

Multiprocessor Software Design

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Summary

Machines intended for parallel computations exhibit a wide variety of architectural designs, including pipeline, vector and array organizations, less traditional associative, data-flow and systolic organizations, and shared-memory MIMD organizations. It is not surprising, therefore, that the software support for these machines exhibits a wide variety of features reflecting the differing designs. Even within a single class of parallel machine, the system software used on different machines within that class may appear radically different. In part this variety arises because the design space for multiprocessor software is richer than for uniprocessor software; for example there are tradeoffs to be selected between performance and reliability, extensibility, fault-tolerance, etc., and the particular choice of design parameters can have a profound effect on the structure of the operating system. Another factor, however, which causes variety between different operating systems is that the costs of various design choices are known much less accurately than they are with uniprocessors, and thus individual multiprocessor operating systems may exhibit a great deal of experimental variability. Fortunately, the design principles are relatively well understood, and may be described in broad terms.

In the case of special-purpose SIMD and associative machines, built with some particular set of applications in mind, a general-purpose host uniprocessor usually takes over most of the resource allocation and scheduling for both itself and for the special-purpose attached processor, which it treats as a peripheral. Consequently the support software on the special-purpose machine is relatively primitive. Since only a small number of programming techniques are appropriate for such machines, they are most easily provided

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to the programmer as machine-oriented extensions to conventional languages, though several systems have language processors which provide optimizers appropriate for the architecture.

In the case of data-flow and systolic machines, conventional programming techniques, which emphasize the incremental updating of stored variables as a means of performing a computation, are inappropriate, and consideration has to be given to more appropriate languages for expressing the algorithms. Programming techniques for these machines are still the subject of research.

Finally, shared memory MIMD machines have many of the properties of multiprogrammed uniprocessors, and as a result the operating system design can be understood in terms of conventional operating systems, with particular emphasis being given to the allocation and control of shared resources, to synchronization and to the communication techniques between processes. However, many parts of the design space still remain to be explored.

In this discussion we will examine the design principles involved in constructing system and application software for the various organizations of multiprocessors, taking into consideration the ways that reliability and extensibility affect those principles. Examples will be drawn from existing and proposed systems.

The bibliography below cites most of the important papers concerned with the software support for multiprocessor systems.

References

- [1] N.E. Abel et al.
TRANQUIL: A language for an Array Processing Computer.
In *Conf. Proc. 1969 SJCC*, pages 57-73. AFIPS Press, 1969.
- [2] W.B. Ackerman and J.B. Dennis.
VAL -- A Value Oriented Algorithmic Language.
Technical Report TR-218, Lab. for Computer Science, MIT, 1979.
- [3] W.B. Ackerman.
Data Flow Languages.
In *Proc. NCC Conf.*, pages 1087-1095. AFIPS Press, 1979.
- [4] S.J. Allan and A.E. Oldehoeft.
A Flow Analysis Procedure for the Translation of High-Level Languages to a Data-Flow Language.
In *Proc. 1979 Int. Conf. on Parallel Processing*, pages 26-34. IEEE, 1979.
- [5] R.W. Allard, K.A. Wolf and R.A. Temlin.
Some effects of the 6600 Computer on Language Structures.
Comm. ACM 7:112-119, 1964.
- [6] E.B. Allen and A.G. Larson.
FORTRAN Extension Design Concepts for Associative Processing.
In *Proc. 1975 Sagamore Conf. on Parallel Processing*, pages 186-191. IEEE, 1975.
- [7] G.L. Anderson and K. Bartlett.
Hardware Allocation of Data System Resources.
Computer Design 13:89-97, 1974.
- [8] H. Anlauff.
Design of a Hierarchical Multiprocessor System for Multi-Level Parallel Computation.
In W. Handler (editor), *Computer Architecture*, pages 223-265. Springer-Verlag, 1976.
- [9] B.W. Arden and A.D. Berenbaum.
A Multi-Microprocessor Computer System Architecture.
In *Proc. 5th Symp. on Operating System Principles*. ACM, 1975.
- [10] J.S. Arnold, D.P. Casey and R.H. McKinstry.
Design of Tightly-coupled Multiprocessor Programming.
IBM Systems J. 13:60-87, 1974.
- [11] Arvind, K.P. Gostelow and W. Plouffe.
An Asynchronous Programming Language and Computing Machine.
Technical Report 114a, University of California, Irvine, 1978.
- [12] Arvind.
Decomposing a Program for Multiple Processor Systems.
In *Proc. 1980 Int. Conf. on Parallel Processing*, pages 7-14. IEEE, 1980.
- [13] J.W. Atwood.
Concurrency in Operating Systems.
Computer 9:18-26, 1976.
- [14] J.L. Baer and D.P. Bovet.
Compilation of Arithmetic Expressions for Parallel Computations.
In *Proc. IFIP Congress*, pages 340-346. North-Holland, 1968.
- [15] J.L. Baer and E.C. Russell.
Preparation and Evaluation of Computer Programs for Parallel Processing Systems.
In L.C. Hobbs (editor), *Parallel Processor Systems, Technologies and Applications*, pages 375-416. Spartan Books, 1970.
- [16] J.L. Baer.
A Survey of some Theoretical Aspects of Multiprogramming.
Computing Surveys 5:31-80, 1973.
- [17] J.L. Baer.
Multiprocessor Systems.
IEEE Trans. on Computers C-25:1271-1277, 1976.
- [18] J.L. Baer and C. Ellis.
Compilation in Distributed Function Systems.
In *Compcon 76*, pages 31-34. IEEE, 1976.
- [19] U. Banerjee, S.C. Chen, D.J. Kuck and R.A. Towle.
Time and Parallel Processor Bounds for FORTRAN-like Loops.
IEEE Trans. on Computers C-28:660-670, 1979.
- [20] J.F. Barlett.
A 'non-stop' operating system.
In *11th Hawaii Conf. on System Sciences*, pages 103-117. 1978.
- [21] G.H. Barnes et al.
The ILLIAC IV computer.
IEEE Trans. on Computers C-17:746-757, 1968.
- [22] V.R. Basilis and J.C. Knight.
A Language Design for Vector Machines.
SIGPLAN Notices 10:39-53, 1975.
- [23] K.E. Batcher.
Sorting networks and their applications.
In *Conf. Proc. 1968 SJCC*, pages 307-314. AFIPS Press, 1968.
- [24] K.E. Batcher.
The Multidimensional Access Memory in STARAN.
IEEE Trans. on Computers C-26:174-177, 1977.
- [25] G. Baudet.
Asynchronous Iterative Methods for Multiprocessors.
Technical Report, Carnegie-Mellon University Computer Science Department, 1976.
- [26] G. Baudet.
Asynchronous Iterative Methods for Multiprocessors.
PhD thesis, Carnegie-Mellon University, 1978.

