A VERY high level introduction to Sombrero can be found in "The Sombrero Single Address Space Project" in the ASU CSE Department Monitor Fall 2005 Issue. A more technical brief overview of the project status can be found in the one page "Sombrero version 0.003 – "Sombrero Distributed SASOS Prototype" Work in Progress submitted to SOSP'05. Both of these can be found under Other Documents.

To get a good handle on what we have been doing lately, Don White's MS thesis and presentation on "Implementation of a Lower Level Architecture for the Sombrero Single Address Space Operating System" are a good place to start.

Other recent research work includes Shyamal Pandya's MS thesis and his associated talk and the paper on it at PDPTA'05. This work is on Network Processors.

A slightly dated but still a good way to get a handle on the current state of Sombrero is to read the December 2003 proposal to NSF on Operating System Design to Reduce the Complexity of Distributed Systems. Another place to start is to read the first 20 pages of Alan Skousen's Ph.D. Dissertation and to look at the presentation he gave at its defense. Probably the quickest way to get a good overview of Single Address Space Operating Systems and Sombrero is to view the slide talks "Single Address Space and Single Address Space Operating Systems" and "The Sombrero Single Address Space Operating System" in that order, followed by reading the short paper "Operating System Structure and Processor Architecture for a Large Distributed Single Address Space". The material in those two talks and that paper are also a little dated now – but it's still a good place to start, especially the paper which is only four pages.

Finally the talk "Effects of the Single Address Space Paradigm on CPU and OS Design for a Distributed Computer System" makes a good attempt at explaining the single address space paradigm and how it differs from the conventional multiple address space paradigm.

# Publications

**"Lower Level Architecture of the Sombrero Single Address Space Distributed Operating System"**
D. Miller, D. White, A. Skousen and R. Tcherepov, *The 18th IASTED International Conference on Parallel and Distributed Computing and Systems (PDCS 2006)*, November 2006.
This paper presents recent additions to the design and implementation of the lower level architecture of Sombrero. This design exploits Sombrero's object-oriented development model to provide an implementation of a lower-level architecture for the Alpha platform. Software representations of the hardware system's major components have been implemented. We contrast differences in the ways these things are designed and operate in a single address space environment with the way they are done in a conventional multiple address space operating system. Features covered include the use of passive servers, simple efficient thread switching and threads blocking within interrupts. Passive and active device drivers are described and the rational for each mode given.

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**"Distributed Scheduling for the Sombrero Single Address Space Operating System**"
D. Miller, A. Skousen and M. Patil, *The 2006 International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA'06)*, June 2006, pages 649-655.
This paper presents a distributed scheduling algorithm for the Sombrero single address space operating system. This algorithm uses the properties of a single address space and the Sombrero support for thread migration to modify and extend scheduling algorithms developed for multiple address space operating systems to the single address space environment. Threads in the distributed system are scheduled among the different nodes so that CPU usage is balanced. A dynamic local-information-based distributed scheduling algorithm is designed, implemented on a simulation, and evaluated. The paper also presents, and the simulation includes, the Sombrero fission/merge mechanism for distributing the virtual address space across multiple nodes and the Sombrero use of virtual addresses as an inter-node addressing mechanism.

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**"Using Network Processors for Packet Filtering"**
B. Millard, S. Pandya and D. Miller, *The 2005 International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA'05)*, June 2005.
This paper presents a hardware/software design and implementation that uses modern network-processors as packet-filtering devices that can be used for advanced network applications such as firewalls, network address translation, intrusion detection, traffic shaping and others. Included are the motivation and design and implementation tradeoffs of a hierarchical and pipelined, packet-filter software package using the Intel IXP 1200 network processor. The 64-bit OS Group set up the test bed for this investigation.

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**"Reduction of Software Development Costs under the Sombrero Distributed Single Address Space Operating System"**
R. Feigen, A. Skousen and D. Miller, *The 2002 International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA'2002)*, June 2002.
Examines the potential for reduction in software complexity of applications developed under Sombrero and gives reasons for this based in the code required to perform the same tasks in the Sombrero and Windows 2000 environments.

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**"The Sombrero Single Address Space Operating System Prototype A Testbed for Evaluating Distributed Persistent System Concepts and Implementation"**
Alan Skousen and Donald Miller, *The 2000 International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA'2000)*, June 2000.
Reviews Sombrero architecture and prototype. Discusses benefits to software engineering from Sombrero SASOS architecture. Introduces some Sombrero DSM consistency mechanisms and has a section on additional observations on Distributed Persistent Concepts and Implementation.

