels of system code. Synapse made it a basic, low-level component for several reasons:

* Performance - DBMS's often incur a large amount of overhead due to being built on top of a file system. Synapse has optimized the OS design for DBMS usage.

* Integrity - The database system provides a fail-safe storage. To do this with acceptable performance, coordination with low-level physical I/O is required.

* Simplicity - Higher levels of the operating system use the database functionality, greatly simplifying their design.

A few points regarding DBMS functionality:

- Relational - It differs from most other currently available relational systems in its low level, production orientation. The data manipulation interface is through language extensions in Pascal and COBOL. Syntax is similar to file I/O in each system plus a construct to provide the select operator.

- Assertions - Relational domains are separate system objects which may have integrity assertions associated with them. When adding or modifying tuples, if attributes are drawn from domains having assertions, they will be checked.

- Transactions - All database activity falls within a per-process transaction. Commit and Rollback statements in the programming languages terminate a transaction and implicitly mark the beginning of the next. Write-ahead log techniques are used to implement transactions [GRAY1]. The log files are mirrored to protect from disk failures.

- Concurrency - Degree three transaction consistency is the default [GRAY2]. Physical locking with escalation is done on tuple, page or table granularity. Lock modes are exclusive or shared. Locks are implicitly placed when data is touched and freed at end of transaction. Deadlock detection is done by maintaining wait-for graphs.

- B*-tree indexes - Indexes are physically separate from data. Index traversal is highly concurrent and deadlock free. Selection expressions are evaluated on the data page. Index keys may be composed of multiple, non-adjoining attributes of different data types.

- Dynamic backup - Relations may be backed up while being modified. At restore time, changes that were being made during the backup are rolled out using the same logging mechanism that implements transaction rollback.

HANDLING FAULTS

Having briefly described each major component of the system, we can now walk through the basic approach to handling faults. The following steps describe the events which occur in a 'worst case' failure scenario. This is one that will cause a complete system restart, as opposed to less critical failures which may be dealt with without restart.

1. Fault is detected. This may be by parity or other internal hardware checks, or by an access violation. The memory system provides 2Kbyte granularity in address mapping with read, modify and execute modes. Access violations for processes executing in user domain are process fatal. There is an addressing mode for system domains termed 'covered' which is read-only for system data structures. If an access violation occurs in a system domain while in this mode, it is process fatal. A process fatal error causes the process (and its current transaction) to be aborted and restarted. An access violation occuring in an uncovered system domain is due to hardware malfunction or software logic error and is system fatal. For system fatal errors, we proceed to the following steps.

2. KOS marks the failed component. If the fault is due to an internal check, the KOS knows the failed component. This information is recorded in non-volatile memory for use during restart.

3. Begin reboot. The KOS halts the system to begin a reboot scenario. Memory is not trusted.

4. Hardware Self-test. The monitor conducts self-test of each unit in parallel. There is extensive self-test code for verifying each component.

5. KOS initializes.

6. Reconfiguration. The KOS reconfigures the hardware if there is a failed component. Accesses to I/O devices are rederived around failed components. Interleaving of memory will be modified if a memory controller has failed.

7. DB initializes. At this point the Database recovery system will restore the database tables to a consistent state. This is done by undoing all uncommitted transactions and redoing all committed transactions whose modifications had not made it out to the disk.

8. EOS initializes.

9. TP initializes. The TP system has maintained state in the database on each application currently running in the system. This information is essentially for each terminal: the person operating it, the current screen, the contents of the variable fields on that screen, and the next program unit to execute. TP will create a process for each terminal, set its state, and start it.

10. Applications continue. All incomplete transactions have had their effects removed, so applications simply run again from the input resupplied by the TP system. For most applications there is no special logic for dealing with restarts. At this point all processes are continuing normally.

Once the system is back up, failed boards can be swapped without time pressure and new boards added without affecting the system.

SUMMARY

The Synapse approach provides protection from a broader class of failures than most other fault-tolerant approaches. A hardware-based approach attempts to anticipate all possible types of failures and provide compensating design to provide continuous operation. This is really an unbounded problem. The approach is effective for many types of failures, but leaves the system just as vulnerable as conventional systems for failures that fall outside the failures handled by the design. Without a transaction-based DBMS, the database may be quite inconsistent when the system comes up. This could be disastrous in a transaction processing application and is specifically addressed by the N+1 system.

The Synapse approach is based on database transactions and deals with human, software, and environmental failures in addition to simple component failures. The hardware architecture is tightly coupled which yields excellent performance, configurability and expandability. The transaction processing software provides users simplicity and ease of use in developing online applications.

Note: Synapse, N+1, Expansion Bus, and Synthesis are trademarks of Synapse Computer Corporation

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A HIGHLY RELIABLE SYSTEM FOR DISTRIBUTED WORD PROCESSING

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1. INTRODUCTION

Syntrex is an office automation company that has designed highly reliable computer systems for word processing applications. In this paper we will describe some of the characteristics of our fully redundant file server, known as Gemini.

2. SYNTREX SYSTEM OVERVIEW

Syntrex builds an intelligent stand-alone word processing terminal called Aquarius. The terminal supports standard word-processing functions such as text editing, printing, a spelling check package, communications software etc. The terminal connects to several standard typewriters and fits easily on a secretary's desk.

Users can connect up to 14 Aquarius terminals in a small cluster system called Gemini[3,5,6]. Gemini consists of a central file server which manages a file system that can be shared by all 14 Aquarii. Gemini is a fully redundant system. It provides users with an "Always Up"™ environment in which to work, in addition to allowing file sharing, and larger storage capacities than one can get with stand-alone, floppy disk systems.

Gemini systems can be connected via an Ethernet-like[4] interface to form SYNNET. Users can access documents across the network in a manner that is totally transparent to the application programs.

The software that runs on a stand-alone word processor is the same software that runs on Gemini and Synnet, so customers can upgrade their systems without having to learn new operating techniques.

3. OPERATING SYSTEM

The Syntrex Operating System (SOS) was developed for the Aquarius. SOS is a sophisticated message switched operating system. We assume that the reader is familiar with standard operating system concepts such as kernels, messages, processes, tasks, etc. These will not be defined in the text that follows. The process and interrupt structure of SOS is similar to that of Thoth[2], where system control relies upon teams of processes to perform specific functions. We have also relied heavily on the concept of a **link**[1,3,7], which is used for inter-process communication, and will be described below.

Many features of the operating system, such as the process scheduler, or the memory management routines have been implemented in different ways at different times during the past three years. The inter-process communication mechanism, which makes this operating system as useful as it is, has undergone only minor coding improvements during that time.

Processes communicate by sending **messages** to one another. The messages are routed from process to process by the SOS kernel(s). A message consists of a message header, followed by an (optional) message body. The header contains information about the link on which the message was sent, an (optional) reply link (see below), the message type, and the length of the message body. Certain pre-defined message types exist for use with well-known processes (such as open a file, write a record, create a new process, etc.)

Messages are sent over **links.** A link is a capability for one-way communication over a channel between two processes. It is important to note that a link is **unidirectional.**

When the kernel is told to send a message on a link, it compares its own machine id with the machine id of the destination process. The Aquarius terminal is given a machine id at the time the operating system is started. If the destination process is located on the same machine, then the message is queued directly to the destination. If the machine id is different, then the kernel places the message on the queue to Gemini. The communication line protocol will transmit the message to Gemini, where it will be routed to its destination machine. The kernel in the destination machine then queues the message to the destination process. It is important to realize that **the communicating processes remain unaware that they are located in different machines.**

When a process creates a new link, it is said to **own** the link. Ownership of a link may not be transferred. The owner of a link will receive any message sent on the link. Until given away, the owner process also **holds** the link. The holder of a link can send a message on the link. Subject to having the appropriate permissions, the holder of a link may give the link away to another process, thus allowing that process to send a message to the link owner. The holder of a link cannot determine the identity of the owner. This helps ensure that there are no hidden dependencies between processes which would make networking difficult.

The distributed nature of the operating system has allowed applications (such as the editor) to be developed without regard to whether the data files are located on a local floppy disk, the local gemini unit, or on a remote gemini located elsewhere. Users have a single, consistent method of accessing files which does not change as the customer expands from a stand-alone terminal to a network of clustered systems.

4. GEMINI

4.1. Overview

Gemini was designed to meet a number of different goals. Primary among them were automatic information backup and minimal customer down-time, as well as ease of use for the customer.

Our user community is extremely non-technical. Procedures such as backing up disks are foreign to normal office operation, and are often avoided or forgotten by users of automated systems. Gemini's automatic real-time

backup alleviates this problem, protecting users against the loss of information and at the same time providing a measure of protection against lost work time due to a down system.

It should be noted that the system is **not** designed to keep a fully redundant system operating at all costs, or to connect Gemini units together to provide load sharing or further redundancy (a la Tandem[5,7]). Rather, the system is designed to continue operating without backup in the face of any **single failure** of hardware or software. This allows the customer to continue to do useful work until such time as a service person can get to the site to repair and restore the damaged half of the system.

Figure 4.1 shows the hardware used in a Gemini. Each half of the system contains a 14 inch Winchester disk drive (this may be expanded to 4 drives per side), a disk controller (DC), an Aquarius Interface board (AI), a block of memory that is shared by both the DC and the AI, plus power supplies, battery backup unit, and phone connection.

The software is designed so that one side of the Gemini is designated "Master", and the other "Slave". Messages from an Aquarius are received and processed simultaneously by the master and the slave. Output from the Gemini is sent to the Aquarius by the **master only**. The slave monitors the communication line while the master is transmitting, and then prepares to receive the next Aquarius message. At any instant, the slave is prepared to take over from the master if a failure occurs.

Communications between the Gemini and the Aquarii take place over 14 high-speed, synchronous communications lines. The link level protocol is a (slightly) modified version of HDLC[3,6]. The frame types referred to below are standard HDLC frame types. For example, RR's are used to acknowledge the receipt of IFRAMES (data packets). RNR's are used to implement flow control when necessary.

4.2. Master/Slave Relationship

The master/slave relationship is built into the software at the lowest possible level of the AI. The individual disk controllers do not know if they are operating as master or slave, or even if they have an active partner at all. They simply respond to messages asking that disk blocks be read or written. The operating system in the DC is essentially the same as that of the individual Aquarius.

The AI is responsible for ensuring that identical messages are being processed on each half of the system. For example, when a message from an Aquarius is received, the master and slave decode the message, and send the (HDLC) frame type to their partner. They compare the frame type they actually received from the communication line with the information from their partner. If the two sides agree, then the frame can be processed. If they don't agree, the frame must be discarded. For Aquarius to Gemini transmissions, the only way the master and slave are likely to disagree is if one side receives the frame correctly, and the other side has a CRC error. This is a possible, but rare occurrence.