- [27] L.H. Bauer.
Implementation of Data Manipulating Functions on the STARAN Parallel Processor.
In *Proc. 1974 Sagamore Conf. on Parallel Processing*, pages 75-96. Springer-Verlag, 1975.
- [28] A.J. Bernstein.
Analysis of Programs for Parallel Processing.
IEEE Trans. on Computers C-15:757-763, 1966.
- [29] G.v. Bochmann.
Architecture of Distributed Computer Systems (Lecture Notes in Computer Science 77).
Springer-Verlag, 1979.
- [30] W.E. Boebert, W.R. Franta, E.D. Jensen and R.Y. Kain.
Design Issues in a Distributed Executive.
In *Compsac 78*, pages 254-258. IEEE, 1978.
- [31] W.E. Boebert, W.R. Franta, E.D. Jensen and R.Y. Kain.
Kernel Primitives of the HXDP Executive.
In *Compsac 78*, pages 595-600. IEEE, 1978.
- [32] R.P. Brent.
The Parallel Evaluation of Arithmetic Expressions in Logarithmic Time.
In J.F. Traub (editor), *Complexity of Sequential and Parallel Numerical Algorithms*, pages 83-102. Academic Press, Inc., 1973.
- [33] P. Brinch Hansen.
The Architecture of Parallel Programs.
Prentice-Hall, 1977.
- [34] P. Brinch Hansen.
Multiprocessor Architectures for Concurrent Programs.
In *Proc. NCC Conf.*, pages 317-323. AFIPS Press, 1978.
- [35] H.E. Brown.
Parallel Processor and Pipeline Computers: An Annotated Bibliography.
Technical Report EL-764-SR, Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94304, 1978.
- [36] J.C. Browne, K.M. Chandy, J. Hogarth and C.C. Lee.
The Effect on Throughput of Multiprocessing in a Multiprogramming Environment.
IEEE Trans. on Computers C-22:728-735, 1973.
- [37] R. Case and A. Padegs.
The Architecture of the IBM 370.
Comm. ACM 21:73-96, 1978.
- [38] *CFD -- A FORTRAN-based Language for ILLIAC IV*
NASA Ames Research Center, 1973.
- [39] D.D. Chamberlin.
Parallel Implementation of Single Assignment Languages (PhD Thesis).
Technical Report TR 19, Stanford University, January, 1971.
- [40] D.D. Chamberlin.
The 'Single-Assignment' Approach to Parallel Processing.
In *Conf. Proc. 1971 FJCC*, pages 263-269. AFIPS Press, 1971.
- [41] T.C. Chen.
Parallelism, Pipelining and Computer Efficiency.
Computer Design 10:69-74, 1971.
- [42] T.C. Chen.
Overlap and Pipeline Processing.
In *Introduction to Computer Architecture*, pages 375-429. SRA, 1975.
- [43] S.C. Chen.
Speedup of Iterative Programs in Multiprocessor Systems.
PhD thesis, University of Illinois Department of Computer Science, 1975.
- [44] L. Cheung.
Techniques for Reducing Dependencies among Instructions for a Parallel Single Processor Computer System.
PhD thesis, Purdue University, 1975.
- [45] T. Christopher et al.
Uniprogramming a Network Computer.
In *Proc. 1978 Int. Conf. on Parallel Processing*, pages 132-138. IEEE, 1978.
- [46] E.G. Coffman, M.J. Elphick and A. Shoshani.
System Deadlocks.
Computing Surveys 3:67-78, 1971.
- [47] M.E. Conway.
A multiprocessor system design.
In *Conf. Proc. 1963 FJCC*, pages 139-146. AFIPS Press, 1963.
- [48] W. Corwin.
The Scheduling of Primary Memory in a Multiprocessor.
PhD thesis, Carnegie-Mellon University, 1979.
- [49] B.A. Crane et al.
PEPE Computer Architecture.
In *Compcon 72*, pages 57-60. IEEE, 1972.
- [50] A.L. Davies.
The Architecture and System Method of DDM1: A Recursively Structured Data Driven machine.
In *Proc. 5th Ann. Symp. on Computer Architecture*, pages 210-215. IEEE and ACM, 1978.
- [51] E.W. Davis.
STARAN/RADCAP System Software.
In *Proc. 1973 Sagamore Conf. on Parallel Processing*, pages 153-159. IEEE and ACM, 1973.
- [52] E.W. Davis.
STARAN Parallel Processor System Software.
In *Proc. NCC Conf.*, pages 17-22. AFIPS Press, 1974.
- [53] J.B. Dennis and E.C. Van Horn.
Programming Semantics for Multiprogrammed Computations.
Comm. ACM 9:143-155, 1966.

