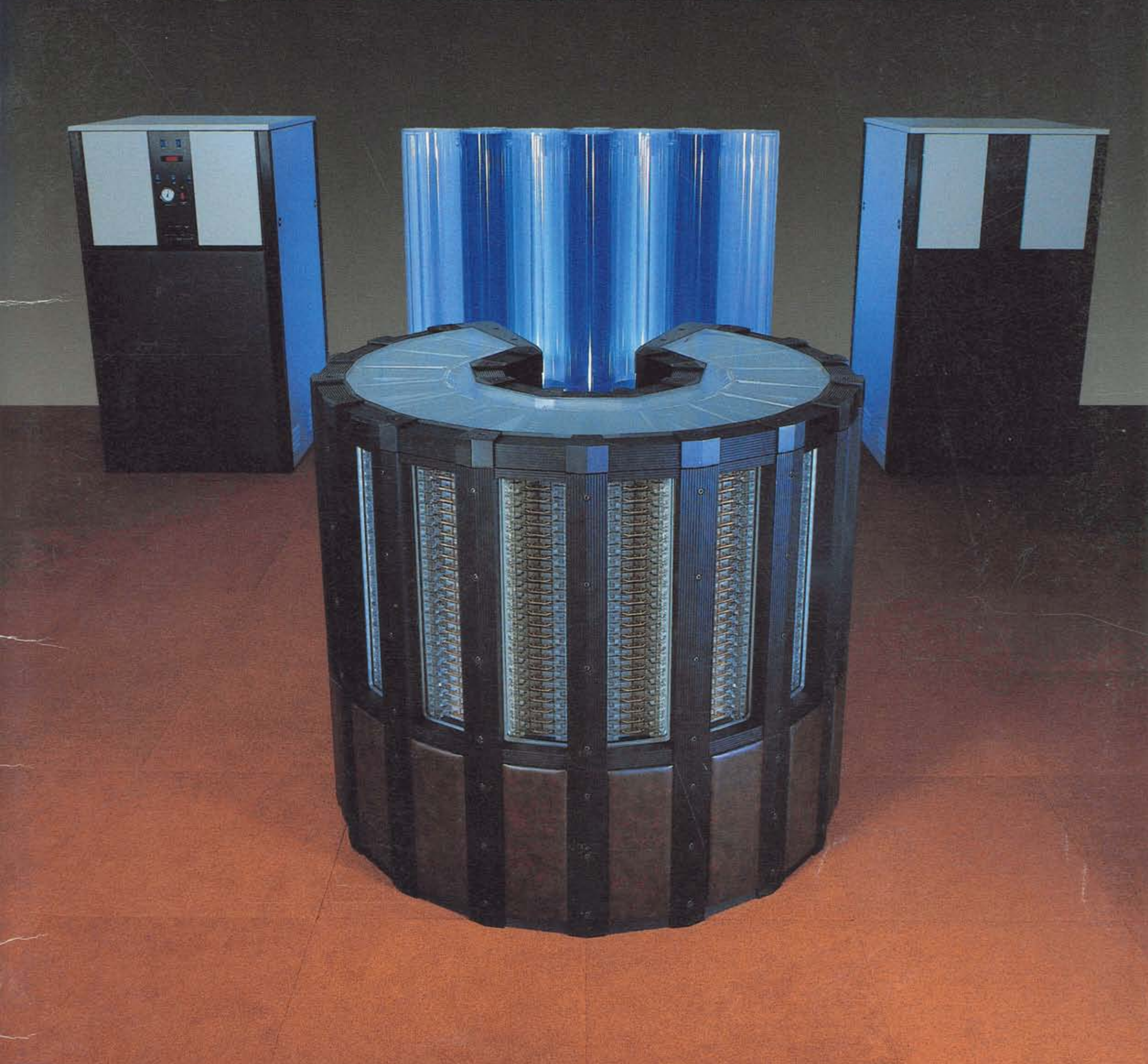
The CRAY-2 Computer System



Cray Research, Inc.

Cray Research's mission is to lead in the development and marketing of high-performance systems that make a unique contribution to the markets they serve. For close to a decade, Cray Research has been the industry leader in large-scale computer systems. Today, the majority of supercomputers installed worldwide are Cray systems. These systems are used in advanced research laboratories around the world and have gained strong acceptance in diverse industrial environments. No other manufacturer has Cray Research's breadth of success and experience in supercomputer development.

The company's initial product, the CRAY-1 Computer System, was first installed in 1976. The CRAY-1 quickly established itself as the standard of value for large-scale computers and was soon recognized as the first commercially successful vector processor. For some time previously, the potential advantages of vector processing had been understood, but effective practical implementation had eluded computer architects. The CRAY-1 broke that barrier, and today vectorization techniques are used commonly by scientists and engineers in a wide variety of disciplines.

With its significant innovations in architecture and technology, the CRAY-2 Computer System sets the standard for the next generation of supercomputers. The CRAY-2 design allows many types of users to solve problems that cannot be solved with any other computers. The CRAY-2 provides an order of magnitude increase in performance over the CRAY-1 at an attractive price/performance ratio.

Introducing the CRAY-2 Computer System

The CRAY-2 Computer System sets the standard for the next generation of supercomputers. It is characterized by a large Common Memory (256 million 64-bit words), four Background Processors, a clock cycle of 4.1 nanoseconds (4.1 billionths of a second) and liquid immersion cooling. It offers effective throughput six to twelve times that of the CRAY-1 and runs an operating system based on the increasingly popular UNIX™ operating system.

The CRAY-2 Computer System uses the most advanced technology available. The compact mainframe is immersed in a fluorocarbon liquid that dissipates the heat generated on the densely packed electronic components. The logic and memory circuits are contained in eight-layer, three-dimensional modules. The large Common Memory is constructed of the most dense memory chips available, and the logic circuits are constructed from the fastest silicon chips available.

The CRAY-2 mainframe contains four independent Background Processors, each more powerful than a CRAY-1 computer. Featuring a clock cycle time of 4.1 nanoseconds — faster than any other computer system available — each of these processors offers exceptional scalar and vector processing capabilities. The four Background Processors can operate independently on separate jobs or concurrently on a single problem. The very high-speed Local Memory integral to each Background Processor is available for temporary storage of vector and scalar data.