The knowledge of the simplex/duplex master/slave state of the machine is handled on a strict need-to-know basis. Consider a system running in simplex (one half active) mode when a message is received from an Aquarius. As above, the protocol handler decodes the frame type and "sends it to the other side". The routine that handles the actual master/slave communications is the only one that knows that the "other side" is not active. So this routine takes the information and pretends it has just been received from the "other side". When the routine returns, the protocol handler discovers that the "other side" has in fact received the same type of packet, and the frame can be processed.

Transmissions from the Gemini to the Aquarius require that the two halves synchronize themselves properly. Since the disks operate independently, it is possible that one disk will respond to a request more quickly than the other (for example, one side may read a block, while the other finds a marginal disk surface and has to retry several times). When the protocol handler in the AI prepares to transmit, it must compare the frame type it wants to send with the frame that its partner has. If the frames are the same, the master initiates the transmission. As mentioned above, the slave does not transmit messages; it monitors the master's transmissions. If the master side dies, the slave will start transmitting (since it now becomes the de facto master). When the master and slave disagree on the type of packet to send, they settle the question by means of a "lowest common denominator" routine. For example, if the master wants to send an IFRAME, and the slave wants to send only an RR, the lowest common denominator is an RR. The master will defer the transmission of the data frame for a while, allowing the slave AI to get the data from its disk controller. Eventually, both the master and slave will have data to transmit, and it will be sent to the Aquarius. Another example would occur if one side runs out of buffers due to a backlog in the disk, and the other side does not. The blocked side will try to send RNR (flow-control) messages, while the other will be sending RR's or IFRAME's. The lowest common denominator in this case is the RNR, resulting in the temporary flow-controlling of the Aquarius.

4.3. Error handling

Many different types of errors can occur with a system such as Gemini. Some result from errors in applications programs, some from communications line failures, hardware failures, and still others from external events (power failures, people tripping over cables etc.) The system is designed to recover completely where possible, to continue operating on one side in the face of a single, non-recoverable error, and to shut down gracefully when necessary.

The Gemini can do nothing about errors in applications programs. However, we have found that almost any error that occurs in an application program running on Gemini can be duplicated on a stand-alone Aquarius. Such errors do not affect the operating condition of the Gemini.

Standard HDLC recovery procedures are used to re-transmit missed or garbled link level messages. The system keeps a log of errors (all errors, not just link level errors) on the disk. If too many recoverable errors occur, the system will make a "trouble brewing" report to the service center (see the Service Genie™, below).

In the case of a serious failure of either the master or the slave, the "bad" side is turned off, and the "good" side continues to run. Aquarius applications are not interrupted. The customer is not informed of the failure. Instead, the Syntrex Service Genie™ places a phone call to the nearest Syntrex Service Center, and reports the failure. The service center then will contact the customer to arrange a convenient time to come out to repair the damaged half of the system. **During the time between the failure and the repair, the users have no automatic backup of their work.**

The Service Genie is designed so that it will continue to place the phone call at regular intervals until it gets through to the Service Center. This avoids the problem of two systems calling simultaneously, and one getting a busy signal.

The system must protect itself against several different classes of errors. First, the physical hardware may fail. These errors usually can be detected by software. They include parity errors, bad disk drives, communication chip failures etc. When this happens, the bad side logs an error on the good side (a panic message), and shuts itself down. The good side will continue to run, and will place the Service Genie call. A second class of failures are catastrophic program failures. This would include such things as freeing an unallocated message buffer, accessing non-existent memory, etc. These normally represent "impossible conditions" and are caught by very defensive programming. Again, an error message is sent to the good side, and the system switches over to simplex operation. Service personnel may read the error logs on both the master and slave in order to determine the cause of a particular failure.

Some errors will pinpoint the location of the failure almost down to the chip level, while others can only indicate a general failure of a side or a board (for example, "DC has gone inactive" gives no indication to the service person as to why the DC shut off, but it does tell him/her which board should be replaced. The defective board can be returned to the service center for analysis, while the customer is back up and running in duplex).

A third class of errors are so-called "soft" program errors. These include communication line errors (bad crc, bad address etc.), expiration of timers etc. In most cases, the software will recover from these errors. However, too many errors may indicate marginally functional hardware. If too many errors occur in a small period of time, the system places a "warning" phone call to the service center. The system will continue to run in duplex mode, even after the Service Genie call.

For some failures, it is not possible to decide whether the master or the slave is the side that is broken. For example, if the two sides agree that they want to send an IFRAME to an Aquarius, but one side's message is 50 bytes long, and the other has a 512 byte message, then obviously the disks have returned different data. The system can not operate in duplex mode if the disks are different, so one side has to be turned off, but there is no way of knowing which message is the correct one. In cases such as this (in itself, an "impossible situation") the slave is arbitrarily declared bad, and the master continues to run. The master will place the Service Genie call. Of course, if the master is the bad side, it is possible that further failures will occur, resulting in the complete shutdown of the system.

Powerfail is an external event that causes both sides of the system to shut down. The Gemini is equipped with battery units that allow it to survive for several minutes after the power fails. During this time, files are closed, and the system ensures that both disks are properly synchronized. When the power is restored, the system can be turned on, and it will run properly in duplex mode. The powerfail is noted in the error log on both sides of the system.

Finally, there is one potential flaw that must be addressed. At one of the first customer sites, someone carelessly knocked the phone off the hook; when a failure did occur, the Service Genie could not make its call! The system ran for several days in simplex mode before anyone noticed that there was a problem. To rectify this, the system is now designed to place an "I'm Alive" call from both the master and the slave on a regular (once per week) basis. The service center keeps track of when these calls are expected. Failure to receive a call indicates a problem that must be investigated.

5. SUMMARY

Syntrex has built an easy-to-use, highly reliable office automation system. The system can be upgraded as needed from a stand-alone system to a small cluster to a network of clusters with a minimal impact on the customer, and with the best possible protection for the customers' information that we have been able to build.

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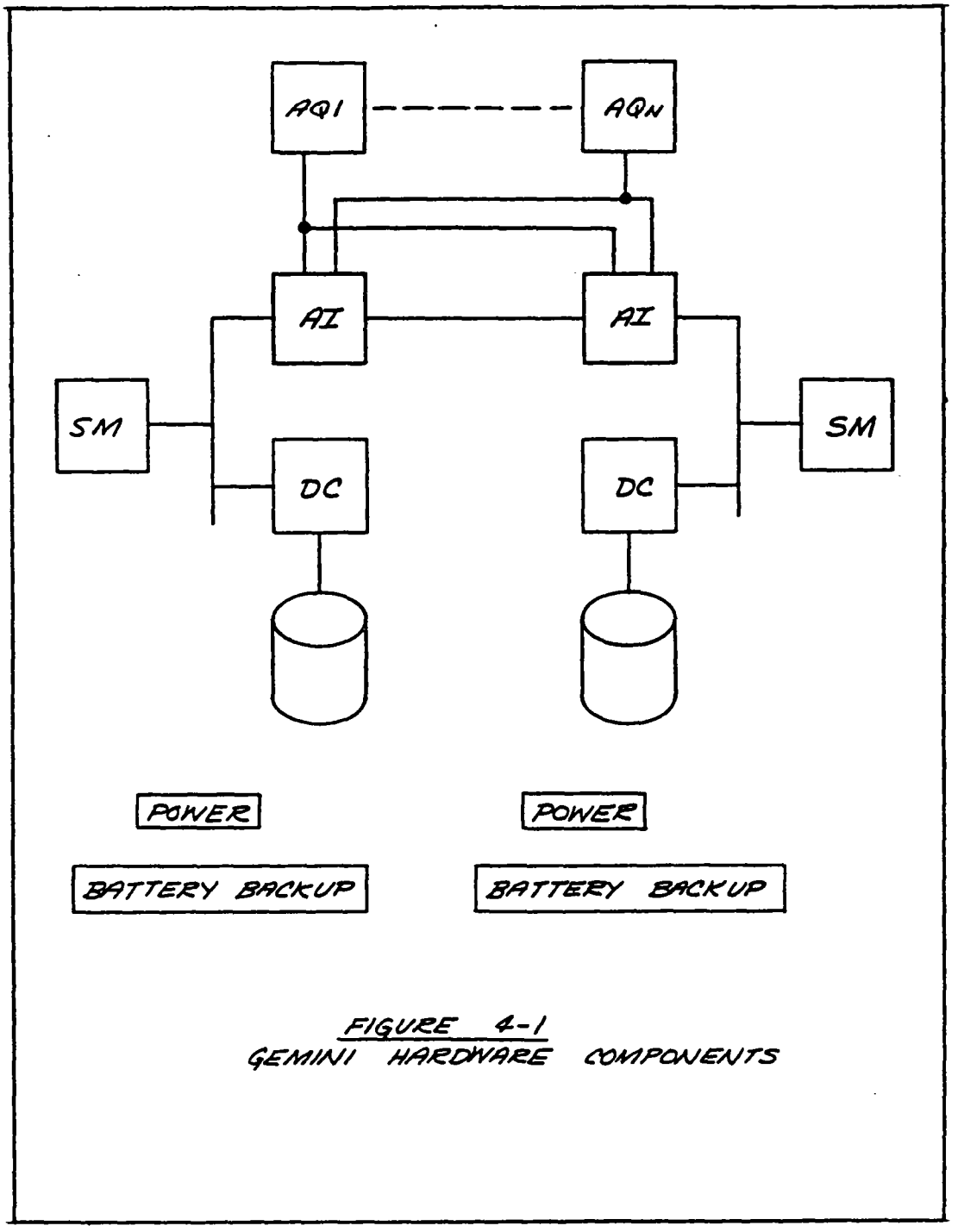

FIGURE 4-1
GEMINI HARDWARE COMPONENTS

DATABASE MANAGEMENT STRATEGIES TO SUPPORT NETWORK SERVICES

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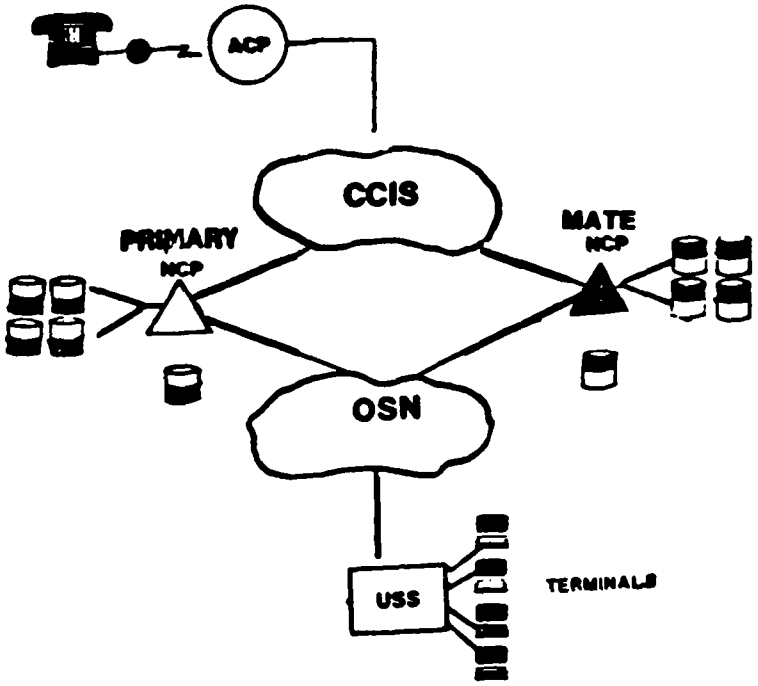
1. INTRODUCTION

The Bell System Telecommunications Network is rapidly evolving in new directions to take full advantage of the emerging Stored Program Controlled (SPC) Network technology. The SPC network is comprised of electronic switching systems, operator systems and distributed databases interconnected by a data network (Common Channel Interoffice Signaling, CCIS). The SPC Network offers opportunities to support many new potential customer services such as expanded 800 [1] and Direct Services Dialing Capability (DSDC) [2].