- [54] J.B. Dennis.
The Varieties of Data-Flow Machines.
In *Proc. 1st Int. Conf. on Distributed Computing Systems*, pages 430-439. IEEE, 1979.
- [55] E.W. Dijkstra.
Cooperating Sequential Processes.
In *Programming Languages*, pages 43-112. Academic Press, 1968.
- [56] J.R. Dingeldine, H.G. Martin and W.M. Patterson.
Operating System and Support Software for PEPE.
In *Proc. 1973 Sagamore Conf. on Parallel Processing*, pages 170-178. IEEE and ACM, 1973.
- [57] J.R. Dingeldine.
Parallel FORTRAN (PFOR) PEPE Assembly Language (PAL) User's Manual.
Technical Report TM-HU-046/400/01, System Development Corporation, Huntsville, Alabama, 1976.
- [58] D.M. England.
Software Strategy and Structure in Multiprocessor Systems.
In *Multiprocessor Systems*, . Infotech, 1976.
- [59] P.H. Enslow Jr. (ed).
Multiprocessors and Parallel Processing.
John Wiley and Sons, 1974.
- [60] P.H. Enslow.
Multiprocessors and Other Parallel Systems: An Introduction and Overview.
In W. Handler (editor), *Computer Architecture*, pages 133-198. Springer-Verlag, 1976.
- [61] P.H. Enslow.
Multiprocessor Organization: A Survey.
Computing Surveys 9:103-129, 1977.
- [62] D.B. Erickson.
Array Processing on an Array Processor.
SIGPLAN Notices 10:17-24, 1975.
- [63] J.A. Feldman and P.D. Rovner.
An Algol-based Associative Language.
Comm. ACM 12:439-449, 1969.
- [64] J.D. Feldman and L.C. Fulmer.
RADCAP -- An Operational Parallel Processing Facility.
In *Proc. NCC Conf.*, pages 7-15. AFIPS Press, 1974.
- [65] J.A. Feldman, J.R. Low and P.D. Rovner.
Programming Distributed Systems.
In *Proc. ACM 1978 Ann. Conf.*, pages 310-316. ACM, 1978.
- [66] T.Y. Feng.
Data Manipulating Functions in Parallel Processing and their Implementation.
IEEE Trans. on Computers C-23:309-318, 1974.
- [67] M.J. Flynn.
Very high-speed computing systems.
Proc. IEEE 54:1901-1909, 1966.
- [68] M.J. Flynn, A. Podvin and K. Shimizu.
A Multiple Instruction Stream Processor with Shared Resources.
In C.L. Hobbs (editor), *Parallel Processor Systems, Technologies and Applications*, pages 251-286. Spartan Books, 1970.
- [69] M.J. Flynn.
Shared Internal Resources in a Multiprocessor.
In *Proc. IFIP Congress*, pages 565-569. North-Holland, 1971.
- [70] M.J. Flynn and A. Podvin.
An Unconventional Computer Architecture: Shared Resource Multiprocessing.
Computing 5:20-28, 1972.
- [71] M.J. Flynn and J.L. Hennessy.
Parallelism and Representation Problems in Distributed Systems.
In *Proc. 1st Int. Conf. on Distributed Computing Systems*, pages 124-130. IEEE, 1979.
- [72] C.C. Foster and E.M. Riseman.
Percolation of Code to Enhance Parallel Dispatching and Execution.
IEEE Trans. on Computers C-21:1411-1415, 1972.
- [73] D.N. Freeman.
IBM and Multiprocessing.
Datamation :92-109, 1976.
- [74] D.P. Friedman and D.S. Wise.
The Impact of Applicative Programming on Multiprocessing.
In *Proc. 1976 Int. Conf. on Parallel Processing*, pages 263-272. IEEE, 1976.
- [75] S.H. Fuller, A.K. Jones and I. Durham (eds).
Cm Review*.
Technical Report, Carnegie-Mellon University Computer Science Department, June, 1977.
- [76] S.H. Fuller, J.K. Ousterhout, L. Raskin, P. Rubinfeld, P.S. Sindhu and R.J. Swan.
Multi-microprocessors: An Overview and Working Example.
Proc. IEEE 66:216-228, 1978.
- [77] P.A. Gilmore.
Structuring of Parallel Algorithms.
J. ACM 15:176-192, 1968.
- [78] P.A. Gilmore.
Matrix Computations on an Associative Processor.
In *Proc. 1974 Sagamore Conf. on Parallel Processing*, pages 75-96. Springer-Verlag, 1975.
- [79] J. Goldberg.
New Problems in Fault-Tolerant Computing.
In *Int. Symp. on Fault-Tolerant Computing*, pages 29-34. 1975.