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**"Using a Single Address Space Operating System for Distributed Computing and High Performance"**
Alan Skousen and Donald Miller, *18th IEEE International Performance, Computing, and Communications Conference Proceedings (IPCCC'99)*, February 1999.
Overviews Sombrero. Has section on the new more general protection mechanism of Sombrero II. Emphasizes distributed system issues like token tracking and distribution of executive structures. Much of the WP10 distributed system material is included and updated here.

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**"Using a Distributed Single Address Space Operating System to Support Modern Cluster Computing"**

Alan Skousen and Donald Miller, *Proceedings of 32nd Hawaii International Conference on System Sciences, (HICSS-32)*, January 1999.

Overviews Sombrero and discusses support for cluster computing. Has comparisons against SASOSs built on stock RISC processors. Has summary of VLSI design simulation and PRAL simulation.

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**"Operating System Structure and Processor Architecture for a Large Distributed Single Address Space"**

Alan Skousen and Donald Miller, *Proceedings of 10th IASTED International Conference on Parallel and Distributed Computing Systems (PDCS98)*, October 1998.

Four page boiled down overview of Sombrero. Good way to get the essence of Sombrero fast.

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**"The Sombrero Distributed Single Address Space Project"**
Alan Skousen and Donald Miller, *2nd USENIX Windows NT Symposium Proceedings*, August 1998.
A one-page write-up that describes the Sombrero prototype and its status at the time.

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## Ph.D. Dissertation, MS Theses and MCS Projects

**Implementation of a Lower Level Architecture for the Sombrero Single Address Space Operating System**

Donald B. White, MS Thesis, Computer Science and Engineering Department, Arizona State University, December 2005.

Includes a design and implementation of some key low level features of Sombrero including device drivers, additions to the Sombrero protocol stack and enhancements to the Sombrero development environment. Exploits Sombrero's object-oriented development model to provide an implementation of a lower-level architecture for the alpha platform. Documents some previously undocumented aspects of Sombrero.

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**SOMBRERO: Implementation of a Single Address Space Paradigm for Distributed Computing Exhibiting Reduced Complexity.**

Alan C. Skousen, Ph.D. Dissertation, Computer Science and Engineering Department, Arizona State University, August 2002.

Most comprehensive discussion of Sombrero. Describes the middle level architecture and the method for constructing the prototype.

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**Distributed Consistency Management in Sombrero, A Single Address Space Distributed Operating System.**

John Olson, MS Thesis, Computer Science and Engineering Department, Arizona State University, August 2002.

Describes in detail the mechanisms proposed in the Sombrero for achieving distributed consistency management.

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**"Reduction of Software Development Costs under Sombrero, a Single Address Space Distributed Operating system"**

Ron Feigen, MS Thesis, Computer Science and Engineering Department, Arizona State University, December 2001.

This thesis examines the potential for reduction in software complexity of applications developed under the Single Address Space Operating System Sombrero versus those developed under a conventional process-oriented operating system, Windows 2000. To test Sombrero's impact on development costs, a set of sample database applications with varying functionality was developed under Windows 2000 and Sombrero. Using accepted software engineering metrics, the software complexity of these systems was compared. The results obtained indicate a substantial reduction of software development costs and defects in a single address space

**"Distributed Scheduling in Sombrero, A Single Address Space Distributed Operating System"**
Milind H. Patil, MS Thesis, Computer Science and Engineering Department, Arizona State University, December, 1999.

This thesis adds a distributed scheduling mechanism to Sombrero that provides for sharing, as well as better usage of resources across the system. It allows threads to be scheduled among different processors and nodes in such a manner that CPU usage is balanced. Key contributions of this research are: using the properties of a single address space and the functionality of Sombrero to allow the threads of a multithreaded activity to be distributed individually; determination of a reasonable distributed scheduling algorithm for the Sombrero single address space environment; and use of a hierarchical clustering mechanism to extend the distributed scheduling algorithm so that it scales well. Includes construction of a simulation of the necessary Sombrero elements e.g., nodes, routers, load tables, and use of it to show that the distributed scheduling algorithm is correct, works in a shared memory environment and scales in a linear manner with respect to the number of messages and tables required for load balancing.

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**“Protection Structures in the Sombrero Operating System”**

Shahjehan A. Khatri, MS Thesis, Computer Science and Engineering Department, Arizona State University, December, 1997.