As observed in [2], these services are based on a distributed architecture with two key network components: the Network Control Point (NCP) which is a database management system and the Action Point (ACP), which is a call processing system.

The basic components of a network service are described in the figure below. When a call is made from a local office to a customer of such a service, the call is routed to an ACP.



The special sequence of digits dialed will control routing, and is actually the address of a unique record maintained within the network which contains call processing instructions. The ACP transmits the dialed address and a request for instructions, through the CCIS network to the NCP that maintains this customer record. The NCP returns the related response through the CCIS network. The ACP routes the call according to instructions received from the NCP. Since the service depends on the NCP, NCP reliability and recovery strategy are critical aspects of the design.

The following section describes the database administration strategy for the proposed DSDC services. Section 3 describes the redundancy built in for reliability and survivability. Section 4 shows how DSDC services are supported with the use of Distributed Database Management concepts such as multicopy updates, concurrency control, audits and recovery.

2. DATABASE ADMINISTRATION

The database of customer records is maintained by a set of NCPs that are distributed geographically across the nation to meet performance, reliability and survivability needs. According to particular market forecasts, NCP capacity, and performance requirements, several NCPs are required to provide service. To meet the reliability objectives, redundant hardware and duplex processing are used. In particular, the NCPs are built using 3B-20D* processors [3]. Each NCP maintains four on-line copies of the customer record database, and the copies are stored on separate disk drives to satisfy reliability and capacity needs.

Survivability considerations result in a mated architecture, where each NCP is assigned a mate at a different geographic site. Copies of each customer record at an NCP are also stored at its mate. One of the two NCPs that contain copies of a customer record, is designated as the primary for that record. If an NCP fails in spite of its redundant hardware, its mate will take over responsibility for handling ACP call processing requests. The geographic distribution of the primary and mate NCPs reduces the probability of their simultaneous failure due to destruction.

Under normal conditions, the entire call processing load associated with a customer record would be handled by the corresponding

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* The 3B-20D is a product of Western Electric Corporation.

primary NCP, while the mate would be used only as an on-line switchable backup.

Besides Call Processing, NCPs would support also customer record updates. An administrative system called the User Support System (USS) would be employed to create new customer records and to modify existing ones. Using terminals connected to the USS, customers of DSDC services could build their records in a customized manner to suit their business needs. The USS would transmit through an Operations Support Network (OSN), each record to the NCP designated as the record's primary.

The primary NCP would be responsible for coordinating the update of its own copies and those stored at the mate NCP. Updates to the four local copies of a customer record and those at the mate are handled by the NCP operating system in a way transparent to the customer, so that it appears externally as if there was a single copy at a single NCP site. In the following discussion, the update of local copies at an NCP site will be considered as a single step of the update algorithms.

3. REDUNDANCY

3.1 Reliability

The NCP databases form a critical element of the network architecture. Failures which disable access to a customer record result in service interruption to that customer. So, the NCPs have to be highly reliable and available. To meet these objectives, the NCPs are built using 3B-20D processors [3]. The processor provides built in error detection, correction, and recovery features to ensure a smooth system operation.

As the term "duplex" implies, there are two identical processors in a 3B-20D. Of these, one is "active" and the other is "standby" at any given time. Each processor has a central control unit which has direct access to its own main memory, and to the disk system of both the processors, and indirect access to the other processor's main memory. During normal operations,the active processor automatically and continuously updates the standby processor's main memory. Thus, if the active processor fails due to either a hardware or a software error, the standby is ready at all times to take over as the active unit. And one processor can be tested, serviced or reprogrammed while the other is in operation. The input/output processor, the disk file controller and the communication links between a primary NCP and its mate are also duplicated. A detailed description of the 3B-20 processor is found in [3].

3.2 Survivability

To meet the survivability needs of the service, each customer record is stored at two geographically separated NCPs. Under normal conditions, the call processing load is split between the two NCPs by an appropriate distribution of customer records. For a particular customer, call processing would always be handled by the corresponding primary NCP. The split can be modified by changing the primary designation of a subset of customer records from one NCP to another, using a network management transaction. If an NCP fails in spite of its redundant hardware, call processing associated with customer records for which it has been designated as primary, is transferred to its mate through the CCIS network. This operational NCP will process calls related to both the customer records for which it has been designated as the primary before the failure, as well as those for which the failed NCP has been the primary.

4. TRANSACTION PROCESSING

The NCP databases are required to support network services. This section shows how the database concepts for multicopy updates, concurrency control, audits, and recovery are implemented to support DSDC services.

4.1 Multicopy Updates

Customers may initiate changes in their service and activate them directly. Updates could be submitted from multiple sources and concurrently 24 hours per day. The coordinating site concept [4,5,6] was chosen to support these multisource, multicopy updates. This requires all changes, independent of their origin, to be forwarded to the primary NCP associated with the record. The primary NCP acts as the coordinating site and is thus responsible to propagate the changes to the copies at the mate. The primary NCP also would verify the transaction for consistency and for authorization, and would log the transaction on disk. If the authorized transaction is valid, the primary NCP would acknowledge the user. This acknowledgment would represent a commitment on the part of the system to complete the transaction even in the case of system failures. At this point the change would be forwarded to the mate NCP, where it would be implemented and activated. Activation of an update means that calls would be processed based on the updated version of the record. The primary NCP would activate the update only after it received an acknowledgment from the mate on the successful completion of the update. Once the update is activated at the primary NCP, the system would create an entry in its completed update

transaction log.

Under normal conditions, the update algorithm would activate the change first at the mate NCP, and then at the primary NCP to reduce the possibility of an "update disappearance." An update is said to "disappear" if some calls are processed using a version of the record which reflects the update while some later calls are processed using an older version of the record which is not affected by this update. Such a disappearance effect is seen if the primary NCP were to activate an update first, process some calls, and subsequently fail before the same update was performed at the mate NCP. In this case, a switch to the mate for call processing would result in the update disappearance since the mate NCP would be processing calls based on the older version.

If communications fail between the primary NCP and the mate NCP, then each NCP would activate the changes without waiting for the mate's acknowledgement and would store in a special history queue all the transactions completed since the failure of the communication link. Since neither NCP is down, the CCIS network would continue sending the call processing messages to the appropriate primary NCP. Similarly, the USS would continue sending customer record updates to the appropriate primary NCP. When communications between the NCPs are restored, the NCPs would exchange history queues.

4.2 Concurrency Control

In DSDC services there would be a need to support concurrent multisource updates of customer records and to assure that updates occur without interfering with each other and that they occur in the order intended by the user [7]. Different users (e.g., customers, operations support personnel, etc.) may concurrently submit update transactions related to the same customer record. Concurrency control would be implemented by a locking mechanism at the primary NCP. After an update has been validated and accepted by the primary NCP, the customer record being updated would be locked at the primary NCP so that further updates (to that record) are not processed until the lock is removed. The record would stay locked at the primary NCP until the update is activated at the primary and the completed transaction logged. This means that under normal conditions, the lock stays until both the primary and the mate are updated. The locking mechanism would enforce the same order of updates at the primary and the mate NCPs. The locking information would be kept in a system lock table, so that in the event of a system failure, this table could be used by the recovery process to identify abnormally terminated update transactions and to restore database consistency [8].

4.3 Audits and Synchronization

In spite of careful design and testing, database inconsistencies may occur. Besides various routine audits on the database, demand audits would be used whenever database inconsistencies are suspected. Audit failures would be reported to the recovery mechanism.

A data inconsistency related to a customer record may be between the on-line copies at the primary site, or between the on-line copies at the mate site, or between the primary and mate copies. Synchronization transactions issued by operations personnel through the support system, would synchronize the contents of all on-line copies of the customer record at the two NCP sites. This could be used to correct update disappearances.

4.4 Recovery Procedures

The main objectives of the recovery process are to restore service as soon as possible and to minimize permanent loss of data. It is also important to eliminate recovery dependencies between the sites of the network. With the exception of major catastrophes, a site should be able to recover by itself, and restore service.

To meet the above objectives, three levels of failures are identified and separate recovery procedures are designed for each. In a first level failure, the failed NCP has enough data available on-site to recover to the pre-failure state. Recovery tools include a roll-forward process [8] using an off-line backup copy and a completed update transaction log. In this case, the update function at the failed site would be suspended and would not be transferred to the mate during the primary's failure.

In a second level failure, an NCP would not have on-site enough data needed for reconstruction. If the off-line copy had been destroyed, a database copy would be created at the mate site and transported to the failed NCP site. If the transaction log alone had been destroyed, then the transaction log at the mate site would be transported to the failed site, where it would be used along with the (local) off-line backup copy to reconstruct the database. In this case, the update function would be switched to the mate during the primary's failure.

In a third level failure, all on-line and off-line at both primary and mate sites would have been destroyed. In this case, the database of customer records at the support system would be used for recovery.

If an NCP fails its call processing function would be transferred to its mate NCP. If the update function is not transferred to the mate, then the failed NCP can resume call processing soon after recovery. This is because no changes would have been made during the failure to the records for which the failed NCP is the primary. On the other hand, if the update function is transferred to the mate NCP, then the failed NCP cannot renew call processing immediately after recovery. This is because the database at the recovered NCP would not include the effects of the recent updates which were received and activated at the mate NCP during the primary's failure. A special history queue of updates would be prepared at the mate site of all transactions completed since the failure. Once the primary NCP has recovered its database, the primary NCP would first apply the updates from the history queue in the mate, and then renew service.

5. SUMMARY

The SPC Network employs many current database techniques to provide a reliable vehicle for customers in constructing services they desire. This paper described how high availability and high reliability could be supported in the distributed database environment of the network services by using standard database techniques, such as multicopy updates, concurrency control, audits, and crash recovery.