- [80] M.V. Gonzalez and C.V. Ramamoorthy.
Recognition and Representation of Parallel Processable Streams in Computer Systems.
In L.C. Hobbs (editor), *Parallel Processor Systems, Technologies and Applications*, pages 335-374. Spartan Books, 1970.
- [81] M.V. Gonzalez and C.V. Ramamoorthy.
Program Suitability for Parallel Processing.
IEEE Trans. on Computers C-20:647-654, 1971.
- [82] M.J. Gonzalez and C.V. Ramamoorthy.
Parallel Task Execution in a Decentralized System.
IEEE Trans. on Computers C-21:1310-1322, 1972.
- [83] M.J. Gonzalez.
Deterministic Processor Scheduling.
Computing Surveys 9:173-204, 1977.
- [84] J.L. Gula.
Operating System Considerations for Multiprocessor Architectures.
In *Proc. 7th Texas Conf. on Computing Systems*. ACM, 1978.
- [85] J. Gurd and I. Watson.
Data Driven System for High Speed Parallel Computing -- Part 1: Structuring Software for Parallel Execution.
Computer Design 19:91-100, 1980.
- [86] M.C. Harrison and J.T. Schwartz.
SHARER, a Time Sharing System for the CDC 6600.
Comm. ACM 10:659-664, 1967.
- [87] M.J. Harrison and W.H. Harrison.
The Implementation of APL on an Associative Processor.
In *Proc. 1974 Sagamore Conf. on Parallel Processing*, pages 75-96. Springer-Verlag, 1975.
- [88] F.E. Heart et al.
A new Minicomputer/Multiprocessor for the ARPA Network.
In *Proc. NCC Conf.*, pages 529-537. AFIPS Press, 1973.
- [89] F.E. Heart et al.
The PLURIBUS Multiprocessor System.
In *Multiprocessor Systems*, pages 307-330. Infotech, 1976.
- [90] C.A.R. Hoare.
Towards a Theory of Parallel Programming.
In C.A.R. Hoare and R.N. Perrott (editor), *Operating System Techniques*, Academic Press, 1972.
- [91] C.A.R. Hoare.
Monitors: An Operating System Structuring Concept.
Comm. ACM 17:549-557, 1974.
- [92] C.A.R. Hoare.
Communicating Sequential Processes.
Comm. ACM 21:666-677, 1978.
- [93] L.C. Hobbs and D.J. Theis.
Survey of Parallel Processor Approaches and Techniques.
In L.C. Hobbs (editor), *Parallel Processor Systems, Technologies and Applications*, pages 3-20. Spartan Books, 1970.
- [94] W. Huen et al.
A Pipelined Dynamo Compiler.
In *Proc. 1977 Int. Conf. on Parallel Processing*, pages 57-66. IEEE, 1977.
- [95] Infotech.
Multiprocessor Systems.
Infotech, Maidenhead, 1976.
- [96] M. Jazayeri et al.
Design and Implementation of a Language for Communicating Sequential Processes.
In *Proc. 1980 Int. Conf. on Parallel Processing*, pages 173-180. IEEE, 1980.
- [97] E.D. Jensen and W.E. Boebert.
Partitioning and Assignment of Distributed Processing Software.
In *Compcon 76*. IEEE, 1976.
- [98] E.D. Jensen, K.J. Thurber and G.M. Schneider.
A Review of Systematic Methods in Distributed Processor Interconnection.
In *IEEE Int. Conf. on Communications*. IEEE, 1976.
- [99] D.E. Jensen.
The Honeywell Experimental Distributed Processor: An Overview.
Computer 11:28-39, 1978.
- [100] P.M. Johnson.
An Introduction to Vector Processing.
Computer Design 17:89-97, 1978.
- [101] A.K. Jones, R.J. Chansler, I. Durham, P. Feiler and K. Schwans.
Software Management of Cm* -- a Distributed Multiprocessor.
In *Proc. NCC Conf.*, pages 657-663. AFIPS Press, 1977.
- [102] A.K. Jones, R.J. Chansler, I. Durham, P. Feiler, D.A. Scelza, K. Schwans and S.R. Vegdahl.
Programming Issues raised by a multiprocessor.
Proc. IEEE 66:229-237, 1978.
- [103] A.K. Jones, R.J. Chansler, I. Durham, K. Schwans and S.R. Vegdahl.
StarOS, a multiprocessor operating system for the support of task forces.
In *Proc. 7th Symp. on Operating System Principles*, pages 117-127. ACM, 1979.
- [104] A.K. Jones and K. Schwans.
TASK Forces: distributed software for solving problems of substantial size.
In *4th Int. Conf. on Software Engineering*, pages 315-330. ACM, 1979.