Common Memory is one of the most important features of the CRAY-2. It consists of 256 million 64-bit words randomly accessible from any of the four Background Processors and from any of the high-speed and common data channels. The memory is arranged in four quadrants with 128 interleaved banks. All memory access is performed automatically by the hardware. Any user may use all or part of this memory.

In conventional memory-limited computer systems, I/O wait times for large problems that use out-of-memory storage run into hours. With the large Common Memory of the CRAY-2, many of these problems become CPU-bound.

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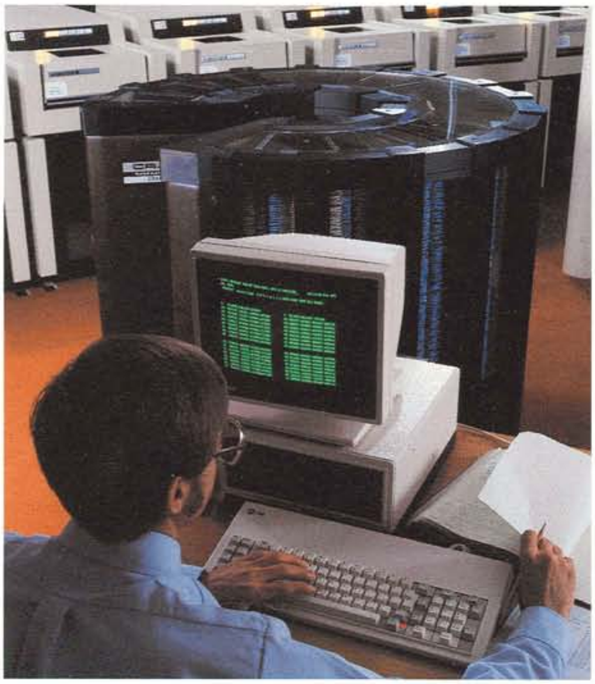


Control of network access equipment and the high-speed disk drives is integral to the CRAY-2 mainframe hardware. A single Foreground Processor coordinates the data flow between the system Common Memory and all external devices across four high-speed I/O channels. The synchronous operation of the Foreground Processor with the four Background Processors and the external devices provides a significant increase in data throughput.

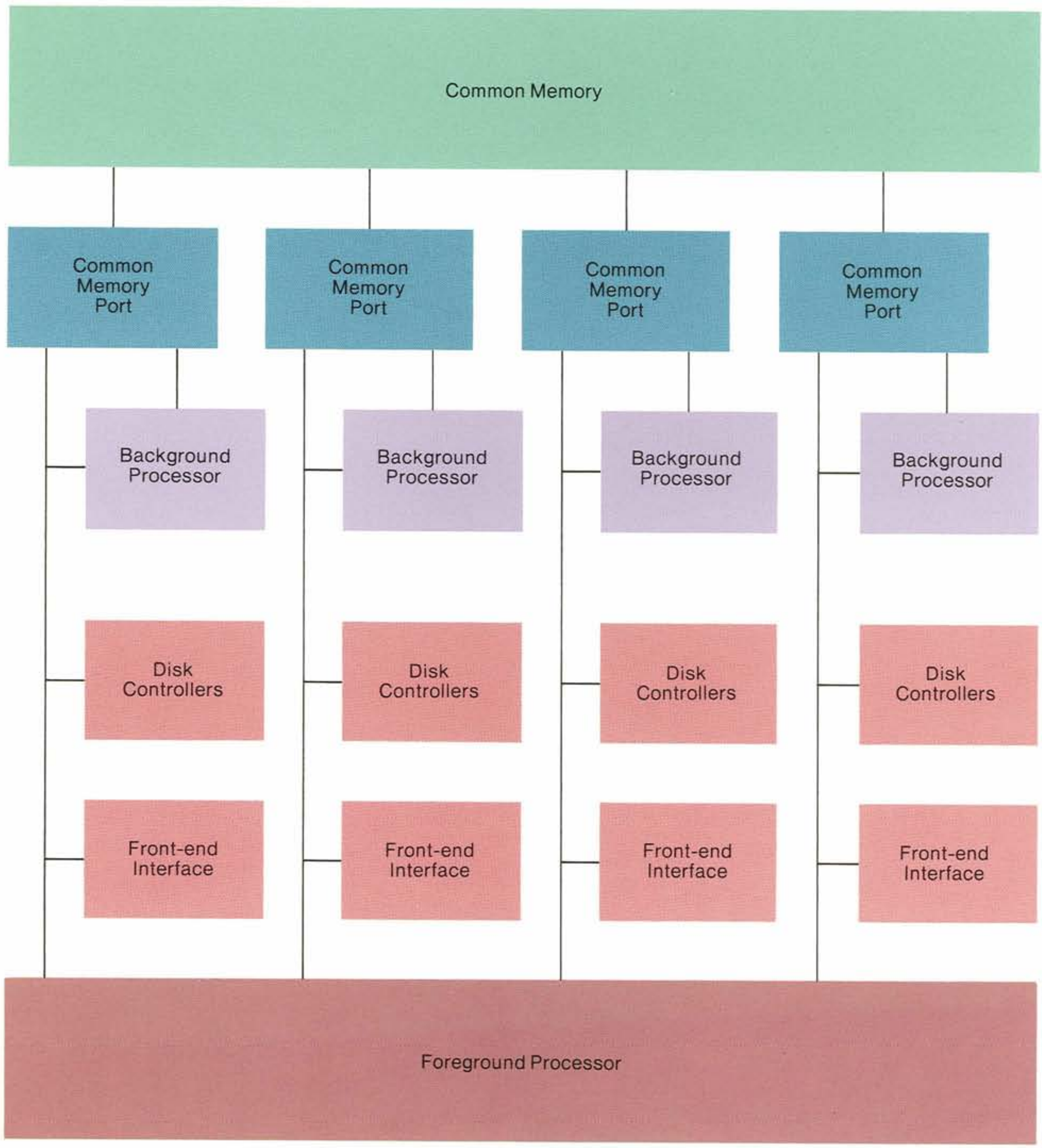
To complement the new CRAY-2 architecture, Cray Research has developed an interactive operating system based on AT&T's UNIX System V. The CRAY-2 Operating System is supported by a FORTRAN compiler based on the proven Cray Research FORTRAN compiler, CFT.