Implements a prototype of the Sombrero software protection data structures and algorithms and simulates its hardware protection buffer (RPLB). Also simulates Alpha-NT page tables, associated VM management and TLB. Uses miss rate and miss penalty to compare expected performance of an RPLB supported by Sombrero’s protection and resource access lists versus a TLB supported by page tables in a process-oriented system.

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**“Sombrero System Interface”**

Mark Carnes, MCS Project Report, Computer Science and Engineering Department, Arizona State University, December, 1996.

Presents the Sombrero System Services Interface (SSI). The SSI provides the functionality of the system call interface in process-oriented systems. The system services are documented in the form of C++ definitions. A C interface is also presented. A comparison is made with the Opal interface and Solaris 2.4 system call interface. In the latter case, it’s demonstrated that the Sombrero SSI is complete enough to allow all the functionality in Solaris to be implemented. Front matter discusses how protection policy is implemented with user authorizing agents, the gateway/signal stub mechanism for executive entry and upcalls to return to the user program. How this can be done while maintaining the integrity of executive data structures is presented.

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**"RPLB Design Project Report"**

Michael J. Torla, MCS Project Report, Computer Science and Engineering Department, Arizona State University, July, 1997.

Specifies a design of a simple hardware Range Protection Look-aside Buffer (RPLB). Describes this design and verifies it in VHDL using Mentor design tools available in the ASU VLSI Design Laboratory. The design is synthesized using Mentor's Autologic II synthesis tool and Synopsys Design Compiler. The Cascade Design Automation static timing analyzer, Tactic, is used to perform timing analysis. Feasibility of an RPLB operating at the rates required for access during the pipelined instructions of a modern RISC processor such as the Alpha 21164 is shown.

**"Sombrero: A Very Large Single Address Space Distributed Operating System"**

Alan C. Skousen, MS Thesis, Computer Science and Engineering Department, Arizona State University, December 1994.

First publication on Sombrero. Contains the main features of the Sombrero and RPLB design. Starts with the assumption that process-oriented systems are essentially a work-around due to inadequate hardware that necessitates reusing the VA space. Given that hardware that provides a very large VA space is now available, this design study looks at how an operating system could take advantage of it and then specifies the design of the additional protection hardware that's needed to support such an operating system. The essential feature of the Sombrero design is its "ubiquitous" protection domains. Program modules are instantiations of object classes that are implemented as Sombrero protection domains. Hardware caching of protection domain object regions, allowable domain crossings and private thread protection domains in the RPLB are crucial to the Sombrero design.

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## Other Documents

**The Sombrero Distributed Single Address Space Project**
CSE Monitor, Computer Science and Engineering Department, Arizona State University, Fall 2005, page 7.

Non-technical introduction to the Sombrero Project, its research objectives and current status.

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**Sombrero version 0.003 – Sombrero Distributed SASOS Prototype**

D. Miller, Work in Progress submitted to SOSP'05, October 2005.

Updates and very concisely describes the current design, prototype and goals of Sombrero.

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**Operating System Design to Reduce the Complexity of Distributed Systems.**

D. Miller, Proposal to National Science Foundation, December 2003.
Describes the state of the Sombrero design and prototype as of December 2003. Concisely overviews its design. Gives near term goals of the project.

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**Sombrero version 0.002 - Sombrero Distributed SASOS Prototype.**

D. Miller, Work in Progress submitted to SOSP'03, October 2003.

Very concisely describes the current design, prototype and goals of Sombrero.

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**"A Hardware Supported Single Address Space Operating System Prototype"**

Donald Miller, Proposal to National Science foundation, November 1998.

Contains Project Summary, Project Description and References Cited sections of proposal to NSF Operating System and Compilers Program in the Computer Communication Research Division. Gives reasons why NSF should fund this work. Includes objectives for the period of the proposed work and expected significance; relation to longer-term goals of the project; and relation to present state of knowledge in the field and work in progress elsewhere; and broader impacts of the research. The simplified Motivation section and the Research Plan sections contain useful information.

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**"Resource Access and Protection in the Sombrero Protection Model, Software Protection Data Structures and Hardware Range Protection Lookaside Buffer"**

A. Skousen and D. Miller, ASU Computer Science and Engineering Department Technical Report TR-95-013, January 1996 (White Paper 02).

The basic document on single node kernel and RPLB design. Most of the central ideas appear in subsequent conference publications. The document is somewhat dated as many of the concepts have been refined and/or presented more clearly in the conference publications. However, space limitations in conference papers have precluded publication of some material. This includes details of control blocks, a comparison of the RPLB matrix with Lampson's Access Matrix, a rationale for the basic protection mechanism supplied by Sombrero and demonstration that the RPLB does indeed implement the desired protection. The original January 1996 WP02f version has been slightly cleaned up for the May 1999 WP02g version available here.