- [105] A.K. Jones and E.F. Gehringer (eds).
The Cm Multiprocessor Project: A Research Review.*
Technical Report, Carnegie-Mellon University
Computer Science Department, August, 1980.
- [106] A.K. Jones and P. Schwarz.
Experience using multiprocessor systems: a status
report.
Computing Surveys 12:121-165, 1980.
- [107] D. Katsuki et al.
Pluribus: An operational fault-tolerant computer.
Proc. IEEE 66, 1978.
- [108] J.A. Katzman.
A fault-tolerant computing system.
In *11th Hawaii Conf. on System Sciences*, pages 85-
102. 1978.
- [109] R.M. Keller, G. Lindstrom and S. Patil.
A Loosely-Coupled Applicative Multiprocessing
System.
In *Proc. NCC Conf.*, pages 613-622. AFIPS Press,
1979.
- [110] P.J. Knueven (Carnegie-Mellon University Computer
Science Department).
A Survey of Languages on SIMD Computers.
1979.
- [111] R. Kober.
The Multiprocessor System SMS 201 -- Combining
128 Microprocessors to a powerful computer.
In *Compton 77*. IEEE, 1977.
- [112] R. Kober and C. Kuznia.
SMS -- A Multiprocessor Architecture for High-Speed
Numerical Calculations.
In *Proc. 1978 Int. Conf. on Parallel Processing*, pages
18-24. IEEE, 1978.
- [113] P.W. Kraska.
Parallelism Exploitation and Scheduling.
Technical Report UIUCDCS-R-62-518, University of
Illinois Department of Computer Science, June,
1972.
- [114] D.J. Kuck.
ILLIAC IV Software and Application Programming.
IEEE Trans. on Computers C-17:758-770, 1968.
- [115] D.J. Kuck, Y. Muraoka and S.C. Chen.
On the Number of Operations Simultaneously
Executable in FORTRAN-like Programs and their
Resulting Speed-up.
IEEE Trans. on Computers C-21:1293-1310, 1972.
- [116] D.J. Kuck.
Multioperation Machine Computational Complexity.
In J.F. Traub (editor), *Complexity of Sequential and
Parallel Numerical Algorithms*, pages 17-48.
Academic Press, Inc., 1973.
- [117] D.J. Kuck et al.
Measurements of Parallelism in Ordinary FORTRAN
Programs.
IEEE Trans. on Computers C-23:37-46, 1974.
- [118] D.J. Kuck.
Parallel Processing Architecture -- A Survey.
In *Proc. 1975 Sagamore Conf. on Parallel Processing*,
pages 15-39. IEEE, 1975.
- [119] D.J. Kuck.
A Survey of Parallel Machine Organization and
Programming.
Computing Surveys 9:29-59, 1977.
- [120] H.T. Kung.
The structure of parallel algorithms.
In M.C. Yovits (editor), *Advances in Computers, Vol.
19*, Academic Press, 1980.
- [121] H.T. Kung and C.E. Leiserson.
Systolic Arrays (for VLSI).
In C.A. Mead and L.A. Conway (editor), *Introduction
to VLSI Systems*, Addison-Wesley, 1980.
- [122] L. Lamport.
The parallel execution of DO-loops.
Comm. ACM 17:83-93, 1974.
- [123] R.G. Lange et al.
Specification for a STARAN Programming Language.
Technical Report GER-16347, Goodyear Aerospace
Corporation, October, 1976.
- [124] R.G. Lange.
High Level Language for Associative and Parallel
Computation with STARAN.
In *Proc. 1976 Int. Conf. on Parallel Processing*, pages
170-176. IEEE, 1976.
- [125] E.L. Lawler and J.M. Moore.
A functional equation and its application to resource
allocation and sequencing problems.
Management Science :77-84, 1969.
- [126] D.H. Lawrie.
Memory-processor connection networks.
Technical Report UIUCDSC-R-73-557, Dept. of
Computer Science, University of Illinois, Feb.,
1973.
- [127] D.H. Lawrie, T. Layman, D. Baer and J.M. Randall.
Glypnir -- A Programming Language for the ILLIAC
IV.
Comm. ACM 18:157-164, 1975.
- [128] T. Layman and D. Baer.
Glypnir Reference Manual.
Technical Report 263, ILLIAC IV Project, University of
Illinois, 1972.
- [129] M. Lehman.
A Survey of Problems and Preliminary Results
Concerning Parallel Processing and Parallel
Processors.
Proc. IEEE 54:1889-1901, 1966.
- [130] G. Le Lann.
An Analysis of Different Approaches to Distributed
Computing.
In *Proc. 1st Int. Conf. on Distributed Computing
Systems*, pages 222-232. IEEE, 1979.