The CRAY-2 Computer System represents a major advance in large-scale computing. The combination of four high-speed Background Processors, a high-speed Local Memory, a huge Common Memory, an extremely powerful I/O capability and a comprehensive software product offers unsurpassed and balanced performance for the user.

Features of the CRAY-2

- ☐ Extremely large directly addressable Common Memory
- ☐ Fastest cycle time available in a computer system (4.1 nsec)
- ☐ Scalar and vector processing combined with multiprocessing
- ☐ Integral Foreground Processor
- ☐ Elegant architecture
- ☐ Extremely high reliability
- ☐ Uses high density memory chips and extremely fast silicon logic chips
- ☐ Liquid immersion cooling
- ☐ An operating system based on industry recognized UNIX system
- ☐ Automatic vectorizing FORTRAN compiler

CRAY-2 system overview



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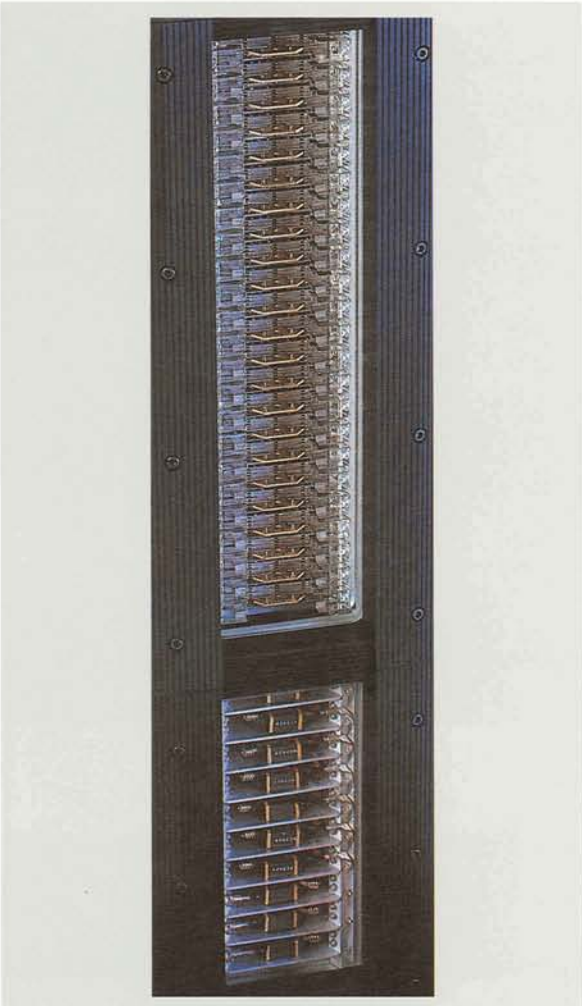
Physical characteristics



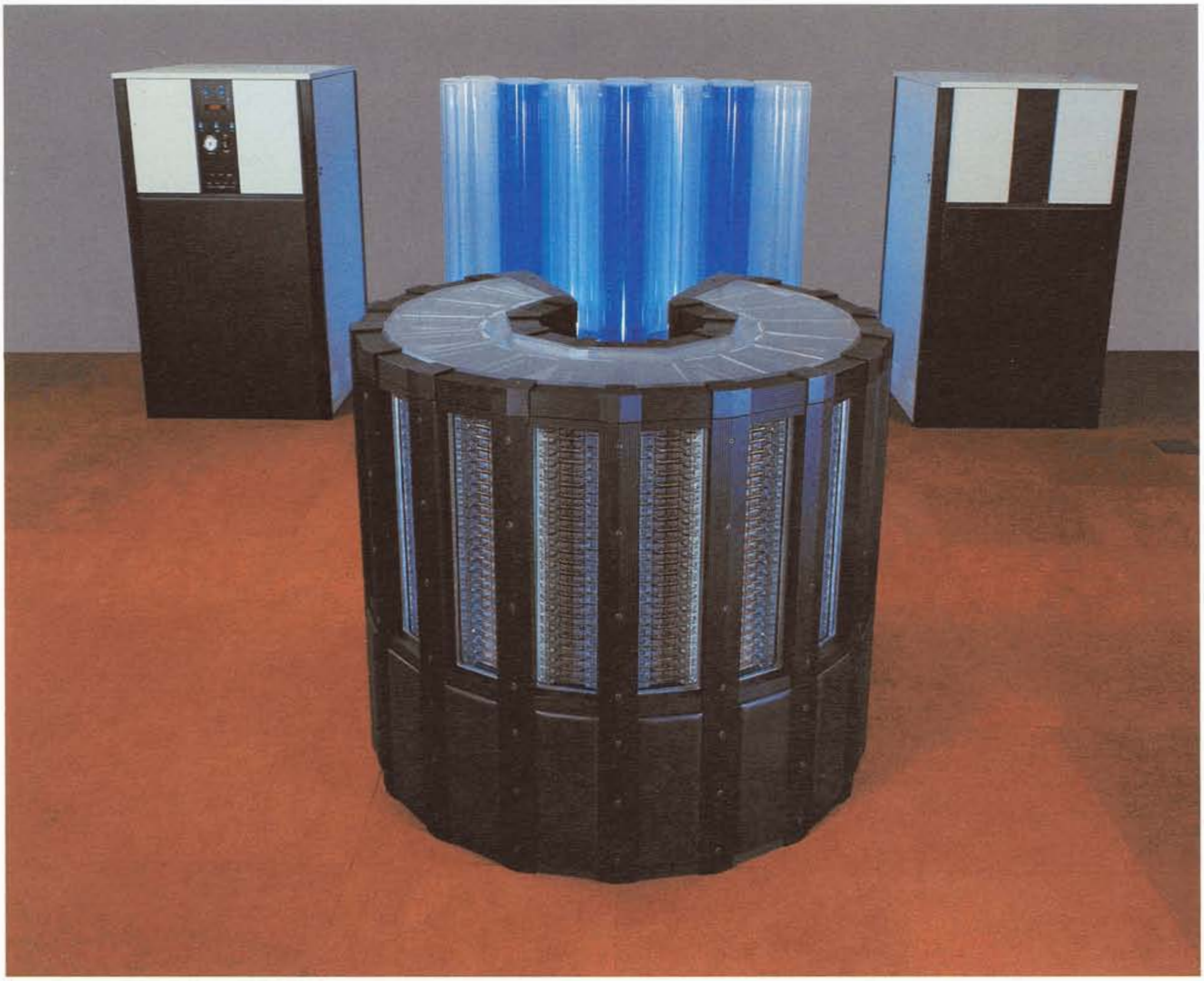
The CRAY-2 mainframe is elegant in appearance as well as in architecture. The memory, computer logic and DC power supplies are integrated into a compact mainframe composed of 14 vertical columns arranged in a 300° arc.