6. ACKNOWLEDGEMENTS

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Experience with a Large Distributed Banking System

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System Overview: The Distributive Computing Facility (DCF), automates the teller function for Demand Deposit Accounts (i.e. checking accounts) and Savings Deposit Accounts at Bank of America. The system, which has been operational for over five years, provides inquiry and memo posting functions to the ten million account database. Updates are "memo" in that the system does not replace the flow of paper instruments (e.g. checks and deposit slips) which is still the basis for updating the true account ledgers. The ledgers are maintained by batch accounting systems using tape-resident account masterfiles. Every morning condensed files produced by these batch systems are loaded onto the DCF system replacing the files from the previous day.

There are about 1100 branches of Bank of America in California, each with an average of one Programmable Control Unit (PCU), one administrative terminal and eight teller terminals. The branches are supported by leased lines which hub into one of two data centers in Los Angeles and San Francisco. The overall network scope is: 10,000 terminals, 1,120 Programmable Control Units (PCU), and 115 communication lines (2400 BPS FDX SDLC) with PCUs multidropped up to 14 per line.

Each data center houses a DCF cluster which provides the transaction services against half of the statewide account data base and supports half the terminal network. Each DCF cluster is comprised of eight DCF Modules connected by a local network. The Module itself is a local computer network comprised of four GA 16/440 minicomputers and is the basic unit of transaction processing in the system. The DCF clusters are linked with a pair of 9600 HDLC lines to allow any terminal to gain access to any account. Both clusters have the same hardware configuration including 40 disk spindles where the database resides.

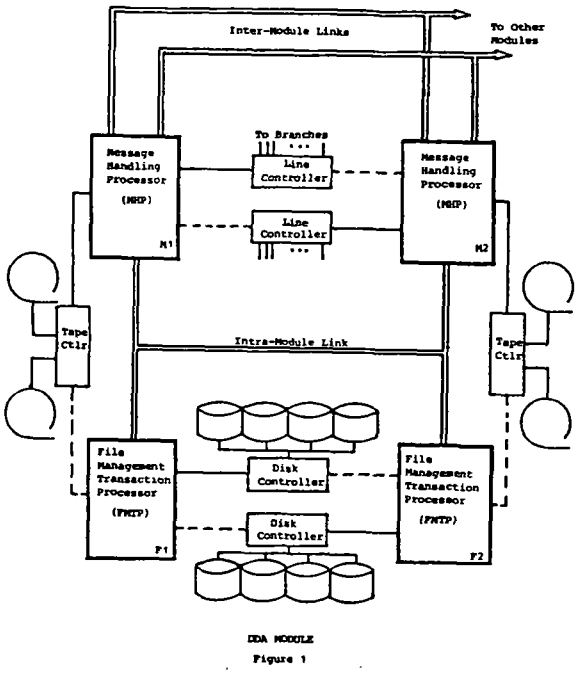
The typical input message is about 20 characters and the response 120. The transaction processing profile is simple and not resource intensive. The mix between inquiry and update transactions is: 60-70% inquiry (3 disk reads), and 30-40% updates (3 reads, 1 replace).

The statewide transaction load is divided approximately 55% in Los Angeles and 45% in San Francisco. The Los Angeles volumes are: 390,000 transactions per average day, over 500,000 transactions per peak day, 84,000 transactions per peak hour, and 30 transactions per peak second

DCF Module: Two of the four processors are communications frontends called Message Handling Processors (MHPs) and the other two are database backends called File Management Transaction Processors (FMTPs). Figure 1 shows the module configuration. The four processors communicate over a 1.2 megabits per second communications bus called the intra-module link. The protocol is SDLC multi-point contention and there is no master station.

Each module also contains a line printer, a TTY, four tape drives and eight disk spindles of 64 megabytes each. The printer, owned by one of the MHPs, is used as a hardcopy log of all status messages originated by any of the processors. The TTY

is used as an emergency system console and for maintenance. It is switchable to any of the four processors. Each MHP owns two tape drives for message logging. These tape drives are switched to the FMTPs for data base load and unload. The disks contain a portion of the data base, the program libraries for MHPs and FMTPs, and control files. Notice that the MHPs have no disk, so they are IPL'd from an FMTP through the intra-module links.



DDA MODULE

Figure 1

The module is configured such that the average load can be handled by half the hardware. Every component has a backup normally sharing the load equally. Backup components automatically assume full processing load when a failure occurs.

During normal operation, one MHP/FMTP pair works on half the module's lines and database, the other pair working on the other half. There is a watchdog timer on each processor. If the processor does not reset the timer periodically, the timer turns the processor off and notifies the peer (MHP or FMTP). If the failed processor is an MHP, the peer MHP assumes responsibility for the module's full complement of lines. If the failed processor is an FMTP, the peer assumes control of the full module database. The MHPs recognize an FMTP failure when message communications are unsuccessful. After a preset interval, the MHPs will assume the inaccessible FMTP is down and begin sending all messages addressed to this module's FMTPs to the single survivor. When a processor is re-IPL'd, it automatically recovers its regular share of equipment and transaction load.

Any work in progress on a failed processor is lost. This simple recovery philosophy is acceptable because a transaction updates at most a single file record. There is no automated message recovery. The terminal users provide the message recovery by submitting a query for an account in the case no response is received, and resubmitting the account update if necessary.

DCF as a Network of Modules: The previous discussion described the hardware and general function of a module. The data and external lines are partitioned over as many modules as necessary to control the network and meet the transaction processing requirements of peak message traffic. Modules are connected with a redundant pair of communication buses identical to the intra-module network described above. However, the inter-module network is distinct from each module's four node intra-module network in that only MHPs are connected.

The determinant of the number of modules is the processing rate of the FMTP and the number of applications. A MHP can handle approximately 50 messages per second and up to 16 lines in normal mode, or 32 during peer failure operation. An FMTP can only handle about four messages per second. Currently the account database and the external lines are partitioned across five modules in each cluster. There is also one module for a DCF cluster management application and two spare modules for expansion in each cluster.

Programs operating in the IBM batch environment use a control file to produce daily database load tapes for each FMTP after the batch ledger posting systems complete. Also on the tapes are routing tables and line/station tables for the related MHPs. These become part of the MHP resident software after the next IPL and inform each MHP as to the PCU configuration and database distribution. The latter table maps a particular branch number to the FMTP which has the database for that branch. Mapping is clearly necessary to properly route messages.

DCF Cluster Management: A DCF cluster presents a single system image to the operations staff without introducing a single point of failure. This capability was implemented because 32 or more independently operated computers could present a difficult operational problem. A special application called the Network Operations Center (NOC) was developed as well as unique hardware to provide remote processor IPL and status display.

The NOC is a set of software developed to provide computer operator console functions. There is a dedicated DCF module where the full set of input and output functions reside. Each processor in the cluster (MHPs and FMTPs) has a set of execution routines that execute commands entered at the NOC. Commands are entered on terminals connected to the NOC FMTP's for execution on any processor. The commands are interpreted by the NOC FMTPs and put into a standard internal form. They are sent through the NOC module's intra-module link to the NOC MHP for routing to the target processor, command responses are routed back to the NOC FMTP and displayed on the originating terminal. In situations where a processor generates a message to the operator, it is logged on the respective module's printer and a copy is forwarded to the NOC module for action/information. The switchable TTY configured in each module serves as an operator console when the NOC is down by switching it to an MHP. A subset of NOC command input and output formatting routines is present in each MHP.

Remote IPL and status display capability was developed for all processors to allow processor IPLs from a single remote panel. Each processor also has software controlled display lights on this panel to indicate normal mode, hard stop, and intervention required conditions. Unique IPL ROM controllers were fabricated for each FMTP and MHP which provide: normal IPL, backup version IPL, and full memory dump. These functions can be activated either from the remote panel or local to the respective processor. In the case of the MHP, the full memory dump goes to tape, with FMTP to disk. There are several additional options for normal and backup IPL on the FMTP. There is normal IPL from program libraries which takes about three minutes. A normal and backup IPL from a memory image is also provided which takes 10 seconds. The library load is only used when new software is introduced.

External Network Management: The external network covers the state of California and involves the facilities of over 50 independent phone companies. It was clear that to provide the required availability extensive diagnostic equipment was necessary to pinpoint problems. This led to the development of the Network Control Center (BANC). Sophisticated telecommunications diagnostic equipment allows network technicians to diagnose problems in the external network. Racal-Milgo T-7 optioned modems provide a side band diagnostic channel which is automatically used by a DEC PDP 11/45 to monitor the line and modem condition. The PDP 11 provides commands that can be transmitted on this side band to exercise or change the status of remote modems.

With respect to the control of the 1100 PCUs, it was decided not to put secondary storage on the PCUs and instead to provide the ability to load them through the

network from a central database of PCU programs. This was done due to the cost of the floppy disk drives (1100 is a large multiplier) and by the need to control the version of the software that was in each PCU. A special application was developed for every module with external lines. This application resides in the FMTPs and can load any number of PCUs concurrently. The line loading caused by the amount of data transmitted, however, necessitates a limit during peak transaction loads. A PCU can be booted by an IPL button on the unit or invoked by an operator command.

Typical Message Flow: Figure 2, shows Northern California Branch 200 and illustrates message flow. The Branch contains a PCU which is one of the drops on a line connected to MHP AM1 in the San Francisco data center. The following examples assume a teller in that branch is negotiating a check drawn a Bank of America branch.

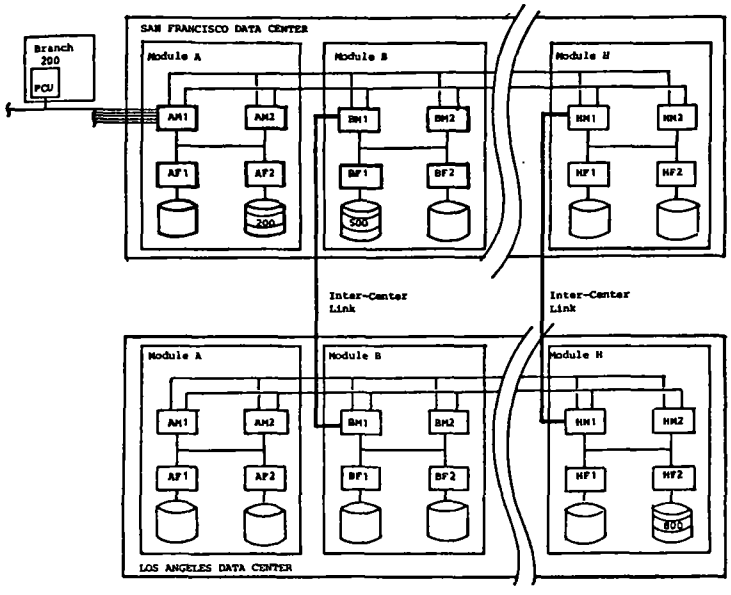


Figure 2

AM1 is continually polling the PCU in branch 200. When the teller enters the transaction and presses the send key, the PCU responds positively to the next poll and sends in the message.