- [131] V.R. Lesser.
A Dynamically Reconfigurable Multiple
Microprocessor.
In *Proc. Int. Workshop on Computer Architecture,
Grenoble*, pages 1-16. 1973.
- [132] B.H. Liebowitz and J.H. Carson.
Tutorial on Distributed Processing.
Compton 77, 1977.
- [133] R. Lipton and F. Sayward.
Response Time of Parallel Programs.
In *Proc. 1977 Int. Conf. on Parallel Processing*, pages
234-242. IEEE, 1977.
- [134] G.R. Lloyd and R.E. Merwin.
Evaluation of Performance of Parallel Processors in a
Real-time Environment.
In *Proc. NCC Conf.*, pages 101-108. AFIPS Press,
1973.
- [135] D.B. Lomet.
Coping with Deadlock in Distributed Systems.
Technical Report RC 7460 # 32196, IBM, December,
1978.
- [136] H. Lorin.
*Parallelism in Hardware and Software: Real and
Apparent Concurrency.*
Prentice-Hall, 1972.
- [137] R.A. MacKinnon.
Advanced Function Extended with Tightly-Coupled
Multiprocessing.
IBM Systems J. 13:32-59, 1974.
- [138] M. Maekawa et al.
Experimental Polyprocessor System (EPOS) --
Operating System.
In *Proc. 6th Ann. Symp. on Computer Architecture*,
pages 196-201. IEEE and ACM, 1979.
- [139] J.G. Marzolf.
AAPL: An Array Processing Language.
In *Proc. 1974 Sagamore Conf. on Parallel Processing*,
pages 230-237. Springer-Verlag, 1975.
- [140] J. McGraw.
Data-Flow Computing: Software Development.
In *Proc. 1st Int. Conf. on Distributed Computing
Systems*, pages 242-251. IEEE, 1979.
- [141] C.A. Mead and M. Rem.
Highly Concurrent Structures with Global
Communication.
In C.A. Mead and L.A. Conway (editor), *Introduction
to VLSI Systems*, Addison-Wesley, 1980.
- [142] R.E. Millstein.
Control Structures in Illiac FORTRAN.
Comm. ACM 16:621-627, 1973.
- [143] R.E. Millstein and C.A. Muntz.
The ILLIAC IV FORTRAN Compiler.
SIGPLAN Notices 10:1-8, 1975.
- [144] R.L. Milton.
Preliminary Results of a comparative analysis of
ILLIAC IV Languages.
In *Proc. 1975 Sagamore Conf. on Parallel Processing*,
pages 172-179. IEEE, 1975.
- [145] W.L. Miranker.
A Survey of Parallelism in Numerical Analysis.
SIAM Review 13:524-547, 1971.
- [146] R. Moulder.
A Data Management System Utilizing the STARAN
Associative Processor.
In *Proc. 1973 Sagamore Conf. on Parallel Processing*,
pages 161. IEEE and ACM, 1973.
- [147] Y. Muraoka.
Parallelism Exposure and Exploitation in Programs.
Technical Report 424, University of Illinois
Department of Computer Science, February,
1971.
- [148] M. Myszewski.
*IVTRAN: A Dialect of FORTRAN for use on the ILLIAC
IV.*
Technical Report, Applied Data Research Inc., 1972.
- [149] A. Newell and G. Robertson.
Some Issues in Programming Multiprocessors.
Behavior Research Methods and Instrumentation
7:75-86, 1975.
- [150] G.J. Nutt.
A Parallel Processor Operating System Comparison.
IEEE Trans. on Software Engineering SE-3:467-475,
1977.
- [151] P.N. Oleinick and S.H. Fuller.
*The Implementation and Evaluation of a Parallel
Algorithm on C.mmp.*
Technical Report CMU-CS-78-125, Carnegie-Mellon
University Computer Science Department, June,
1978.
- [152] S.M. Ornstein et al.
Pluribus: A Reliable Multiprocessor.
In *Proc. NCC Conf.*, pages 551-559. AFIPS Press,
1975.
- [153] N.S. Ostlund.
*Attached Scientific Processors for Chemical
Computations.*
Technical Report LBL-10409 UC-32, NRCC,
Lawrence Berkeley Laboratory, UC, January,
1980.
- [154] J.K. Ousterhout, D.A. Scelza and P.S. Sindhu.
Medusa: an experiment in distributed operating
system structure.
Comm. ACM 23:92-104, 1980.
- [155] J. Ousterhout.
*Partitioning and Communication in a Distributed
Operating System.*
PhD thesis, Carnegie-Mellon University, 1980.
- [156] J.L. Owens.
The Influence of Machine Organization on
Algorithms.
In J.F. Traub (editor), *Complexity of Sequential and
Parallel Numerical Algorithms*, pages 111-130.
Academic Press, Inc., 1973.