The upper part of each column contains a stack of 24 modules and the lower part contains power supplies for the system. Total cabinet height, including the power supplies, is 45 inches, and the diameter of the mainframe is 53 inches. Thus, the "footprint" of the mainframe is a mere 16 square feet of floor space.

An inert fluorocarbon liquid circulates in the mainframe cabinet in direct contact with the integrated circuit packages. This liquid immersion cooling technology allows for the small size of the CRAY-2 mainframe and is thus largely responsible for the high computation rates.

Physical characteristics

- ☐ Occupies only 16 sq ft of floor space
- ☐ Stands 45 inches high; diameter is 53 inches
- ☐ Weighs 5500 pounds
- ☐ 14 columns arranged in a 300° arc
- ☐ Liquid immersion cooling
- ☐ Uses 16-gate array logic chips
- ☐ Three-dimensional modules
- ☐ 320 pluggable modules
- ☐ 195 KW power consumption
- ☐ 400 Hz power from motor generators
- ☐ Chilled water heat exchange



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Architecture and design

In addition to the cooling technology, the CRAY-2's extremely high processing rates are achieved by a balanced integration of scalar and vector capabilities and a large Common Memory in a multiprocessing environment.

The significant architectural components of the CRAY-2 Computer System include four identical Background Processors, 256 million 64-bit words of Common Memory, a Foreground Processor and a maintenance control console.

Each of the four identical Background Processors contains registers and functional units to perform both vector and scalar operations. The single Foreground Processor supervises the four Background Processors, while the large Common Memory complements the processors and provides architectural balance, thus assuring extremely high throughput rates.

Onsite maintenance is possible via the maintenance control console.

Background Processors

Each Background Processor consists of a computation section, a control section and a high-speed Local Memory. The computation section performs arithmetic and logical calculations. These operations and the other functions of a Background Processor are coordinated through the control section. Local Memory is used to store temporarily scalar and vector data during computations. Each Local Memory is 16,384 64-bit words.

Control and data paths for one Background Processor are shown in the block diagram (opposite page).

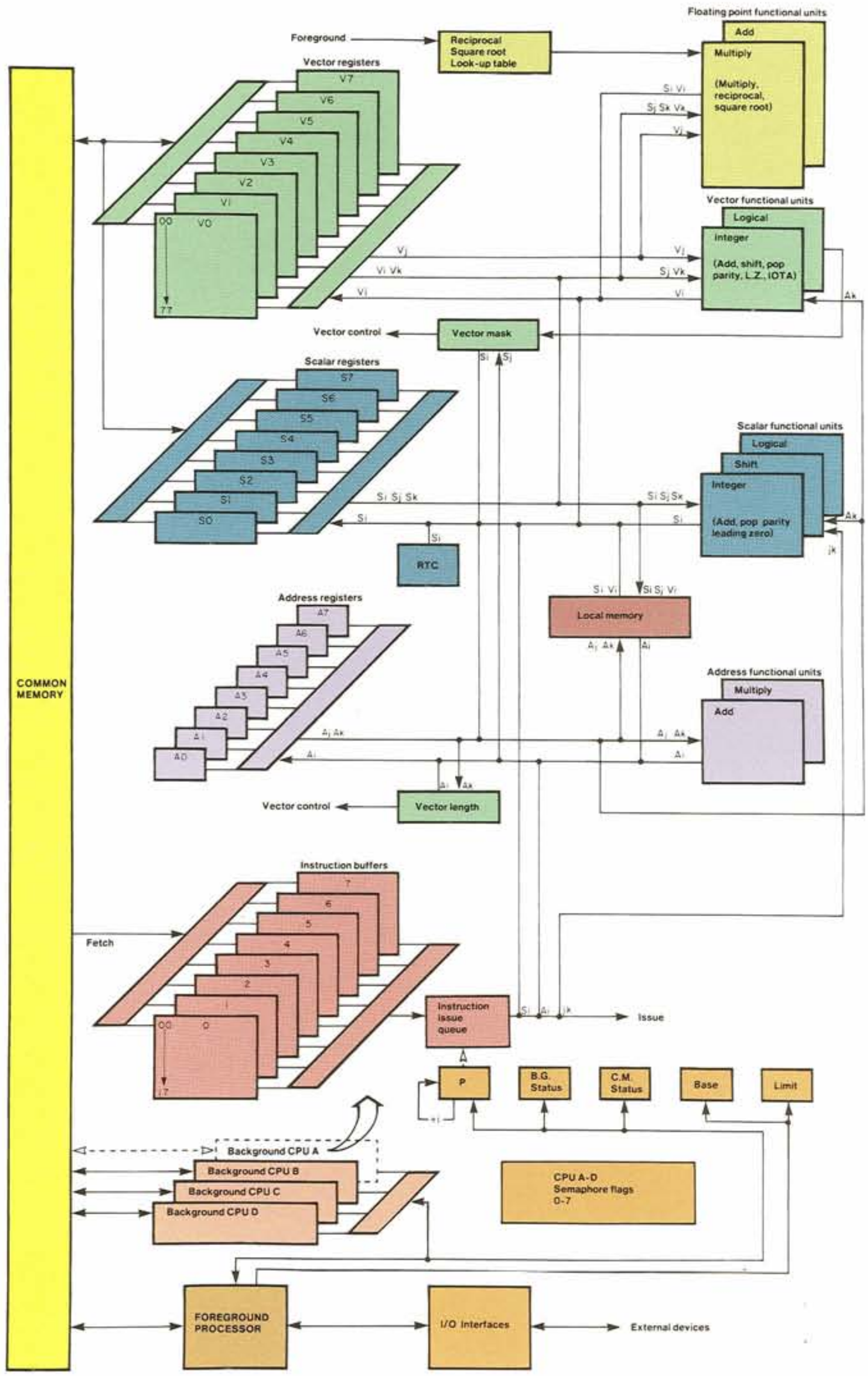
Computation section

The computation section contains registers and functional units that operate together to execute a program of instructions stored in memory.

