VictoriaFalls:
Scaling Highly-Threaded Processor Cores

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Outline

- Highly-Threaded Processors
- VictoriaFalls Overview
- Scaling Challenges & Implementation
- Performance Scaling
- Summary

Highly-Threaded Processors

- Optimize for Throughput and Application Parallelism
  - > Most Important Commercial Server Applications are Heavily Threaded
  - > Parallelism through Aggregation (Multi-instance, Multi-process)
  - > Virtualized Server Environments (e.g. Logical Domains)
- Attack the Memory Wall
  - > Commercial Workloads Exhibit Poor Memory Locality
  - > For a Single Thread, Memory Latency is the Bottleneck to Improving Performance
  - > Diminishing Returns with Increased Cache Sizes in Terms of Both Performance and Die Area Efficiency
- Trade off Thread Latency for Thread Throughput
  - > For a Single Thread, Only Modest Throughput Speedup is Possible By Reducing Compute Time (Increased Frequency, ILP)

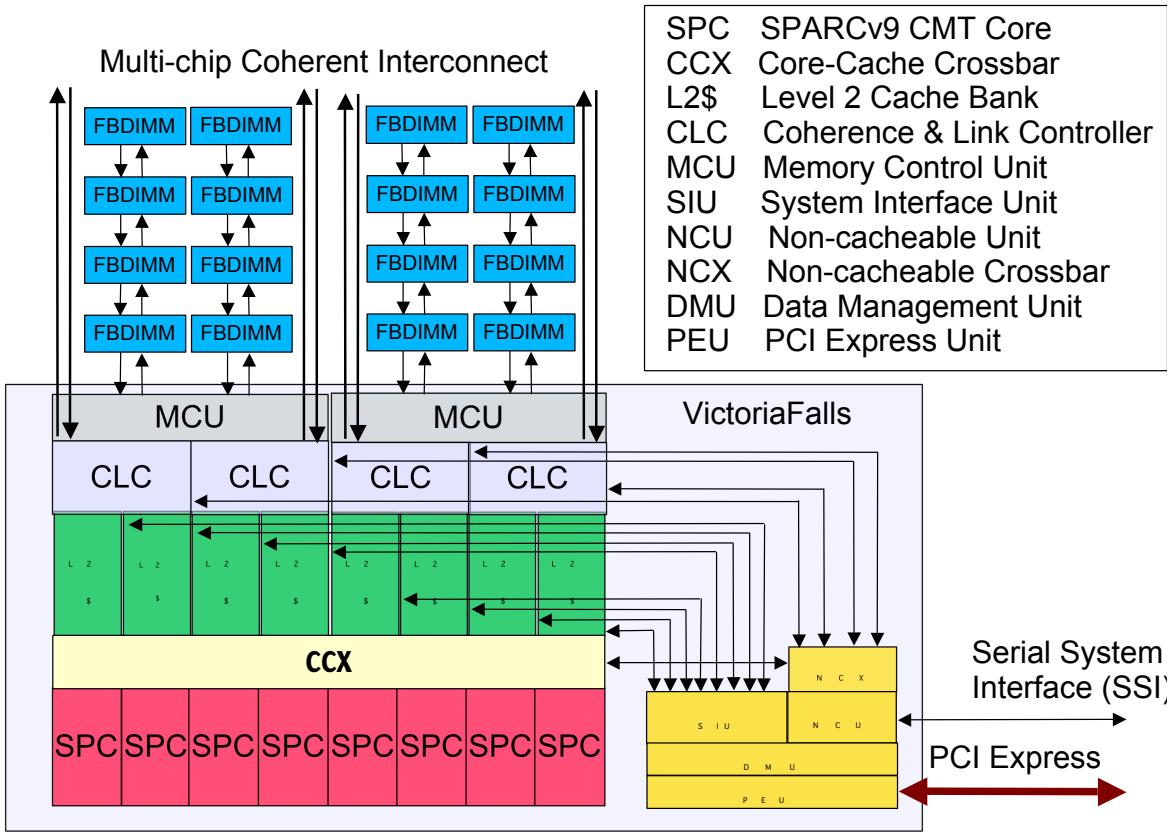
Highly-Threaded Processors

- Architected as Core-centric Designs to Maximiz Thread Count within Die Area Limits
  - > Relatively High Thread Count per Core
  - > Many Cores Imply Small Cores and Associated L1 Caches
  - > Modest Capacity Shared Outermost Cache (L2$)
- Managing High Concurrency at All Levels of the Design is the Major Scaling Challenge
  - > Core and Core-L2$ Interconnect
  - > L2$
  - > Memory & Multi-chip Interconnect