The message has been mapped by the PCU onto a standard DCF message format and the target application has been identified. AM1 stamps the message with its ID, the line ID, and the PCU ID for use later in routing the response. AM1 selects the appropriate application routing algorithm. For Demand Depost Application (DDA) messages, the account number being debited is separated into its component parts: branch number and account number within branch. The routing table mentioned above is indexed to identify the location of the necessary branch data. Two cases will be discussed:

Case 1: This occurs if the check is drawn on Branch 200, and the data for branch 200 is on San Francisco Module A as shown. AM1 does input routing, determines that the data is on AF2 and sends the message to AF2 on the intra-module link. AF2 queues the message and when next-on-queue, the DDA software is brought into memory, memo reduction in balance for the account is effected, and the response to the teller is sent back to AM1 on the intra-module link.

Case 2: This occurs if the account being debited is domiciled in branch 800. The data for this branch is on HF2 in Los Angeles. The input message routing algorithm of AM1 yields the Los Angeles center ID. AM1's inter-center routing table yields the inter-module link address of BM1 which has one of the inter-center links to Los Angeles. This is a two entry table, containing BM1 and HM1. After each inter-center routing action ocurs in AM1, the entries are flipflopped to attempt to evenly load both paths to Los Angeles. BM1 is then sent the message over the inter-module link. BM1 goes through the same input routing process as AM1, and further discovers that it has the link to the Los Angeles center, so the message is sent over the inter-center link.

BM1 in Los Angeles then performs the same input routing as the previous two MHP's. HF2 is identified as the target FMTP, and it receives and processes the message as described above.

When HF2 has processed the message, the response is returned to HM2 through the intra-module link. HM2 does response routing based on the originating MHP ID (SF-AM1), discovers it belongs to San Francisco and accesses the inter-center routing table to make the appropriate routing decision to transmit the response back to AM1.

In any of the above flows, a single processor or link failure will not affect the sucessful transmission of the message unless a processor fails while that message is in transit and before being sucessfully transmitted to the next point. The paths chosen for transmission clearly would be different if one of the links or processors mentioned above were down. If both paths to a target are down, an error message is returned to the teller. If both paths are down preventing a response from being returned to its origination point, the message is discarded after being logged to the NOC. If an intercenter link is down, the MHP with the down line will forward a message to the other gateway MHP. If both lines are down, the second gateway to get the message will recognize this situation and dispose of the message as described above based upon whether it is an input or response message.

Software: The operating software was specially constructed by Bank Staff in a joint development with the vendor. The FMTP has extensive software error handling logic. This was developed because application software and disk-related system support functions reside there. All of these were identified as much more likely to change than the MHP software. The FMTP handles two types of errors: Recoverable and Non-recoverable.

Recoverable errors are those that can be associated with a particular message. These types of errors are defined to be those occuring when the software is not operating in interrupt handling state. Examples are stack overflow or underflow, protection violation, or invalid request for supervisor services. The occurance of this type of error causes diagnostic information to be captured and the message to be discarded.

A Non-recoverable error is defined to be one which occurs during interrupt handling or a recursive error condition generated by the inability to recover from a suspected recoverable error. When such an error occurs, a memory dump is taken and the processor halted. This causes an automatic switchover of disks to the surviving FMTP and a switchover notification message to be sent to the NOC.

FMTP switchover processing occurs when a processor fails and the peer must assume responsibility for all the disks. This involves handling the interrupt from the System Safe Controller of the failed FMTP, initializing the disk controllers that are now to be managed by the survivor, reading in the file control blocks and high level indices, and preparing for application access of these files.

Switchback processing occurs after a failed FMTP has IPL'd and is requesting responsibility for its normal complement of disks prior to resumption of transaction processing. After the restarting FMTP has IPL'd itself by accessing the disks through the dual ported controller, it sends a message to the survivor requesting responsibility for its disks. The restarting FMTP then opens its complement of files and begins normal transaction processing. MHPs detect that the restarting FMTP is available for processing when it begins to respond to its "I'm alive" messages which all processors exchange on a regular basis.

Operational Experience: The system is very successful from a performance, availability, and operability standpoint. Using representative data from the peak hour in Los Angeles (10:00 a.m.): 87% of transactions receive a response within 3 seconds (as measured at the PCU), 99% of transactions receive a response within 6 seconds, FMTP database load takes less than one hour.

Because of the distributed nature of this system, the scheme for calculating the availability statistics warrants some explanation. The duration of unavailability of any component is recorded by the operations staff. The unavailability of a duplicated component does not affect the user, so does not affect the computed availability numbers. When both prime and backup components are unavailable, the user is affected. The availability statistics reflect the severity of the outage as well as the duration. For instance, the DDA data is distributed over 40 disk spindles in each center. The data is not duplicated. If a spindle is unavailable for 40 minutes, 1/40th of the database is down. Central site unavailabity for that outage is one minute. If a DDA module is unavailable for 40 minutes (both MHPs or both FMTPs), 1/5th of the database is unavailable. The central site unavailability for that incident is eight minutes. The monthly figures are then figured by taking these weighted unavailability statistics and dividing by the committed minutes of operation for the month to yield the monthly statistic.

End user unavailability is the central site unavailability plus the network unavailability. Network unavailability is average PCU unavailability due to PCU problems plus average PCU unavailability due to line problems. Using Los Angeles statistics for the first seven months of 1982, DCF delivered 99.96% central site availability and 99.64% end user availability. The causes of the end-user perceived unavailability are: 50% due to line problems, 39% due to PCU problems, and 11% due to central site problems

During the first seven months of 1982, the Los Angeles data center averaged 63 line problems per month. These took an average of 287 minutes to resolve. There were 54 PCU failures per month averaging 260 minutes of outages. 266 teller and 139 administrative terminals failed on average per month. These numbers represent the number of times vendors were called to resolve problems. The trouble calls from users to the network technicians average well over 2000 per month. The network technicians are able to resolve about 50% of trouble calls themselves. They are able to do this in large part because of the Network Control Center (BANC).

The contribution of central site unavailability tc overall unavailability is quite low (11%). The month of June in 1982 was analyzed in detail because it appeared fairly representative. The following central site failures were recorded: 23 failures, 128 minutes of component unavailability, 6 minutes average to fix with only five failures visible to users because of redundancy and automatic backup This resulted in 30 minutes of module unavailability for the month which was recorded as 6 minutes of central site unavailability (30 minutes / 5 modules in the cluster).

Conclusions: The system is highly available and central site unavailability contributes very little to the overall system unavailability. If any improvements were to be made, attention to the communication line unavailability would have the best potential for improvement. Several design features of DCF have clearly had a beneficial impact on availability:

1. Redundancy: Redundant components with automatic switchover reduces the visibility of failures to end users.

2. Granularity: Spreading the load over multiple modules also reduces the impact of a total module failure.
3. Rapid IPL: The ability to IPL the FMTPs in 10 seconds creates situations in which an IPL is the first thing done when strange things happen, not the last.

The above features must be set in the context of a system having no message integrity. Processor failures cause message loss. The system does not have a 24 hour operating requirement, allowing hardware maintenance, software maintenance, and testing to occur at off-hours.

A significant factor contributing to central site availability is the stability of the software, with less than three changes being made per month. These are mostly MHP table changes reflecting a change in terminal, line, or PCU configuration. Very few software caused outages are visible to users. This is somewhat deceptive however. During the initial conversion of the system, the availability was consistently over 99% even when the software was very failure prone. This was a result of the granularity, rapid IPL capability plus the fact that most errors were FMTP application software failures of the recoverable variety where processor shutdown did not occur.

The overall conclusion to be drawn is that a network of minicomputers have been effectively used to support a large terminal based application in place of a more traditional mainframe approach. The Distributive Computing Facility is setting the standard within Bank of America for the operability and availability of online systems.

Distributed Database Support

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1. Introduction

In a traditional real-time system all data reside in a central database and transactions operating on the database are handled completely within one central computer. By a transaction we mean a sequence of operations which transfer the database from one consistent state to another one. This sequence is atomic, that is, it is executed completely or not at all.
More formally expressed a transaction defines both a success-unit (it is executed completely or not at all) and an integrity unit (the data it uses is not accessible by other transactions). It is the responsibility of the programmer to define where in a program a transaction starts and ends. The transaction handling system of the DBMS will then guarantee that the transaction is executed properly.

In a distributed system data reside in many computers and the execution of a transaction in such a system usually means that data in many different computers have to be accessed. That is, the transaction processing is distributed and it is the responsibility of the network data manager to guarantee that a transaction is executed completely or not at all. This can be a tricky problem in the general case. However we have found that by splitting a transaction into a main transaction and one or more secondary transactions which cooperate according to certain rules, the transaction control can be simplified. It becomes especially simple if all real time updating of the database is replaced by so called delayed updating. Delayed updating means that the database is updated after that the system has signalled to the user that the transaction has been completed. The network datamanager in the nodes involved will guarantee that the requested updates really are done. The delay before the database is updated can vary from just some milliseconds to batch update during the night (application defined).

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*) Acknowledgements

We want to thank our colleagues, S. Arnborg, T. Beerda, Tsj. Beetstra, H. Ljungkvist, P. Öman, B. Sanden, J.J. Schenk and L. Zwanenburg in Apeldoorn and Järfälla for their valuable contributions in the discussions on distributed processing.

2. Architecture

In our model a distributed database system consists of a set of nodes which are interconnected via public and/or via local networks. The relevant nodes in such a system can be classified as:

- terminal node:
  handles one or more workstations and executes dialogue-oriented parts of transactions. This node type has no local database.

- database node:
  contains a local database and all software needed to handle it. Data in such a database can be accessed from other nodes. No workstations are directly connected to a database node.

- complete node:
  include both terminal node and database node capabilities.

Networking nodes, e.g. gateways, are not regarded in this paper. We assume that high level transmission services up to the transport level of the OSI reference model are available at each node.

The above node types can be combined to form different types of distributed database system structures. Moreover, the architecture permits one computer to hold more than one node. For example, one computer can hold one or more database nodes where each such node is an independent unit. Each node has a unique logical name, own data etc. The node names are globally known and are used to address the nodes.

From an application programmer's point of view the distributed database consists of a set of logical databases. Logical node names are used as references when an application process in one node wants to access data in another node. To find the proper node name, the requesting process can use a locate function. This function will either consult directories or execute a user defined algorithm to get the proper node name.

Structure of application

The application programs are structured into Main Transaction Programs (MTPs) and Secondary Transaction Program (STPs) and these cooperate to execute transactions.