Computation section characteristics

- ☐ Twos complement integer and signed magnitude floating-point arithmetic
- ☐ Address and arithmetic registers
  - Eight 32-bit address (A) registers
  - Eight 64-bit scalar (S) registers
  - Eight 64-element vector (V) registers; 64 bits per element
- ☐ Address functional units
  - Add/subtract
  - Multiply
- ☐ Scalar functional units
  - Add/subtract
  - Shift
  - Logical
  - Population/parity
  - Leading zero count
- ☐ Vector functional units
  - Logical
  - Integer
    - Shift
    - Add/subtract
    - Population/parity
    - Leading zero count
    - Compressed iota
- ☐ Floating-point functional units
  - Add/subtract
  - Multiply/reciprocal/square root
- ☐ Scatter and gather vector operations to and from Common Memory

CRAY-2 system organization



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Local Memory

Each Background Processor contains 16,384 64-bit words of Local Memory. Local Memory is treated as a register file to hold scalar operands during computation. It may also be used for temporary storage of vector segments where these segments are used more than once in a computation in the vector registers. The access time for Local Memory is four clock periods, and accesses can overlap accesses to Common Memory. This Local Memory replaces the B and T registers on the CRAY-1 and is readily available for user jobs. One application is for small matrices.

Local Memory characteristics

- ☐ 16,384 64-bit words
- ☐ Holds scalar and vector operands during computation
- ☐ Temporary storage of vector segments
- ☐ Four-clock-period access time to first word
- ☐ Overlapping register accesses with Common Memory accesses
- ☐ Replaces CRAY-1 B and T registers

Control section

Each Background Processor contains an identical independent control section of registers and instruction buffers for instruction issue and control.

Control section characteristics

- ☐ Eight instruction buffers, each holding 64 16-bit instruction parcels
- ☐ 128 basic instruction codes
- ☐ 32-bit Program Address register
- ☐ 32-bit Base Address register
- ☐ 32-bit Limit Address register
- ☐ 64-bit real-time clock
- ☐ Eight Semaphore flags to provide interlocks for Common Memory access
- ☐ 32-bit Status register

Each Background Processor has a 64-bit real-time clock. These clocks and the Foreground Processor real-time clock are synchronized at system start-up and are advanced by one count in each clock period.

Background Processor intercommunication

Synchronization of two or more Background Processors cooperating on a single job is achieved through use of one of the eight Semaphore flags shared by the Background Processors. These flags are one-bit registers providing interlocks for common access to shared memory fields. A Background Processor is assigned access to one Semaphore flag by a field in the Status register. The Background Processor has instructions to test and branch, set and clear a Semaphore flag.

Common Memory

One of the primary technological advantages of the CRAY-2 Computer System is its extremely large directly addressable Common Memory. Featuring 268,435,456 words, this Common Memory is significantly larger than that offered on any other commercially available computer system. It allows the individual user to run programs that would be impossible to run on any other system. It also enhances multiprogramming by allowing an exponential increase in the number of jobs that can reside concurrently in memory (that is, that can be multiprogrammed).

Common Memory is arranged in four quadrants of 32 banks each, for a total of 128 banks. A word of memory consists of 64 data bits and 8 error correction bits (SECDED). This memory is shared by the Foreground Processor, Background Processors and peripheral equipment controllers. Each bank of memory has an independent data path to each of the four Common Memory ports. Each bi-directional Common Memory port connects to a Background Processor and a foreground communications channel.

Total memory bandwidth is 64 gigabits or 1 billion words per second.

Common Memory characteristics

- ☐ 256 million words
- ☐ 64 data bits, 8 error correction bits per word
- ☐ 128 banks; 2 million words per bank
- ☐ Dynamic MOS memory technology

Foreground Processor and I/O section

The Foreground Processor supervises overall system activity among the Foreground Processor, Background Processors, Common Memory and peripheral controllers. System communication occurs through four high-speed synchronous data channels.

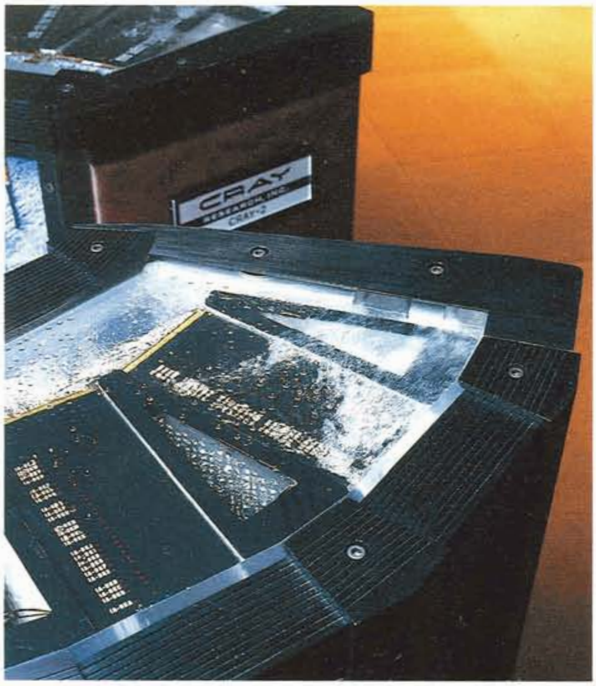
Firmware control programs for normal system operation and a set of diagnostic routines for system maintenance are integral to the Foreground Processor.