VictoriaFalls Chip Multiprocessor

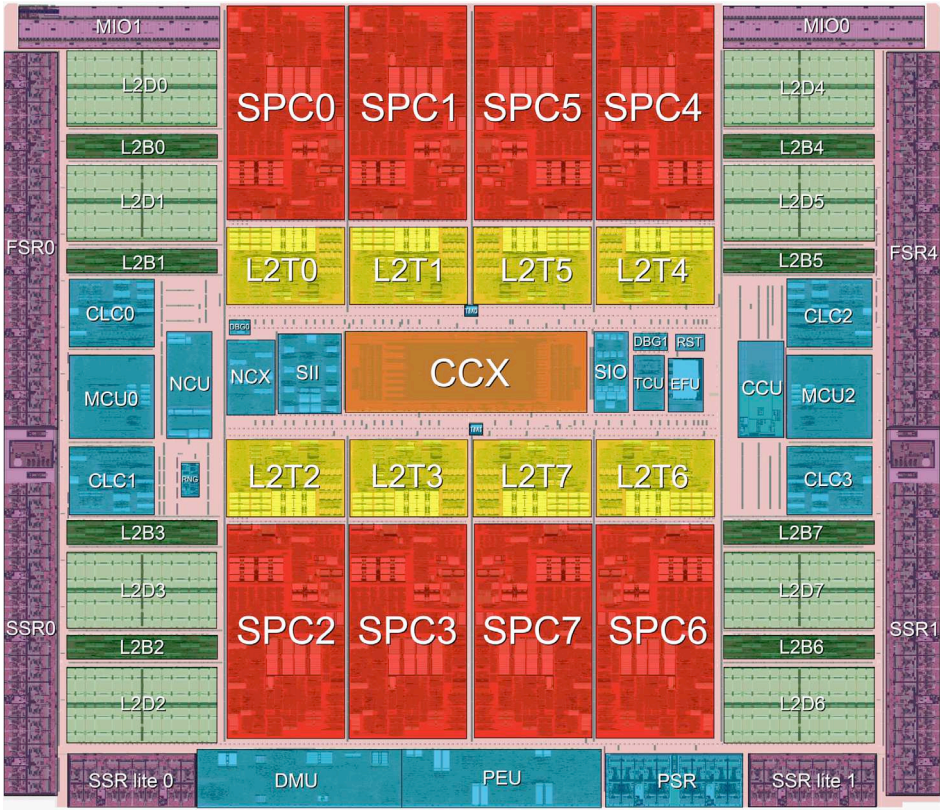
- 8 Core CMP with 8 Strands per Core @ 1.4Ghz
- Niagara2 SPARCv9 Core
  - > 2 x 8-stage Integer Units (4 Threads per Pipe) – Single Issue per Pipe
  - > 12-stage Pipelined FGU (except divide/sqrt)
  - > Integrated Crypto Accelerator
  - > 16KB 8-way SA L1-I$, 32B Lines, Write-through
  - > 8KB 4-way SA L1-D$, 16B Lines, Write-through
  - > 64 Entry Fully Associative I-TLB
  - > 128 Entry Fully Associative D-TLB
- 4 MB Shared L2$
- 2 Dual-Channel FBDIMM Memory Controllers
- Integrated PCI Express I/O Bridge
- Multi-chip Coherence Links

High Level Block Diagram



SPC	SPARCv9 CMT Core
CCX	Core-Cache Crossbar
L2$	Level 2 Cache Bank
CLC	Coherence & Link Controller
MCU	Memory Control Unit
SIU	System Interface Unit
NCU	Non-cacheable Unit
NCX	Non-cacheable Crossbar
DMU	Data Management Unit
PEU	PCI Express Unit