- [157] W.W. Patterson.
Some thoughts on associative processing languages.
In *Proc. NCC Conf.*, pages 23-26. AFIPS Press, 1974.
- [158] G. Paul and M.W. Wilson.
An Introduction to Vectran and its use in Scientific Applications Programming.
In *Proc. 1978 LASL Workshop on Vector and Parallel Machines*, pages 176-204. LASL, 1978.
- [159] R. Perrott and D. Stevenson.
ACTUS -- A Language for SIMD Architectures.
In *Proc. 1978 LASL Workshop on Vector and Parallel Machines*, pages 212-218. LASL, 1978.
- [160] D.L. Presberg and N.W. Johnson.
The Paralyzer: IVTRAN's Parallelism Analyzer and Synthesizer.
SIGPLAN Notices 10:9-16, 1975.
- [161] N. Quaynon and A. Bernstein.
Operating Systems for Hierarchical Multiprocessors.
In *Proc. 7th Texas Conf. on Computing Systems*. ACM, 1978.
- [162] C.V. Ramamoorthy, K.M. Chandy and M.J. Gonzalez.
Optimal Scheduling Strategies in a Multiprocessor System.
IEEE Trans. on Computers C-21:137-146, 1972.
- [163] C.V. Ramamoorthy and M.J. Gonzalez.
A Survey of Techniques for Recognizing Parallel Processable Streams in Computer Programs.
In *Conf. Proc. 1969 FJCC*, pages 1-15. AFIPS Press, 1972.
- [164] C.V. Ramamoorthy, J.H. Park and H.F. Li.
Compilation Techniques for Recognition of Parallel Processable Tasks in Arithmetic Expressions.
IEEE Trans. on Computers C-22:986-998, 1973.
- [165] C.V. Ramamoorthy and H.F. Li.
Pipelined Processors -- A Survey.
In *Proc. 1975 Sagamore Conf. on Parallel Processing*, pages 40-62. IEEE, 1975.
- [166] C.V. Ramamoorthy and W.H. Leung.
A Scheme for Parallel Execution of Sequential Programs.
In *Proc. 1976 Int. Conf. on Parallel Processing*, pages 312-316. IEEE, 1976.
- [167] C.V. Ramamoorthy and H.F. Li.
Pipeline Architectures.
Computing Surveys 9:61-102, 1977.
- [168] L. Raskin.
Performance evaluation of multiprocessor systems.
Technical Report CMU-CS-78-141, Carnegie-Mellon University Computer Science Department, August, 1978.
- [169] H.K. Resnick and A.G. Larson.
DMAP: A Cobol Extension for Associative Array Processors.
SIGPLAN Notices 10:54-61, 1975.
- [170] G. Reyling.
Performance and Control of Multiple Microprocessor Systems.
Computer Design 13:81-86, 1974.
- [171] J.G. Robinson and E.S. Roberts.
Software Fault-Tolerance in the Pluribus.
In *Proc. NCC Conf.*, pages 563-569. AFIPS Press, 1978.
- [172] J.G. Robinson.
The Pluribus Fault-Tolerant Computer.
In *Compcon 79*, pages 45-48. IEEE, 1979.
- [173] J.F. Ruggiero and D.A. Coryell.
An auxiliary processing system for array calculations.
IBM Systems J. 8:118-135, 1969.
- [174] J. Rumbaugh.
A Data Flow Multiprocessor.
IEEE Trans. on Computers C-26:138-146, 1977.
- [175] R.M. Russell.
The Cray-1 Computer System.
Comm. ACM 21:63-72, 1978.
- [176] G.E. Sayre.
STARAN: An Associative Approach to Multiprocessor Architecture.
In W. Handler (editor), *Computer Architecture*, pages 199-221. Springer-Verlag, 1976.
- [177] R.A. Schmidt.
A Parallel Operating System for an MIMD Computer.
In *Proc. 1980 Int. Conf. on Parallel Processing*, pages 3-4. IEEE, 1980.
- [178] P. Schneck.
Movement of Implicit Parallel and Vector Expressions out of Program Loops.
SIGPLAN Notices 10:103-106, 1975.
- [179] D.P. Siewiorek, K. Vini, H. Mashburn, S.R. McConnel and M. Tsao.
A case study of C.mmp, Cm* and C.vmp: Part 1 -- experience with fault tolerance in multiprocessor systems.
Proc. IEEE 66:1178-1199, 1978.
- [180] D.P. Siewiorek, V. Kini, R. Joobbani and H. Bellis.
A case study of C.mmp, Cm* and C.vmp: Part 2 -- predicting and calibrating reliability of multiprocessor systems.
Proc. IEEE 66:1200-1220, 1978.
- [181] R.L. Sites.
An Analysis of the Cray-1 Computer.
In *Proc. 5th Ann. Symp. on Computer Architecture*, pages 101-106. IEEE and ACM, 1978.
- [182] J. Srodawa.
Positive Experience with a Multiprocessor System.
Computing Surveys 10:73-82, 1978.
- [183] K.G. Stevens Jr.
CFD -- A FORTRAN-like Language for the ILLIAC IV.
SIGPLAN Notices 10:72-76, 1975.
- [184] D. Stevenson.
Programming the ILLIAC IV.
Technical Report, Carnegie-Mellon University Computer Science Department, 1975.