Control circuitry for external devices is also located within the CRAY-2 mainframe.

Foreground communication channels

The Foreground Processor is connected to four 4-gigabit communication channels. These channels link the Background Processors, Foreground Processor, peripheral controllers and Common Memory. Each channel connects one Background Processor, one group of peripheral controllers, one Common Memory port and the Foreground Processor. Data traffic travels directly between controllers and Common Memory.

CRAY-2 technology



Technological innovations on the CRAY-2 include the use of liquid immersion cooling and the eight-layer, three-dimensional modules.

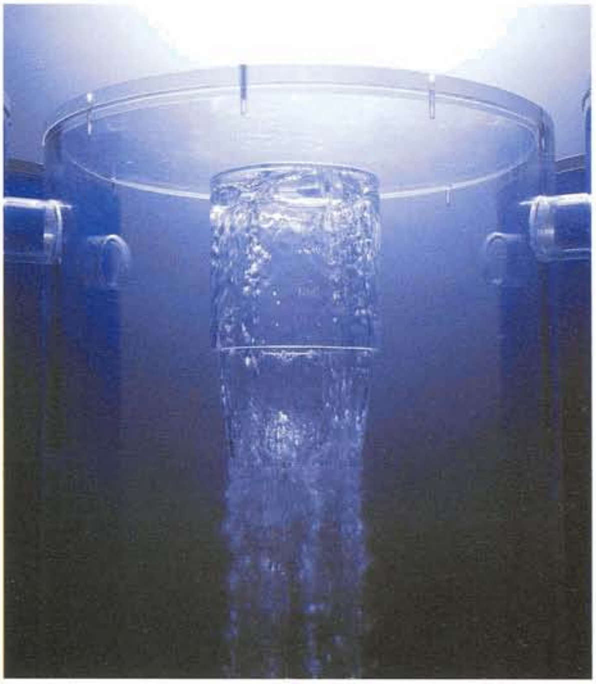
Liquid immersion cooling

Effective cooling techniques are central to the design of high-speed computational systems. Densely packed components result in shorter signal paths, thus contributing to higher speeds. Traditionally, the tradeoff has been lower reliability due to increased operating temperatures, but this is no longer a limitation. The liquid immersion cooling technology used by the CRAY-2 is a breakthrough in the design of cooling systems for large-scale computers. It places the cooling medium in direct contact with the components to be cooled, thus efficiently reducing and stabilizing the operating temperature and increasing system reliability.

The CRAY-2 mainframe operates in a cabinet filled with a colorless, odorless, inert fluorocarbon fluid. The fluid is nontoxic and nonflammable, and has high dielectric (insulating) properties. It also has high thermal stability and outstanding heat transfer properties. The coolant flows through the module circuit boards at a velocity of one inch per second and is in direct contact with the integrated circuit packages and power supplies.

Liquid immersion cooling characteristics

- ☐ The key to densely packed electronics
- ☐ "Valveless" cooling system
  - 200 gallon closed system
  - Room temperature cooling ranges
  - Accompanying stand pipe and reservoir
  - Shell and tube heat exchange
- ☐ Chilled water cooling
- ☐ Fluorocarbon fluid
  - Colorless
  - Odorless
  - Inert: nontoxic and nonflammable
  - High insulant properties
  - High thermal stability
  - High heat transfer capacity



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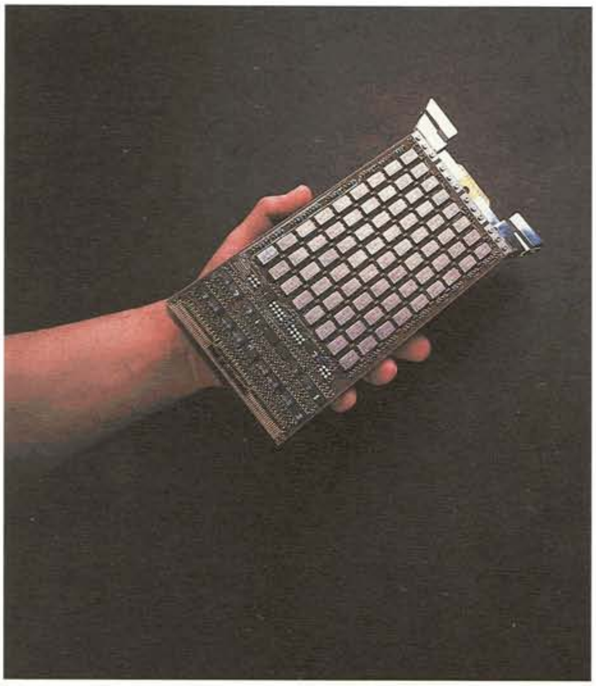


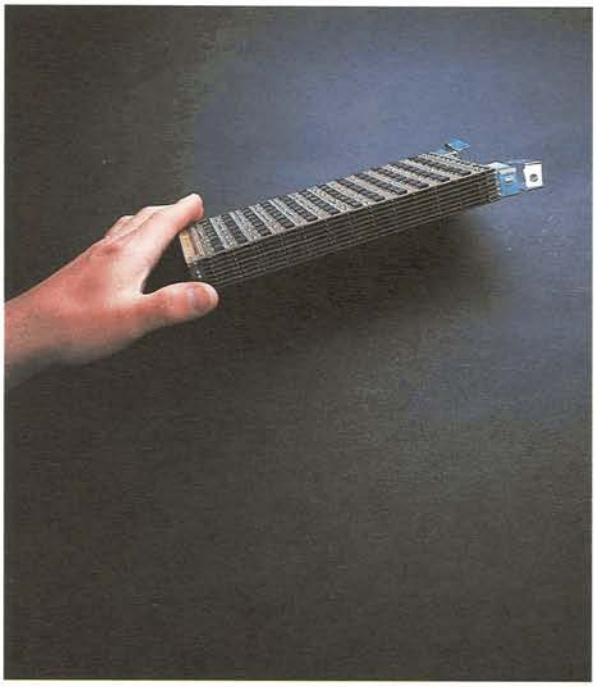
Module technology design

The CRAY-2 hardware is constructed of synchronous networks of binary circuits. These circuits are packaged in 320 pluggable modules, each of which contains approximately 750 integrated circuit packages. Total integrated circuit population in the system is approximately 240,000 chips, nearly 75,000 of which are memory.