VictoriaFalls Micrograph



65nm CMOS

11 Metal Laye

709 Signal I/

1831 Total I/(

~Niagara2 CM Power

~Niagara2 CM Die Area

1st Level Scaling: Core & L2$ Crossbar

- SPC Memory Model
  - TSO Compliance Maintained by Combination of Core Load/Store Unit and the L2$ Crossbar
  - Exceptions are Instructions That Need not Support TSO
- Non-blocking Core-L2$ Crossbar
  - Establishes Memory Order between Transactions from the Same and Different L2$ Banks
  - Guarantees Delivery of Transactions to L2$ Banks in the Same Order
  - 180GB/sec Hit Bandwidth
- Concurrency
  - 8 Deep Store Buffer per Thread
  - Up to 384 Transactions per Processor (L2$ Limit)

TSO: Total Store Order

2nd Level Scaling: L2$

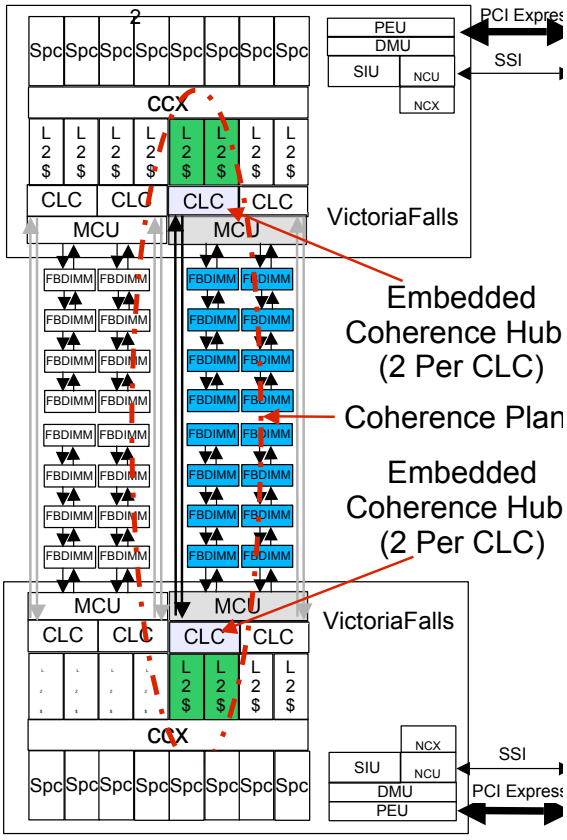
- 4MB Shared L2$
  - 8 Banks with Independent L2$ Pipelines
  - 64B Cache Lines, Writeback, Modified-LRU Replacement
  - Maintains Directory of L1$ Tags
- Minimizing L2$ Conflicts
  - Limited Thread Speculation
  - High Set Associativity (16-ways per Bank)
  - Set Index Hashing
- Micro-parallelization Challenge
  - Divide Serial Code Segments Among Concurrent Worker Threads
  - Lock-free Synchronization Primitives
  - Reduced Synchronization Overheads Communicating Through Common L2$ Optimized for Core-to-Core Communication
  - No L1-D$ Probes due to Hot Locks, Real or False Data Sharing

3rd Level Scaling: Memory & Multi-chip

- Memory Bandwidth
  - > Result of Fine-grain Vertical Threading (Niagara2 Core), Core Count and Modest L2$ Size
  - > 50%-80% Core Pipeline Utilization Typical on Commercial Workloads
  - > Commercial Workloads Can Exceed 15GB/sec Average Memory Bandwidth on a Single CMP
  - > Requires Multiple On-die Memory Controllers with Concurrent Read/Write Channel Scheduling
- Snoopy-based Coherent Interconnect
  - > Physical Addresses Partitioned Across 4 Coherence Planes
  - > Multiple Busses Replaced with Point-to-point Links
  - > Direct Chip-to-chip or Hub/Star Physical Topologies
  - > Multi-bank L2$ Provides Ample Snoop Bandwidth