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**Implementing a Very Large Single Address Space across Multiple Nodes: Memory Partitioning, Protection Domain Migration, Kernel Replication, Consistency and Fault Tolerance"**

A. Skousen and D. Miller, ASU Computer Science and Engineering Department Technical Report TR-95-021, January 1996 (White Paper 10).

The basic document on the distributed system features of Sombrero. Most of the central ideas appear in subsequent conference publications. The document is somewhat dated as many of the concepts have been refined and/or presented more clearly in the conference publications. However, space limitations in conference papers have precluded publication of some of the material. This includes very large memory partitioning, and some details of operations on the Copy Set and Parent Graphs and of control and execution migration. The original January 1996 WP10e version has been slightly cleaned up for the May 1999 WP10f version available here.

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# Presentations

**Implementation of a Lower Level Architecture for the Sombrero Single Address Space Operating System**
MS Thesis Defense Presentation, by Donald White, ASU, August 2005.

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**Implementation of IXP1200 Network Processor Packet Filtering Software and Parameterization for Higher Performance Network Processors**

MS Thesis Defense Presentation, by Shyamal Pandya, ASU, May 2003.

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**Sombrero: Implementation of a Single Address Space Paradigm for Distributed Computing Exhibiting Reduced Complexity.**

Ph.D. Dissertation Defense Presentation, by Alan Skousen, ASU, August 2002.

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**Distributed Consistency Management in Sombrero, A Single Address Space Distributed Operating System.**

MS Thesis Defense Presentation, by John Olson, ASU, August 2002

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**“Reduced Development Costs in the Sombrero Operating System”**

MS Thesis Defense talk by Ron Feigen in December 2001.

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**“The Sombrero Single Address Space Operating System Prototype A Testbed for Evaluating Distributed Persistent System Concepts and Implementation”**

Presentation by Donald Miller at PDPTA'2000, Los Vegas, Nevada, June 2000.
Stresses distributed consistency management in a SASOS.

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**"Distributed Scheduling in Sombrero, A Single Address Space Distributed Operating System"**

MS Thesis Defense talk by Milind Patil in August 1999.

Covers a distributed scheduling algorithm for Sombrero and a simulation demonstrating its properties. Demonstrates its load balancing functionality, correctness and scalability

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**"Using a Single Address Space Operating system for Distributed computing and High Performance"**

20 slide presentation by D. Miller at IPCCC'99 in Scottsdale Arizona on February 10, 1999.

Stresses distributed system Sombrero features and effects of a single address space on OS design.

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**“Single Address Spaces and Single Address Space Operating Systems”**

CSE Department Colloquium presentation by D. Miller to ASU Student Chapter of the IEEE Computer Society, September 15, 1998.

Introduction to Single Address Spaces and Single Address Space Operating Systems.

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**“The Sombrero Single Address Space Operating System”**

CSE Department Colloquium presentation by D. Miller to ASU Student Chapter of the IEEE Computer Society, September 29, 1998.

Overview of Sombrero SASOS.

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**"Operating System Structure and Processor Architecture for a Large Distributed Single Address Space"**

14 slide talk given by Alan Skousen at PDCS Conference in Las Vegas on October 31 1998.

Stresses the motivation for building a hardware-supported SASOS.

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**“Single Address Spaces, Single Address Space Operating Systems and Sombrero**

57 slide presentation by D. Miller in late June 98 to Mungi Group at UNSW and also (partially) to Grasshopper Project at University of Sydney.

Overview of single address spaces and SASOSs and fairly complete description of Sombrero. This talk was broken up into two talks and slightly updated for the student chapter of the IEEE at ASU – see above.

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**“Protection Structures in the Sombrero Operating System”**

MS Thesis Defense talk by Shah Khatri in December 1997.

Covers Sombrero protection data structures and the Protection and Resource Access List (PRAL) Simulation. Compares PRAL/RPLB performance with Page Table/TLB performance.

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**“Effects of the Single Address Space Paradigm on CPU and OS Design for a Distributed Computer System”**

Talk given by D. Miller to ASU 64-bit OS Group during 97-98 academic year

Early, not quite complete talk, on the multiple address space to single address space paradigm shift. Has Sombrero Principals and an added slide (slide 14) from “Single Address Spaces, Single Address Space Operating Systems and Sombrero” presentation with our best current parsing of the essence of the Multiple to Single Address Space Paradigm Shift.

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