- [185] H.S. Stone.
Parallel processing with the perfect shuffle.
IEEE Trans. on Computers C-20:153-61, 1971.
- [186] H.S. Stone.
Problems of Parallel Computation.
In J.F. Traub (editor), *Complexity of Sequential and Parallel Numerical Algorithms*, pages 1-16.
Academic Press, Inc., 1973.
- [187] H.S. Stone.
Introduction to Computer Architecture.
SRA, 1975.
- [188] H. Sullivan, T.R. Bashkow and D. Klappholz.
A Large-Scale, Homogeneous, Fully-Distributed Parallel Machine, II.
In *Proc. 4th Ann. Symp. on Computer Architecture*, pages 118-124. IEEE and ACM, 1977.
- [189] R.J. Swan, S.H. Fuller and D.P. Siewiorek.
Cm* -- a modular multi-microprocessor.
In *Proc. NCC Conf.*, pages 637-644. AFIPS Press, 1977.
- [190] R.J. Swan, A. Bechtolsheim, K.W. Lai and J.K. Ousterhout.
The implementation of the Cm* multi-microprocessor.
In *Proc. NCC Conf.*, pages 645-655. AFIPS Press, 1977.
- [191] R.J. Swan.
*The Switching Structure and Addressing Architecture of an Extensible Multiprocessor, Cm**.
PhD thesis, Carnegie-Mellon University, 1978.
- [192] *Tandem 16 System Introduction*
Tandem Computers, 1977.
- [193] L.G. Tesler and H.J. Enea.
A Language Design for Concurrent Processes.
In *Conf. Proc. 1968 SJCC*, pages 403. AFIPS Press, 1968.
- [194] K.J. Thurber and L.D. Wald.
Associative and Parallel Processors.
Computing Surveys 7:215-255, 1975.
- [195] K.J. Thurber.
Large Scale Computer Architecture.
Hayden Book Company, 1976.
- [196] K.J. Thurber.
Parallel Processor Architectures -- Part 1: General Purpose Systems.
Computer Design 18:89-97, 1979.
- [197] Texas Instruments.
ASC, a description of the Advanced Scientific Computer System.
Technical Report M1001P, Texas Instruments, Inc., April, 1972.
- [198] G. Tjaden and M. Flynn.
Detection and Simultaneous Execution of Independent Instructions.
IEEE Trans. on Computers C-19:889-895, 1970.
- [199] R.M. Tomasulo.
An Efficient Algorithm for Exploiting Multiple Arithmetic Units.
IBM J. Research and Development :25-33, 1967.
- [200] M.M. Tsao.
A Study of Transient Errors on Cm*.
Master's thesis, Carnegie-Mellon University, 1978.
- [201] L.L. Walker.
Multiprocessor Operating System Design.
In *Operating Systems*, . Infotech, 1972.
- [202] W.J. Watson.
The TI ASC -- a highly modular and flexible super computer architecture.
In *Conf. Proc. 1972 FJCC*, pages 221-228. AFIPS Press, 1972.
- [203] W.J. Watson and H.M. Carr.
Operational Experiences with the TI Advanced Scientific Computer.
In *Proc. NCC Conf.*, pages 389-397. AFIPS Press, 1974.
- [204] D. Wedel.
FORTRAN for the Texas Instruments ASC System.
SIGPLAN Notices 10:119-132, 1975.
- [205] D.E. Wilson.
The PEPE Support Software System.
Compton 72 :61-64, 1972.
- [206] A. Wray.
Vectoral -- A Vector Algorithmic Language for ILLIAC.
In *Proc. 1978 LASL Workshop on Vector and Parallel Machines*, pages 174-175. LASL, 1978.
- [207] W.A. Wulf and G.C. Bell.
C.mmp -- a multi-mini-computer.
In *Conf. Proc. 1972 FJCC*, pages 765-777. AFIPS Press, 1973.
- [208] W.A. Wulf et al.
HYDRA: The Kernel of a Multiprocessor Operating System.
Comm. ACM 17:337-345, 1974.
- [209] W.A. Wulf, R. Levin and C. Pierson.
Overview of the Hydra Operating System.
In *Proc. 5th Symp. on Operating System Principles*, pages 122-131. ACM, 1975.
- [210] W.A. Wulf and R. Levin.
A Local Network.
Datamation :47-50, 1975.
- [211] W.A. Wulf and S.P. Harbison.
Reflections in a pool of processors -- An experience report on C.mmp/Hydra.
In *Proc. NCC Conf.*, pages 939-951. AFIPS Press, 1978.

- [212] W.A. Wulf, R. Levin and S.P. Harbison.
Hydra: An Experimental Operating System.
McGraw-Hill, 1980.
- [213] S.S. Yau and H.S. Fung.
Associative Processor Architecture -- A Survey.
Computing Surveys 9:3-28, 1977.