Multi-chip Interconnect

- Distributed Points of Global Ordering
  - > Coherence Planes Operate Independent of One Another
  - > Physical Address Conflicts Serialized by Coherence Hubs
- Cache States
  - > MOESI States Tracked by L2$
  - > C2C Transfers on Snoop Hits to M, O, E and S (MCU Node) States
- Independent Packet Processing Between 3 Virtual Channels
- OOO Snoop Responses
  - > Fairness Algorithm
  - > Progress Beyond Stalled Snoops

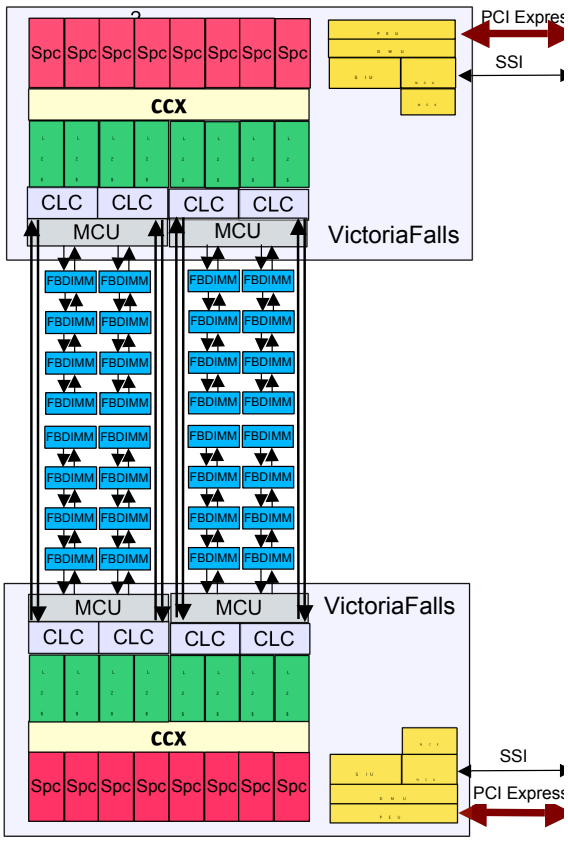


Multi-chip Interconnect

- Physical Layer
  - 14 Transmit and 14 Receive Lanes per Channel
  - 4.8GT/sec, 8.4 GB/sec Raw Link Bandwidth per Direction
  - Clock Recovery, Bit/symbol Alignment, Initialization and Training
- Reliable Point-to-point Data Link Layer
  - Fixed Size Frames: 144bit Payload + 24bit CRC
  - 7.2GB/sec Payload BW, 6.4GB/sec Peak Data BW per Link, Full-Dupl
  - Hardware Frame Replay, Link Retrain and Lane Failover with Full CR Continuance
- Virtual Channels
  - Request/Request-ack
  - Response
  - Data/Critical Data
- Transaction Layer
  - 3/7/18-Byte Packets, May Cross Frame Boundaries
  - Weighted Round Robin Arbitration of Egress Virtual Channel Queues

Dual-chip Architecture

- 16 SPARC Cores
  - 128 Threads
- Coherent Interconnect
  - 4 Coherence Links, Full-Duplex
  - 65GB/sec Raw Bisection
- 8 FBDIMM Channels
  - 42GB/sec (Theoretical Peak) Read
  - 21GB/sec (Theoretical Peak) Write
  - DDR2-667
- Integrated I/O Bridges
  - 2 x8 Lane PCI Express Ports @ 2.5GT/sec per Lane Full Duplex
  - 1024 Concurrent IO Address Translations (Virtual-to-Real, Real-to-Physical)
  - Relaxed DMA Ordering