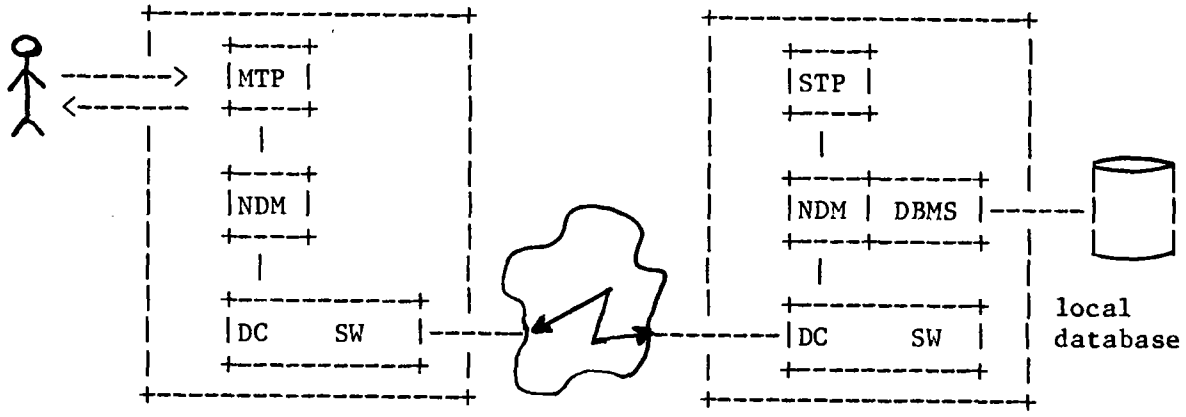
MTPs are front-end programs and the execution of such a program is initiated by a user. The execution of a MTP takes place in a terminal node or in a complete node. MTPs handle the man-machine dialog, processes information and accesses the database, both local and non local databases can be accessed. A non local access means that a command message is sent to that node which holds the data requested. An answer message will later return the results.

STPs are back-end programs which are executed in nodes containing local databases. The execution of such a program is initiated by a command message sent from a MTP or another STP. Normally a STP performs some processing of data before the answer is sent back.

When the execution of a MTP or a STP starts, a Main Transaction (MT) or a Secondary Transaction (ST) is created. The execution of a transaction means that one MT and zero or more STs are executed. MT is responsible for the execution of the transaction and it will coordinate the execution of the involved STs. When the MT is finished the transaction is also finished from the user's point of view. However, the transaction need not to be finished from the system's point of view at that moment. In next section we will further develop these concepts.

Software architecture

The software architecture is shown in the figure below:



Every local database is self contained and is managed by a local DBMS, which handles among other things local database accesses, access conflicts within a node and recovery within a node. The DC SW implements the network independent transport services defined in the OSI reference model (layer 1, 2, 3 and 4). MTP and STP are the application program discussed previously.

NDM (Network Data Manager) is the new component and this administers all non local database accesses and it will guarantee that the distributed database remains consistent. NDM belongs to the session layer in the OSI reference model and communicates with NDMs in other nodes via the DC SW. Locally it communicates with the DBMS. The following functions are handled by NDM. 1) access to data in other nodes. This includes support for addressing of nodes and support for message handling. 2) distributed transaction handling to guarantee the consistency of the distributed database. 3) access conflicts between nodes. 4) recovery which involves many nodes. 5) locate support to find in which nodes data are stored.

3. Distributed transaction handling

The notion transaction is defined in the introduction. In a non distributed sytem the end user interaction and the database processing will in general proceed in parallel. The database reflects the most current situation, that is, it is in accordance with the most recent transaction.

In a distributed system the Network Data Manager is responsible for the execution of the MT and the related STs. MTs and STs can cooperate in many different ways. We have found that a great deal of applications can be handled with three types of cooperation. For each cooperation type we have defined a ST type. The ST types are:

sub transaction:

A ST of this type is always executed simultaneously with the invoking MT and forms with respect to transaction commitment and cancellation one integrated transaction, that is

- database modifications generated by the sub transaction will only become definitive after commitment by the MT at the end of the MT.
- a premature cancellation of the MT (by itself or by the system) also cancels the sub transactions.
  So the functions "COMMIT" and "ROLLBACK" having a MT as subject will extend their scope such that also the sub transactions executed or under execution in other nodes will be involved in the functions.

When a sub transaction has finished its task it will get the status ´ready-to-commit´. A sub transaction in ´ready-to-commit´ state can only be committed or rolled-back by the invoking MT. This ST type is used for real time updating of a database.

side transaction:

A side transaction is - like a sub transaction - a ST which is executed simultaneously with the invoking MT. The difference is that when it has finished its task all database modifications it has generated are definitive. NDM gives no support in the revocation afterwards by the MT.

Although this fact restricts the usage of a side transaction, there is still an important area where it can be applied successfully, namely for for inquiry of a database. An inquiry never needs rollback and therefore can be performed as a side transaction.

The advantage of a side transaction is that its control requires less internal transmission of control information and consequently it has a better throughput and responsiveness.

delayed transaction:

A ST of this type runs independently of the invoking MT and it is never executed simultaneously with the MT. Invocation calls for delayed transactions will namely be effectuated only after the MT has terminated normally. Cancellation of a MT implies cancellation of the invocation requests for delayed transactions done by the MT. It is because of this fact that the delayed transaction will not be able to return output information to the MT.

NDM guarantees that invocation calls for delayed transactions are forwarded to the right destination nodes and that the requested delayed transactions really are executed completely. The guarantee is valid even if there are times problems with the physical communication lines or if an involved computer crashes. If for some reason a requested delayed transaction cannot be started or finished in a proper way a system failure has happened and NDM will take care of this and send a message about the incident to an operator at some network control center.

Delayed transactions may themselves also invoke other delayed transactions e.g. in the node of the originating MT (post processing).

By considering a transaction as a MT and one or more STs of different types we assume that application system design can become simpler. Only in those systems where real time update is a necessity are STs of type sub transaction required. We believe that many applications handle only transactions which consists of side transactions and delayed transactions.
Side transactions are used for querying the database and delayed transactions for updating the database.

The advantages of this approach are:
- short response time. The user has not to wait until all updates really are done.
- works also in offline situations.
- small overhead in NDM for recovery purposes.
- priorities can be assigned to queries and updates. There are also possibilities to postpone updates during peak hours.

The drawback of this approach are:
- the values in the database are not completely up to date. The updates are not done immediately.
- the distributed database can be inconsistent for some time. However it will converge to a consistent state gradually.

These drawbacks have little importance in applications where the risk for access conflicts is small and/or where it does not matter if the data are absolutely up to date: for example in banking systems it does not matter if the balance of an account becomes negative, many reservation systems accept overbooking.

4. Restart

To be able to restart after a local database crash, back-up copies of the local databases have to be taken regularly. A back-up copy at one node can be taken independently of the other nodes in the network. A back-up copy can be taken when a local database is in a consistent state. This happens when all MTs, sub transactions and delayed transactions in a node are completely finished. By closing a node for new updating transactions a local database will soon enter a consistent state. Normally this happens quickly, however if a node contains sub transactions in a 'ready-to-commit' state and the invoking MTs are in other computers and these are down, it can take a long time before a consistent state is reached.

The restart procedures must cover the following error situations:
- line failure
- local database crash
- error in after-image log

To be able to recover from these error situations NDM must contain some extra overhead. The amount of overhead needed for delayed transactions is rather small because delayed transactions have only a local scope. However the overhead needed to handle recovery of sub transactions is both complicated and extensive.

Moreover a distributed database system must also be able to restart after many coincident errors. The normal restart procedures work well if one or many line errors occur and/or one or many local databases crashes at the same time. This is also valid for different combinations of line errors and errors in the after image logs. However, if a local database and its after-image log are damaged at the same time a catastrophe has happened, that is, it is not possible to restart with information available locally. This situation also arises when a node is totally destroyed because of fire, sabotage etc. To restart from such a situation information stored in other nodes is needed. Special restart procedures must be used and these often require manual participation. The restart from a catastrophe is simplified very much if only delayed transactions are used for database updates.

5. Conclusions

Dividing a transaction in a Main Transaction (the user oriented process) and Secondary Transactions (the database processes) will help to develop secure and reliable distributed systems. In addition the use of only delayed transactions for updating will make transaction processing much simpler. In that case local COMMIT and ROLLBACK happens, and this simplifies restart and recovery. Only the secure execution of the local delayed transactions must be guaranteed.

In how many applications is real time updating a user requirement? We believe that many applications can be developed with only the use of STs of type delayed for distributed database updates.

Distributed Data Management Issues in the LOCUS System*

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1. Introduction

The LOCUS project at UCLA has taken the view that issues in distributed computer operation should be primarily addressed at the operating system level, so that all clients: data bases, transaction processors, language systems, and application software can take advantage of the solutions. Accordingly, LOCUS, a Unix compatible, distributed operating system operational on an Ethernet of VAX computers at UCLA, provides a very high degree of network transparency, both for the file system and tasks. A global name facility, supported by partial replication, is provided. High reliability features such as support for replicated files across the network, nested transactions, and graceful partitioned operation are all present. A LOCUS bibliography is given at the end of this paper.

However, the best test of a distributed operating system results from its use by applications. For example, one expects the existence of network transparency plus operating system reliability features would make it feasible to obtain considerable distributed data management functionality merely by running a single machine data base system in a LOCUS-like environment. (Parallel processing of an individual query would have to be added, of course.) But a test of this stategy is necessary.

In pursuing this approach to distributed data management at UCLA, a number of data base issues related to distribution have surfaced. In this note, we wish to comment on three of them: name spaces, the relationships among transaction mechanisms, and multilevel logs. We turn to these now.

2. Distributed Name Spaces

The distributed file system component of an operating system must provide a distributed name space supported by at least partially replicated catalogs. The name space of a data base management system is similar to a file system name space. If the underlying distributed operating system (DiOS) provides a global and transparent name space, together with extensive replication and recovery support after partitioned operation, as found in LOCUS, then substantial advantage may be obtained by an appropriate mapping of the distributed data base management system's (DDBMS) name space onto the DiOS's name space. This section indicates how that mapping can be done.

Consider the nature of the DDBMS name space. It should be global and transparent, using partial replication for the supporting catalogs, in order to provide flexibility and ease of use [Popek83]. The strongest motivation for replication support for a global name space is the flexibility it provides when combined with transparency. When a transparent, global name space is provided, applications can easily move from being centralized to being distributed. If, in addition, the name space is compatible with a centralized DBMS (CDBMS) then the applications of the CDBMS can be directly transported to the DDBMS and run without modification.

Two considerations suggest it should also be hierarchical in nature. In a large distributed system, name collisions at the data base level could be frequent (for example, many *employee* data bases). A hierarchical name space would avoid this problem. Further, if the DDBMS supports partitioned relations**, a hierarchical relationship among them is natural.

*This research has been supported by Department of Defense contract DSS-MDA-903-82-C-0189.

** Partitioned relations provide, in normal operation, the ability to store portions of relations at different sites, and yet have the data base system make their composition transparent to the user.

One critical aspect of a distributed system's name space is the affect of a failure on the support mechanism. A user should see minimum adverse affects after a failure. Consider a catalog replicated at two sites and the affect of a communication failure between the sites. Catalog operations on the two catalog copies must be able to continue independently and a catalog merge algorithm must be able to make the two copies consistent when the failure is corrected. The partitioned operation concept is this view that functions can continue to be provided in spite of failures and the underlying system will make things "right" when the failure is resolved. In LOCUS, partitioned operation and merge is provided as an integral part of the directory system used to support the name space.