The pluggable modules are three-dimensional structures with an 8 x 8 x 12 array of circuit packages. Eight printed circuit boards form the module structure. Circuit interconnections are made in all three dimensions within the module. Each module measures 1 x 4 x 8 inches, weighs 2 pounds, consists of approximately 40% integrated circuits by volume and consumes 300 to 500 watts of power.

The CRAY-2 Common Memory consists of 128 memory banks with two million words per bank. Each memory bank occupies a circuit module.

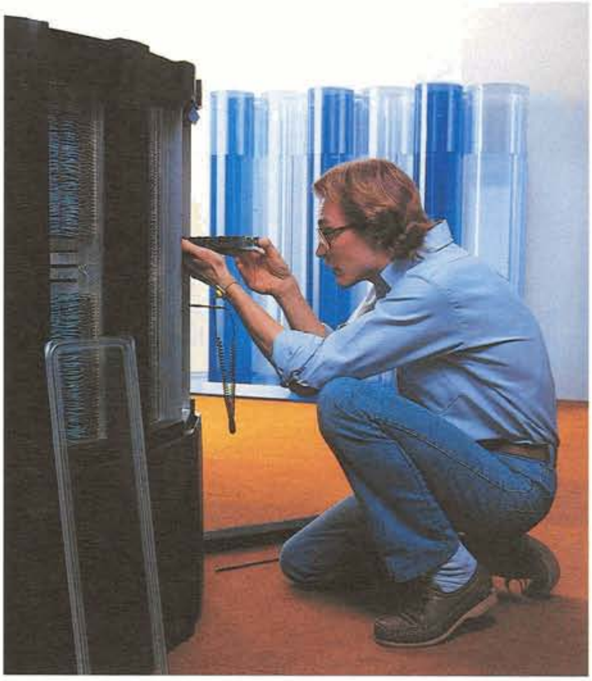
CRAY-2 logic networks are constructed of 16-gate array integrated circuits packaged in three-dimensional structures.



CRAY-2 reliability

A notable increase in reliability is another benefit of the immersion cooling technology. All components rapidly dissipate heat to the fluid, thus preventing high chip temperatures. These chip temperatures are substantially lower than those achieved by other types of cooling and result in significantly reduced chip failure rates. Efficient heat dissipation also prevents destructive thermal shocks that might result from large temperature differentials and fluctuations.

In addition, a fifteen-to-one decrease in module count per CPU from the CRAY-1 and a ten-to-one reduction in memory module count enhance failure isolation, producing a corresponding increase in maintenance efficiency.



CRAY-2 maintenance

If a module should fail, effective and timely maintenance is a routine operation. Diagnostic software quickly isolates the problem to the failing module. The immersion fluid is quickly pumped into the reservoir adjacent to the mainframe. The front panel is easily removed for ready access to the module, which can then be replaced. The front panel is then reinstalled and the fluid quickly returned to the mainframe. The entire operation requires only a few minutes. Once the system is restarted, further diagnosis and repair of the faulty module can occur on site.

CRAY-2 software

Cray Research has made a major commitment to the development of a comprehensive and useful user environment through an aggressive software development program.

The CRAY-2 Computer System comes with state-of-the-art software including an operating system based on AT&T UNIX System V, an automatic vectorizing FORTRAN compiler, a comprehensive set of utilities and libraries and a C language compiler. The software has extensive development objectives beyond initial deliveries, including expanded networking capabilities and application program migration.

The choice of an operating system based on UNIX provides the CRAY-2 user with a well-defined program development environment joined with the advanced computational power of the CRAY-2. The user can access the power of the system through the FORTRAN compiler (CFT) and the optimizing library routines. CFT is a proven compiler that performs automatic vectorization and will conform to the ANSI X3.9-1978 FORTRAN 77 standard.

Software summary

- ☐ The CRAY-2 Operating System, based on the proven UNIX System V and enhanced to fit the large-scale scientific computer environment
- ☐ CFT, a vectorizing and optimizing FORTRAN compiler
- ☐ An optimized FORTRAN mathematical and I/O subroutine library
- ☐ A scientific subroutine library optimized for the CRAY-2
- ☐ A multitasking library that allows user partitioning of an application into concurrently executing tasks
- ☐ A wide variety of system utilities to support the needs of interactive and batch processing
- ☐ A C language compiler that supports the needs of system software written in C language
- ☐ CAL, the CRAY macro assembler, that provides access to all CRAY-2 instructions

CRAY-2 Operating System

The CRAY-2 Operating System is based on UNIX System V, an operating system developed by AT&T Bell Laboratories. In recent years, versions of UNIX have become available on many different computer systems. UNIX is written in a high-level language called C and contains a kernel and a large, diverse set of utilities and library programs.

The kernel is the heart of the system. It has a simple, well-constructed and clean structure with short and efficient software control paths. It supports a small number of system call primitives that library and application programs can use together to perform more complex tasks. The kernel is procedure-oriented, encompassing many processes that dynamically share a common data area used to control the operation of the CRAY-2 system. The system is oriented towards an interactive environment with a hierarchical file structure. This structure features directories, user ownership and file protection/privacy.

The kernel of the CRAY-2 Operating System has been substantially enhanced in the areas of I/O processing and in the efficient use of very large data files. Other significant enhancements include support for asynchronous I/O, improved file system reliability, multiprocessing and user multitasking.

Users may initiate asynchronous processes to communicate with one another and to pass data between them. A variety of command structures (shells) are possible. The CRAY-2 Operating System offers a standard shell; others may be created to provide different command interfaces for the users. A batch processing capability is provided for efficient use of the system by large, long-running jobs.

The operating system supports high-level languages (including FORTRAN and C) and the mechanism to deliver a common operating system environment across a variety of interconnected computer systems. It delivers the ultimate in computational performance possible on the CRAY-2.