Dual-chip Local Memory Coherent Read

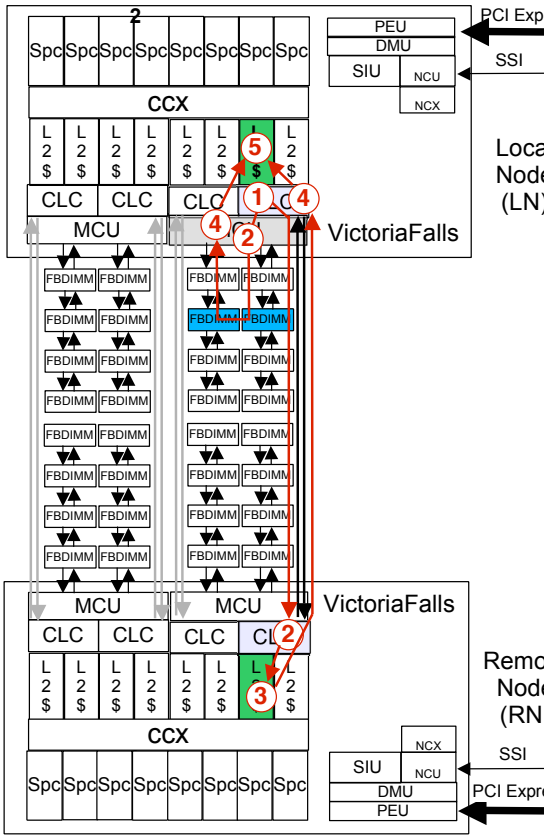
1 LN Coherence Hub serialization. Forwards read request to LN MCU & snoop request to RN CLC.

2 LN MCU FBDIMM access. RN CLC forwards snoop request to RN L2$ bank.

3 RN L2$ bank snoop operation. Returns snoop response and potentially C2C data to LN CLC.

4 LN CLC forwards snoop response, memory and C2C data to LN L2$ bank as they arrive.

5 LN L2$ bank bypasses resolved return data to upstream cache and fills allocated L2$ entry.



Dual-chip Remote Memory Coherent Read

1 LN CLC forwards read request to RN CLC.

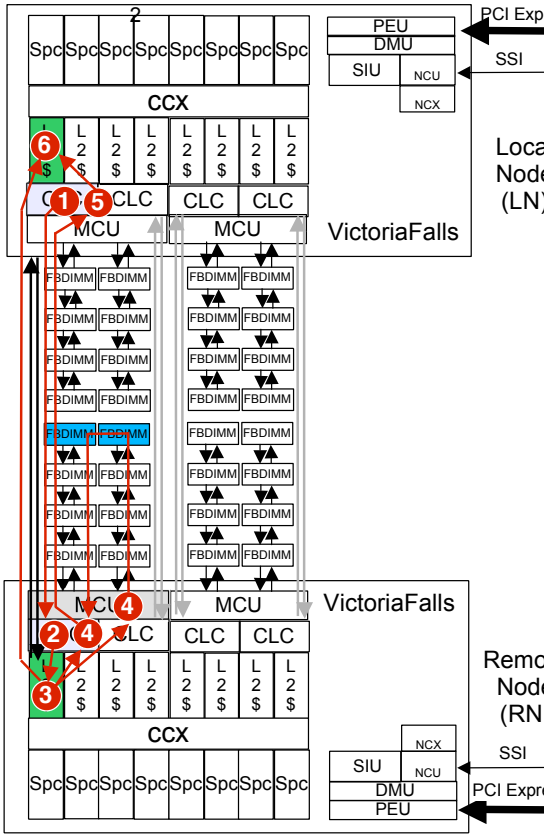
2 RN Coherence Hub serialization. RN CLC forwards Request-ack to LN L2$ Bank and snoop request to RN L2$ Bank.

3 RN L2$ bank snoop operation, returns snoop status result to RN CLC to activate read request to RN MCU.

4 LN MCU FBDIMM access if no L2$ copyback. RN CLC forwards snoop response and memory or copyback data to LN CLC.

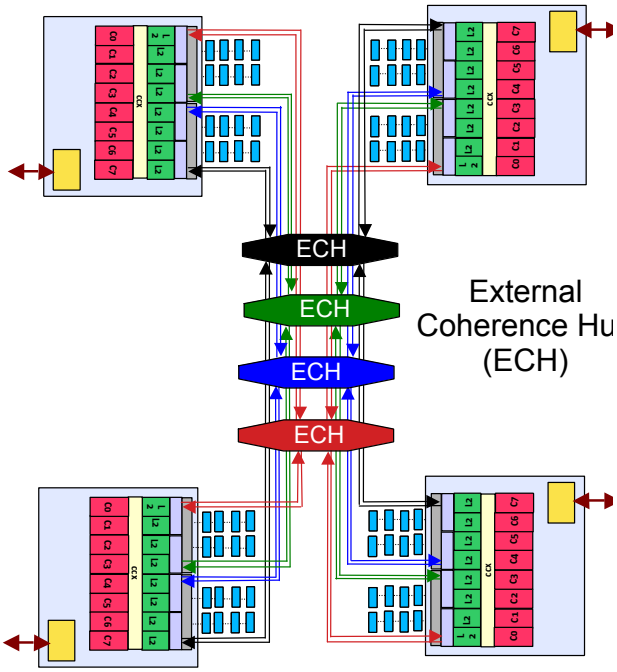
5 LN CLC forwards snoop response and return data to local L2$ bank as they arrive.