2.1. DDBMS To DiOS Name Mapping

The DiOS's name mechanisms can provide most of the name support if the DDBMS's name space is directly mapped to the DiOS's name space. For example, the directory recovery procedure would perform the merge and conflict detection of the DDBMS's name catalog required after network reconnection. In this way the DDBMS does not rebuild much of the functions of the DiOS. Also, with one common mechanism, functionality and performance improvements are shared by both "users".

The alternative is for the DDBMS to build its own name space within files of the DiOS. In this case, the DDBMS must duplicate many of the functions provided by the DiOS: replication of the appropriate entries, partition merges of the catalogs, etc. On the other hand, performance tuning is DDBMS specific. The catalog could look much like a normal relation, for example. Representation of the hierarchy may be confusing when displayed in this fashion, however.

There are other DDBMS tables, such as protection catalogs, which also share common characteristics with the naming facility. They benefit in a similar fashion from use of the underlying system directory management facilities.

2.2. DiOS Requirements

Mapping the DDBMS's name space onto the DiOS's name space places several requirements on the DiOS's name support mechanism.

First the user needs to be able to associate some variable length data with each directory entry in order to store the catalog information. The user must be able to change the data (update the catalog information) and the system must be able to detect conflicting updates (that result from partitioned operation, for example). Lastly, the DDBMS must be able to specify a particular entry easily. For this purpose there should be a directory entry identifier equivalent to a tuple identifier, as if the catalog were a real relation.* The DDBMS can then have tuple identifiers for all relation and catalog tuples and only be concerned at the access method level about representation.

2.3. A Proposed Mapping

Given the DiOS functions proposed above, the DDBMS name space can be supported in the following manner.

For each node in the DDBMS hierarchy there will be a directory in the DiOS file system. The children of the node will be entries in the directory. In addition each entry will contain any additional data describing the child node. All other catalogs will be maintained in a child directory with tuples being directory entries in their directory. The catalog's information will be stored in the user supplied data of the directory entries that comprise the catalog. In order for the recovery mechanism to perform properly the name of a directory entry must be a unique key for the catalog.

* We assume the relational model for discussion purposes.

A case study is presently being completed to test this view of distributed data management. The single machine Ingres database system is being integrated into the distributed LOCUS environment, using a name map quite similar to what has just been outlined [Thiel83].

3. Transactions in a Distributed Environment

It is becoming the conventional wisdom that the atomic character of transactions in distributed environments, especially in the face of failures, will be increasingly important. Nested transactions have been suggested as a natural consequence of assembling independently developed software packages, and as a way to limit the effect of intra-transaction failure. A commonplace example would be a program X, itself a transaction, that involves an existing database function, uses a prepackaged transaction-processor for another service, and performs some of its own updates directly to the underlying file system. Assume that both the DB and TP are built to perform their functions atomically.

3.1. The Problem

Currently available transaction mechanisms are inadequate as tools to support such an environment. First, it is typical in virtually all available systems today that the transaction facility is implemented in the application package: the data base system, the transaction-processor, etc. The interfaces to these functions that are made available to clients (people or programs) are simple:

```
Begin_transaction
Abort_transaction
End_transaction
```

are typical. This approach makes it impossible in general to construct the program X mentioned above and assure its atomicity. The reason is illustrated by the code fragment below.

```
X:  BEGIN TRANS   DB
      :
    BEGIN TRANS   TP
      :
    FILE WRITE
      :
    END TRANS     DB
      :
    END TRANS     TP
```

Failure between the two END TRANS calls means that the DB transaction completed while the TP transaction aborted. (Note that properly nesting the called transactions does not solve the problem either.)

Further, of course, it is the responbility of X's recovery software to undo its own file updates. This amounts to building another transaction mechanism. Its decision to complete or abort also cannot be synchronized from the available interfaces.

3.2. Possible Solutions

There are several approaches to this problem of assembling nested transactions. First, if an inverse operation exists for each transaction (e.g. DEBIT/CREDIT, CREATE/DELETE), or if an UNDO log is retained, and it is possible to determine which transactions completed and aborted, and recovery mechanisms can be run immediately upon resumed operation, (so that the results of apparently completed transactions have not yet been seen), then the completed transactions can be undone. In a distributed envrionment however, it is difficult in general to fulfill this last requirement.

Second, one could require that the functional interface to each transaction mechanism be altered to give finer control. At least a PREPARE command must be made available, whose semantics are the familiar internal step of the two phase commit protocol. Then it is possible to compose transactions by having the parent transaction PREPARE all of the participants before completing any of them. It is still the responsibility of the application program X to implement its own transaction mechanism, to make sure that all participant transactions are PREPARED before ENDing them, and to record sufficient information in its log so that recovery operates correctly.

Lastly, one could provide a full nested transaction in a basic distributed operating system. All application packages would use it in the standard simple way, and the mechanism is built once. This is the approach taken in the Locus system. While the mechanism is extensive (approximately 7000 lines of C code for two phase commit, intra and inter transaction synchronization, version stacks and associated control software) the mechanism executes surprisingly fast, primarily imposing a cost at the end of the parent transaction that is just a few times greater than that required to close all resources anyway. This approach is very attractive if one can accept a homogeneous distributed operating system base. Otherwise, the other options need to be considered.

3.3. Multi-Level Logs

Transaction implementations typically involve extensive use of logs and supporting facilties. Many applications create *objects* which are log-like for reasons other than transaction support. Therefore, a log *type* could be considered as a reasonable facility to be provided by the underlying system. When the transaction support is provided by the OS then the generalized log *type* provided by the OS would permit all the OS's applications to use this object type for any log-like activities. Since a DBMS represents one major class of OS applications it is reasonable to expect that database related applications may well be able to take advantage of a log object type. Therefore we are examining a multi-level log mechanism.

As an example, consider a three level software system composed of a operating system kernel, a DBMS and a editor built on top of the DBMS. At the operating system level many types of asynchronous and synchronous events may be logged: configuration changes, software failures, device errors, two-phase coordinator commit points, etc. At the DBMS level more data needs to be logged, including software failures, usage data, partitioned operation information and catalog recovery information. The editor may keep a keystroke file or information in order to provide the user with an *undo* function. Such logging facilities are being investigated as part of the LOCUS based distributed database effort.

4. Conclusion

Repeatedly it appears that one can profitably avoid solving the same problem at multiple levels in computing systems. To do so however requires understanding the tasks to be accomplished at each level, so that commonality and restructuring can be accomplished. Each of the approaches raised in this note is an attempt to develop this commonality.

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Research in Database Programming:

Language Constructs and Execution Models

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1. The Database Programming Languages (DBPL) Project

The DBPL project at the University of Hamburg is centered around the integration of database models and programming languages. It is motivated by the insight that most of the interfaces used to access real databases are not stand-alone data sublanguages but complex programs requiring the functionality of a high-level programming language and of a database model, both integrated into a unilingual and homogeneous framework [SCHM77], [SCHM78]. The relational approach to databases and Pascal-like programming languages, both known for their well-designed data structuring capabilities, have proven as a framework particularly suitable for that integration effort.

The usefulness of high level database programming languages has been demonstrated by several successful applications of the database programming language Pascal/R [SCHM80]. It is used for teaching database management courses, for database applications (e.g., 50 Mbytes in fishery research [BIOM81]), for the development of database programming methodologies [BROD81], and as a target language for very high level languages like TAXIS at the University of Toronto, and the natural language system HAM-ANS at the University of Hamburg.

The DBPL project evolved from ideas resulting from the design and implementation of Pascal/R from 1975 to 1979. The project has the objective to investigate in more depth language constructs and execution models for essential database programming problems. In particular, issues of query evaluation and transaction management as well as their mutual interaction are addressed. The project takes a high level approach in the sense that it emphasizes the development of high level language constructs together with their transformation and evaluation over representational issues. A notion central to our approach is that of a selector for relation variables providing abstract access to subrelation variables. The concept of a selected relation variable is used to essentially support query evaluation as well as transaction and integrity control.

The DBPL project (principal investigator: Joachim W. Schmidt) is supported by the Deutsche Forschungsgemeinschaft (DFG) under grant no. Schm. 450/2-1.

2. The Selector Concept

Since, in practice, several users contribute to the data integrated into a relation, individual users often do not require access to full relation variables. In the following, we sketch the notion of a selector [MALL82] that provides access to selected parts of relation variables.

The uniqueness of key values within a relation provides a basis for selecting and altering individual relation elements. Let us assume that the relation, relk, has a key composed of the two attributes k1 and k2. In Pascal/R syntax the statement

```
IF SOME r IN relk (<r.k1,r.k2> = <kv1,kv2>)
THEN relk :& [ <..,kv1,..,kv2,..> ]
ELSE relk :+ [ <..,kv1,..,kv2,..> ];
```

replaces (:&) the value of the relation element with the specific key value, <kv1,kv2>, by a record <..,kv1,..kv2,..>, or inserts (:+) a new element, if an element with this key value does not exist. The above statement is equivalent to the assignment

```
relk := [ EACH r IN relk: NOT (<r.k1,r.k2> = <kv1,kv2>),
          <..,kv1,..,kv2,..> ];
```

If we switch from the set-like perception of relations taken so far to an array-like or table-like view, the above statement can be interpreted as an assignment of the record <..,kv1,..,kv2,..> to the relation element identified by its key value, <kv1,kv2>. We identify a relation element by means of a so-called element selector and write, e.g., relk[kv1,kv2]. Assigning a record variable, rec, to a selected relation element, relk[kv1,kv2] := rec, is defined to be equivalent to the following conditional assignment:

```
IF <rec.k1,rec.k2> = <kv1,kv2>
THEN relk := [EACH r IN relk: NOT(<r.k1,r.k2> = <kv1,kv2>), rec]
ELSE {exception};
```

The notion of an element selector can be generalized to selectors denoting arbitrary subrelation variables. This is achieved through the concept of a selector generator that allows for the definition of selectors based on arbitrary selection predicates. The above element selector, for example, is equivalent to the definition

```
SELECTOR sk (kf1:k1type; kf2:k2type) FOR rel: relktype;
BEGIN EACH r IN rel: <r.k1,r.k2> = <kf1,kf2> END;
```

which introduces a selector name, parameters, a formal base relation and a selection predicate. The notation relk[kv1,kv2] is therefore equivalent to relk[sk(kv1,kv2)] selecting the relation relk through the selector, sk, with the key value, <kv1,kv2>, as actual parameter.

In its most general form, a selector is based on an arbitrary selection predicate p

```
SELECTOR sp (...) FOR rel: reltype;
BEGIN EACH r IN rel: p(r,...) END;
```

and the assignment relk[sp(...)] := rex is equivalent to

```
IF ALL x IN rex (p(x,...))
THEN relk := [EACH r IN relk: NOT p(r,...),
              EACH x IN rex: TRUE]
ELSE {exception};
```

A predicative notation for the selection of subrelations is of high value for the definition of access rights and integrity constraints as well as for the definition of generalized access paths (permanent selectors). Sections three and four describe how the strategies for query evaluation and transaction management applied in the DBPL project take advantage of selectors.