CRAY-2 FORTRAN Compiler and Libraries

The CRAY-2 FORTRAN compiler, CFT Version 2, is based on CFT, the highly successful CRAY-1 compiler that was the first in the industry to automatically vectorize codes.

CFT Version 2 automatically vectorizes inner DO-loops, provides normal program optimization and exploits many of the unique features of the CRAY-2 architecture. It does this without sacrificing high compilation rates.

The compiler and FORTRAN library offer current Cray customers a high level of source code compatibility by making available FORTRAN extensions, compiler directives and library interfaces available on other Cray Research products.

The FORTRAN library and a library of highly optimized scientific subroutines enable the user to take maximum advantage of the architecture of the hardware. The I/O library provides the FORTRAN user with convenient and efficient use of external devices at maximum data rates for large files.

Multitasking

Multitasking is a feature that allows two or more parts of a program to be executed in parallel. This results in substantial throughput improvements over serially executed programs. The performance improvements are in proportion to the number of tasks that can be constructed for the program and the number of Background Processors that can be applied to these separate tasks.

In conjunction with vectorization and large memory support, a flexible multitasking capability provides a major performance step in large-scale scientific computing. The user interface to the CRAY-2 multitasking capability is a set of FORTRAN-callable library routines that are compatible with similar routines available on other Cray products.

CRAY-2 FORTRAN features

- ANSI standard compiler
- Automatic optimization of code
  - Vectorizes inner loops
  - Uses Local Memory
- Portability of application codes is a primary goal
- Very high compilation rates
- Library routines
  - Scientific library
  - I/O library
  - Multitasking library

C Language

The C programming language is a high-level language used extensively in the creation of the CRAY-2 Operating System and the majority of the utility programs that comprise the system. It is a modern computer language that is available on processors ranging from microcomputers to mainframe computers and now to Cray computers. C is useful for a wide range of applications and system-oriented programs. The availability of C complements the scientific orientation of FORTRAN.

Utilities

A useful and appropriate set of software tools assist both interactive and batch users in the efficient use of the system. Operational support facilities enable proper management of the system.

CAL

The CRAY-2 Assembler, CAL Version 2, provides a powerful macro assembly language that allows the user to take advantage of all CRAY-2 instructions, while using an instruction syntax and macro capability that is similar to the CRAY-1 assembler.

Applications

The CRAY-2 Computer System provides balanced performance for computationally intensive large-scale applications. Generating solutions to many important problem classes depends heavily on the number of data points that can be considered and the number of computations that can be performed. The CRAY-2 provides substantial increases over its predecessors with respect both to the number of data points and the computation rate. Researchers and engineers realistically can apply the CRAY-2 to problems previously considered computationally intractable, as well as solving more commonplace problems faster and with greater accuracy.

One such application is the simulation of physical phenomena — the analysis and prediction of the behavior of physical systems through computer modeling. Such simulation is common in weather forecasting, aircraft and automotive design, energy research, geophysical research and seismic analysis. The CRAY-2 opens the door to true three-dimensional simulation in a wide variety of problem domains. The CRAY-2 also offers a challenging opportunity for new solutions to applications in such fields as genetic engineering, artificial intelligence, quantum chemistry and economic modeling.

The CRAY-2 offers dramatic improvements in throughput via the balanced exploitation of large memory, fast vector and scalar computation rates and multiprocessing. Problems with previously prohibitive I/O requirements can now fit in memory. Vectorization and multiprocessing promote very high computation rates. In practical terms, this means that problems previously considered large-scale become medium- or even small-scale on the CRAY-2. And problems previously considered unsolvable or too costly to solve become solvable and economically feasible with the CRAY-2.

Applications

- ☐ Fluid dynamics
- ☐ Circuit simulation and design
- ☐ Structural analysis
- ☐ Energy research
- ☐ Weather forecasting
- ☐ Atmospheric and oceanic research
- ☐ Quantum chemistry
- ☐ Artificial intelligence
- ☐ Genetic engineering
- ☐ Signal image processing
- ☐ Molecular dynamics
- ☐ Petroleum exploration and extraction
- ☐ Process design
- ☐ Economic modeling

Offering advanced architecture, advanced technology and advanced software, the CRAY-2 clearly leads the industry in large-scale computing. The CRAY-2 leads in technology by offering the fastest processor clock cycle (4.1 nanoseconds), the largest memory (256 million words) and four vector and scalar multiprocessing Background Processors. The CRAY-2 leads the industry in computer architecture by applying the fastest or most dense components available and packaging them in three-dimensional modules immersed in liquid coolant. The CRAY-2 leads the industry in software by converting an industry recognized and accepted operating system and tailoring it to the needs of large-scale computers, by providing a FORTRAN compiler that automatically takes advantage of the system architecture and by offering extensions available to the operating systems that promote efficient use of the system.

About Cray Research, Inc.

Cray Research, Inc. was organized in 1972 by Seymour R. Cray, a leading designer of large-scale scientific computers, and by a small group of associates experienced in the computer industry. The company was formed to design, develop, manufacture and market large-capacity, high-speed computers. The first model produced was the CRAY-1 Computer System.

Mr. Cray has been a leading architect of large scientific computers for more than 25 years. From 1957 to 1968, he served as a director of Control Data Corporation (CDC) and was a senior vice president at the time of his resignation in early 1972. In that time, he was the principal architect in the design and development of the CDC 1604, 6600 and 7600 Computer Systems. Prior to his association with CDC, Mr. Cray was employed at the Univac Division of Sperry Rand Corporation and its predecessor companies, Engineering Research Associates and Remington Rand. Mr. Cray has been the principal designer and developer of both the CRAY-1 and the CRAY-2 Computer Systems.

Today, Cray Research is the world leader in supercomputers, with over 100 CRAY-1 and CRAY X-MP systems installed worldwide. The company employs nearly 2500 people and operates manufacturing, research, development and administrative facilities in Chippewa Falls, Wisconsin and the Minneapolis, Minnesota area. The company has sixteen domestic sales and support offices and eight subsidiary operations in Western Europe, Canada and Japan.

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