6 L2$ forwards/bypasses resolved return data to upstream cache and fills L2$.

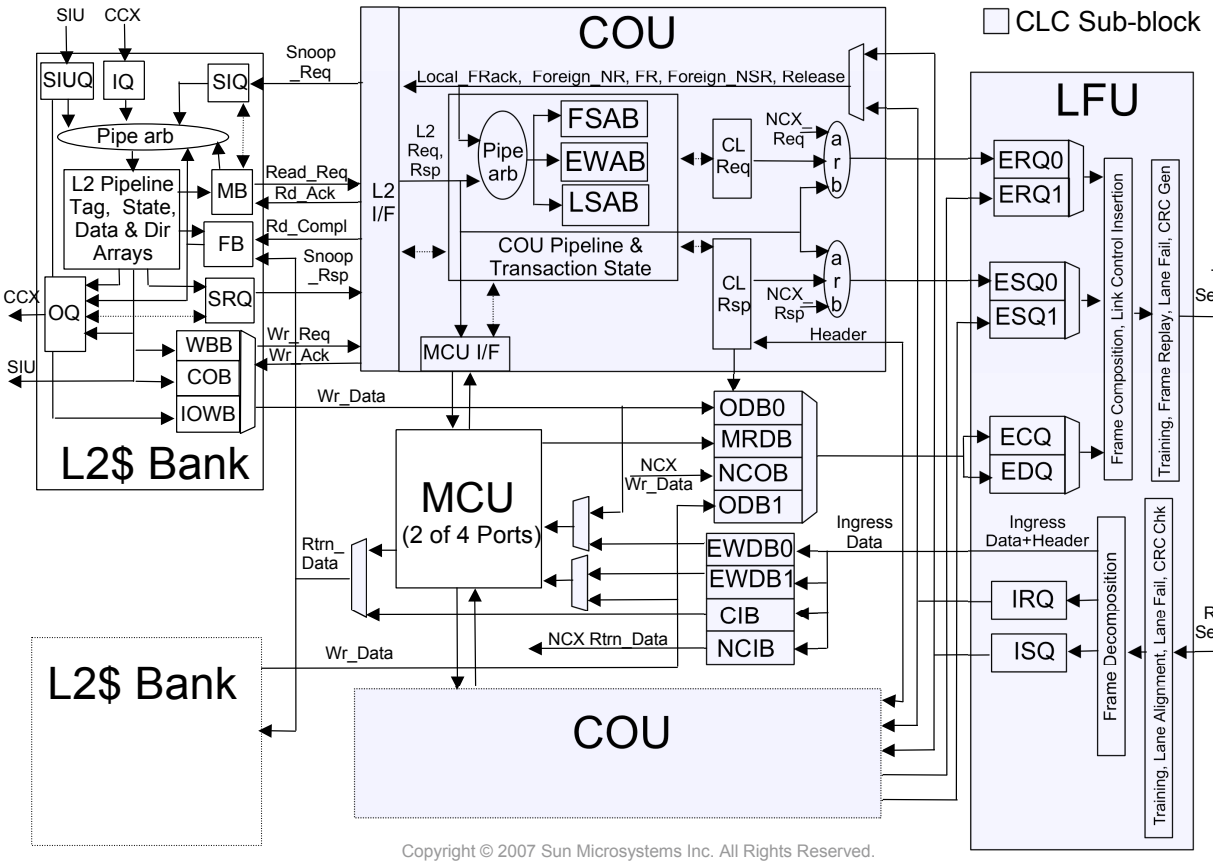


Quad-chip Architecture

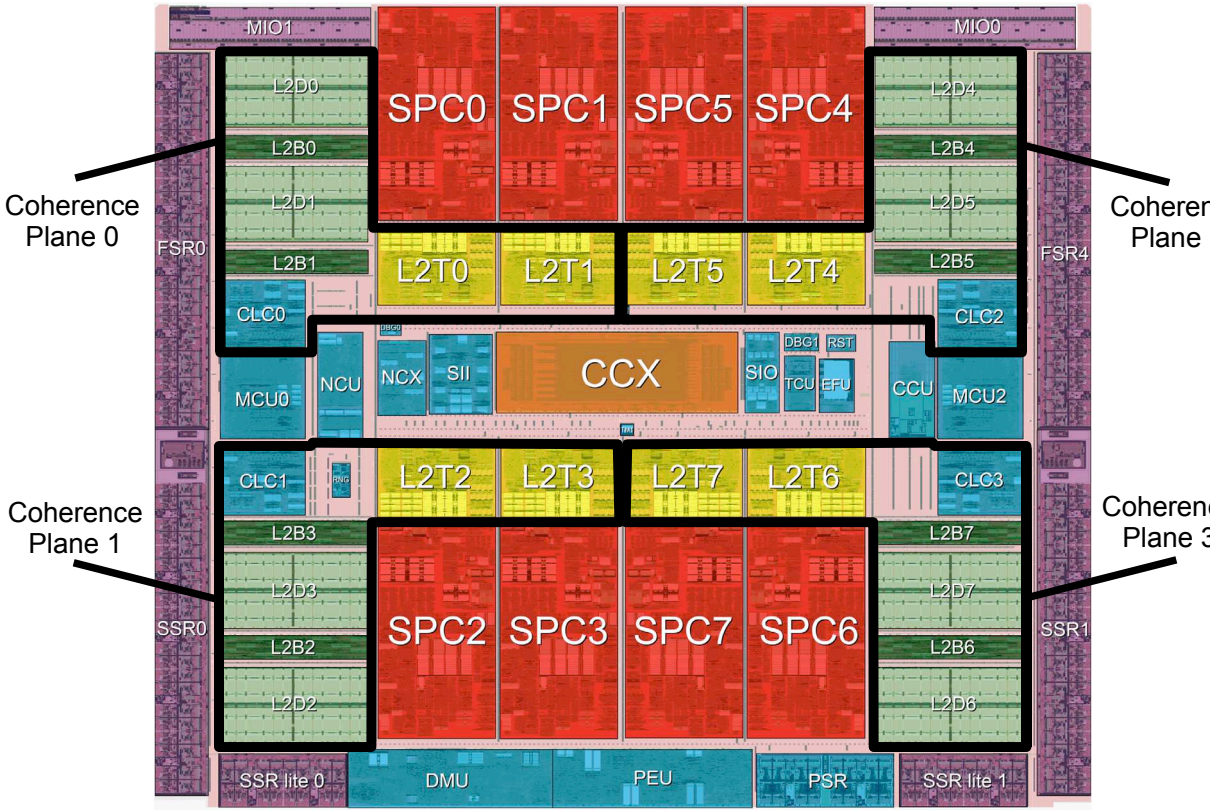
- 32 SPARC Cores
  - > 256 Threads
- Coherent Interconnect
  - > 4x4 Coherence Links, Full-Duplex
  - > 130GB/sec Raw Bisection
- 16 FBDIMM Channels
  - > 84GB/sec (Theoretical Peak) Read
  - > 42GB/sec (Theoretical Peak) Write
- 4 Integrated I/O Bridges
- 4 External Coherence Hubs
  - > Global Ordering
  - > Snoop Response Aggregation
  - > Data Filtering
  - > Destination Flow Control