3. Query Evaluation

From a database programmer's point of view, a query is a relation-valued expression based on a selection predicate. The predicate is a well-formed formula of an applied many-sorted predicate calculus with existential and universal quantifiers where the "sorts" are the range relations (relation expressions) to which element variables are bound.

A general evaluation procedure for relational expressions performs the following steps [JARK82a]:

(1) It applies logical transformations to the expression that
- standardize the expression (e.g., transform into prenex normal form) in order to simplify subsequent transformations,
- simplify the query (remove redundancy) to avoid double work, and
- ameliorate the query (e.g., apply the range nesting method as described below) to streamline the evaluation and to allow special case procedures to be applied.

(2) It maps the transformed expression into alternative access plans.

(3) It chooses the cheapest access plan and executes it.

This procedure provides the framework for our research activities in query evaluation [JARK82b].

The recognition and adequate processing of special classes of expressions plays an important role in our approach to query optimization. We have identified syntactic properties of a class of quantified queries, so-called perfect expressions [JARK83], lending itself to particularly efficient evaluation. Perfect expressions include quantified tree queries and certain classes of cyclic queries. We have developed range-nesting techniques that, given some perfect expression, produce an equivalent (range-) nested expression, which subsequently controls a stepwise execution of the evaluation procedure (inner nestings first). At each evaluation step a subexpression is evaluated that is at most as complex as

```
[EACH r IN rel: SOME/ALL x IN rex ( p(r,x) )]
```

where rex denotes an already evaluated inner expression and where p(r,x) stands for a conjunction of dyadic terms. Certain combinations of comparison operators and quantifiers, e.g.,

```
[EACH r IN rel: ALL x IN rex ( r.A < x.A )]
```

give rise to further simplification of a single step, e.g.,

```
[EACH r IN rel: r.A < MIN(rex,A)]
```

and so contribute to a 'cheap' evaluation of quantified queries that are usually perceived as being rather 'expensive'.

The method can be improved further by explicitly making use of permanent selectors. Prior to its evaluation, any subexpression can be checked if it is equivalent to some selector predicate, for which the corresponding selector is supported by an access path. If so, a

subexpression, [EACH r IN rel: p(r,..)], can be replaced by the equivalent selected variable, rel[sp].

Advanced access methods are explored with respect to their usefulness for our approach to query processing. We are especially interested in multi-dimensional access methods, i.e., access methods that efficiently support access over attribute combinations. Such access methods directly implement various classes of conjunctive intra-relational queries, such as point queries, range queries and partially specified queries. Thus, they are the prime candidates for the support of permanent selectors.

Finally, we are working on extending the scope of query optimization from one expression to a set of expressions. In database programming languages where concurrent access to databases is supported by language constructs for the formulation of compound database operations (transactions), there are two lines of attack. First, we are working on the simultaneous optimization of all expressions contained in one transaction (vertical scope extension), and second, we are investigating the idea of a shared query optimizer that processes expressions of a set of active transactions simultaneously (horizontal scope extension). Both approaches have specific coordination requirements with respect to concurrency control (e.g., minimizing the chance of transaction backup). Furthermore, they differ in the set of viable architectural alternatives for their implementation (e.g., vertical scope extension can be implemented by linking a completely separate query optimizer to each transaction, whereas horizontal scope extension always requires some sort of synchronization). In addition to a substantial improvement of overall performance we expect to achieve further insight into the complex interdependencies of query evaluation and transaction management.

4. Transaction Management

In addition to concepts for data selection, a database programming language has to provide linguistic support for transaction definition. A transaction is a compound database operation that transforms a database from one consistent state into another. In [REIM81] and [MALL82], the procedure concept of high level programming languages has been extended to a transaction concept by adding the semantics that transactions are executed either entirely or not at all.

A set of transactions can be executed in parallel if no transaction changes a (selected) relation shared with another transaction. It is the responsibility of the concurrency control component of a database system to make sure that a (selected) relation variable with the access right, WRITE, is imported exclusively, i.e., by only one transaction at a time. Since selected relation variables, as introduced in section two, are variables in their own right, transactions can import them and can operate concurrently on non-overlapping partitions of the same relation.

In the DBPL project, we investigate two types of predicative approaches to concurrency control. The (predicate) locking method avoids conflicts between parallel transactions a-priori by guaranteeing the disjointness of (selected) relation variables before the database is accessed. Since the disjointness test is purely based on access

intentions (predicates) locking of predicates has the disadvantage that, in general, more conflicts are signaled than may actually occur.

An alternative method analyzes conflicts a-posteriori when the actual data changed by parallel transactions are known. The test for disjointness consists of querying these data by the predicates defining the selected variables that are imported by the transaction to be analyzed. An execution of a transaction is conflict-free, if and only if the query against the data changed by the transactions that completed during its execution produces an empty relation.

Since the performance of pure a-priori approaches as well as of pure a-posteriori approaches is acceptable only under extreme - pessimistic resp. optimistic - assumptions about the transaction load, we are experimenting with combined methods that are adaptable to changing load profiles. Another motivation for combined methods is the insight that concurrency control and query optimization require coordination. We are working on a basically a-posteriori transaction handler that schedules, however, 'read-only' transactions due to a-priori principles. In that case the query optimizer can simultaneously evaluate queries of read-only transactions without risking that any of these transactions has to be restarted because of a conflict.

5. Current status of the DBPL Project

The design of the database programming language DBPL has been completed using Modula-2 as its algorithmic kernel [MALL82], [SCHM83]. Language compiler, query optimizer and concurrency manager are being implemented on a VAX-11 under VMS in Modula-2, which our group moved from a PDP-11 to the VAX-11 and adapted to the VMS environment [KOCH82].

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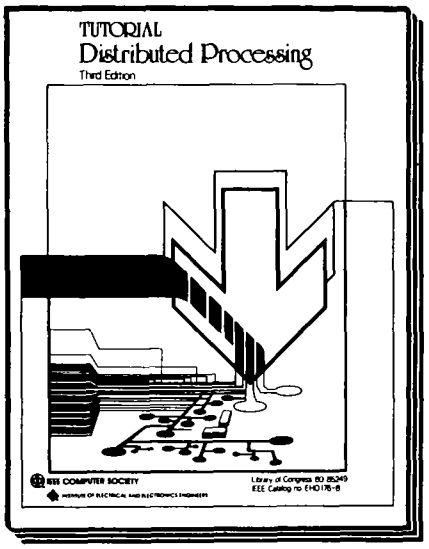

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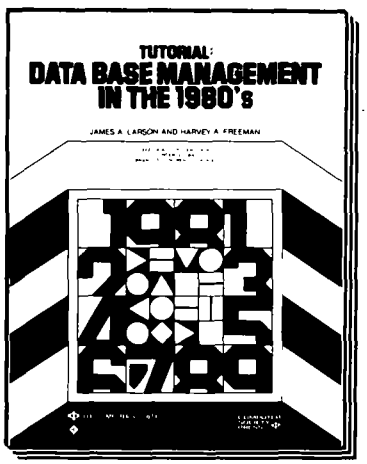

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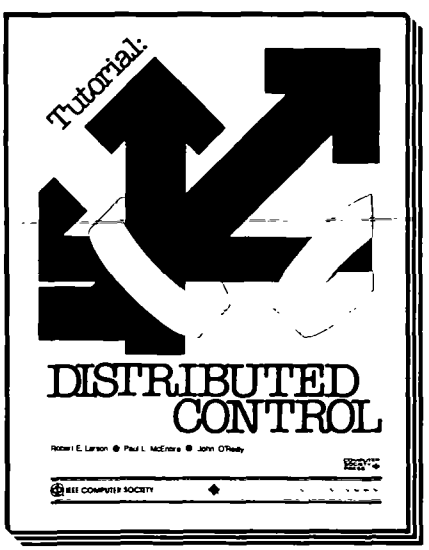

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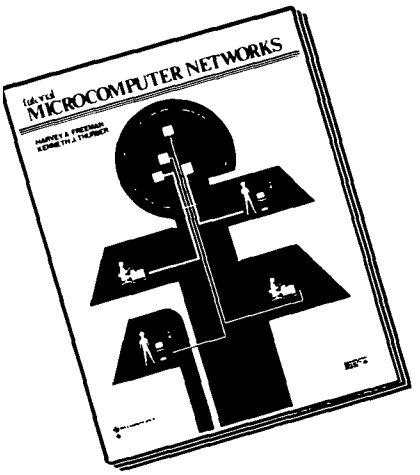

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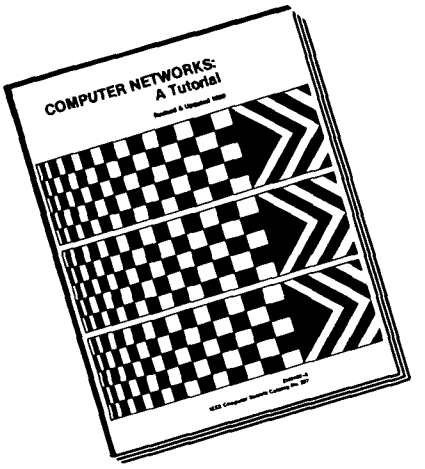
395 (ISBN 0-8186-0136-1): December 1981, 288 pp. **NM, $20.00; M, $15.00**



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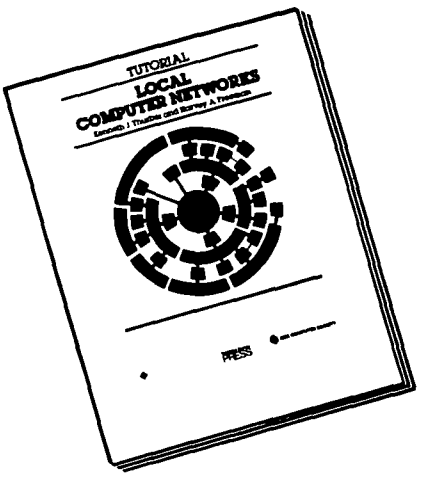

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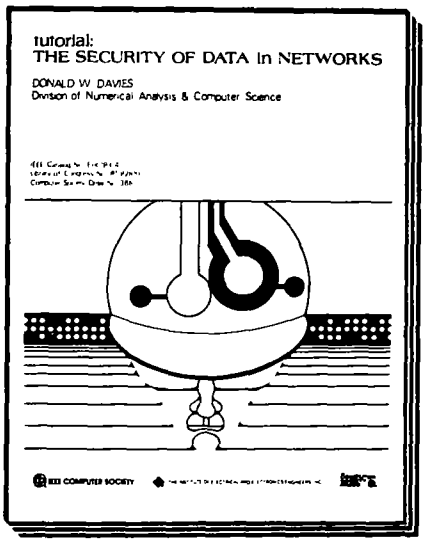

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