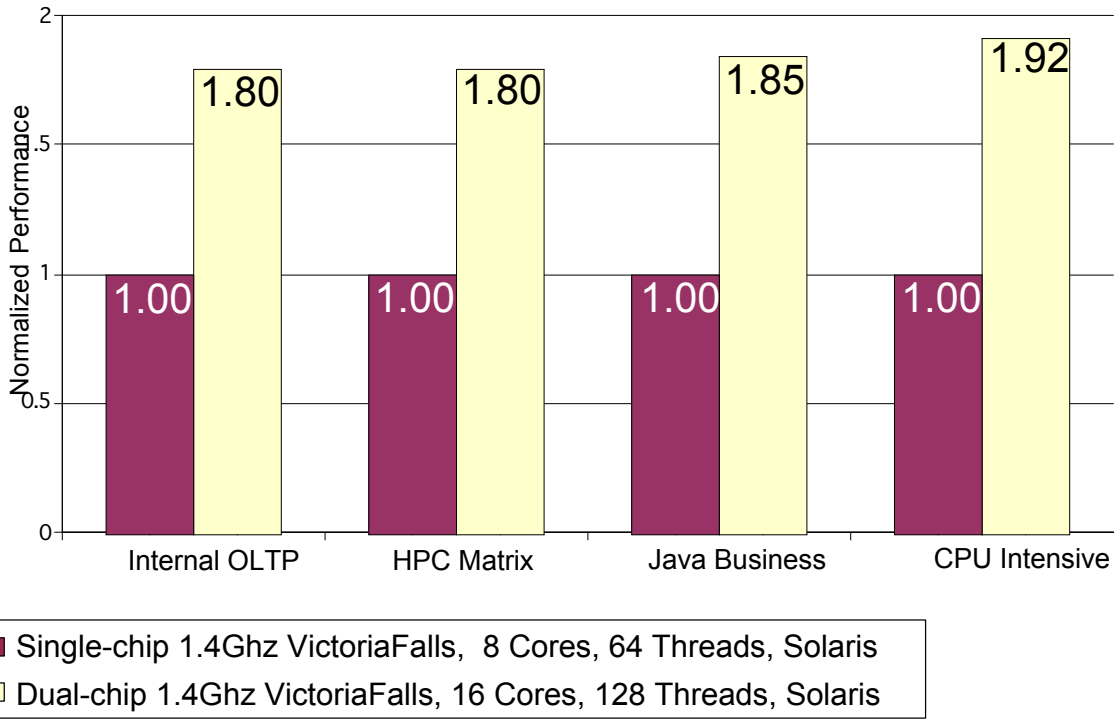
Coherence Plane Microarchitecture



Coherence Plane Layout



Performance Scaling



Summary

- VictoriaFalls Scales Throughput Performance via Multi-bank Caches, Multi-port Memory Controllers and Multi-plane Coherent Interconnects.
- VictoriaFalls is Comparable to the Niagara2 Chip Multiprocessor in Terms of Die Area and Power Envelope.
- VictoriaFalls Enables Large (128 to 256) Thread Count, High Capacity and High Throughput Performance in Dense, Power-Efficient Form Factors.

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Microarchitecture Terminology

- L2$ Bank – 8 Instances
  - IQ: Core Input Queue
  - SIUQ: System (DMA) Input Queue
  - SIQ: Snoop Input Queue
  - SRQ: Snoop Response Queue
  - OQ: Output Queue
  - MB: Miss Buffer
  - FB: Fill Buffer
  - WBB: Writeback Buffer
  - COB: Copyback Buffer
  - IOWB: I/O Writeback Buffer
- Link Framing Unit (LFU)
  - ERQ0, ERQ1: Egress Request Queues
  - ESQ0, ESQ1: Egress Status Queues
  - ECQ: Egress Critical Data Queue
  - EDQ: Egress Data Queue
  - IRQ: Ingress Request Queue
  - ISQ: Ingress Status Queue
- Coherence & Ordering Unit (COU) – 8 Instances
  - LSAB: Local Snoop Address Buffer
  - FSAB: Foreign Snoop Address Buffer
  - EWAB: External Writeback Address Buffer
- CLC Datapath – 4 Instances
  - ODB0, ODB1: Output Data Buffers
  - MRDB: Memory Return Data Buffers
  - NCOB: Non-Cacheable Output Buffer
  - EWDB0, EWDB1: External Writeba Data Buffers
  - CIB: Copyback Input Buffer
  - NCIB: Non-Cacheable Input Buffer