MULTIPROCESSORS AND HETEROGENEOUS ARCHITECTURES

CS6410

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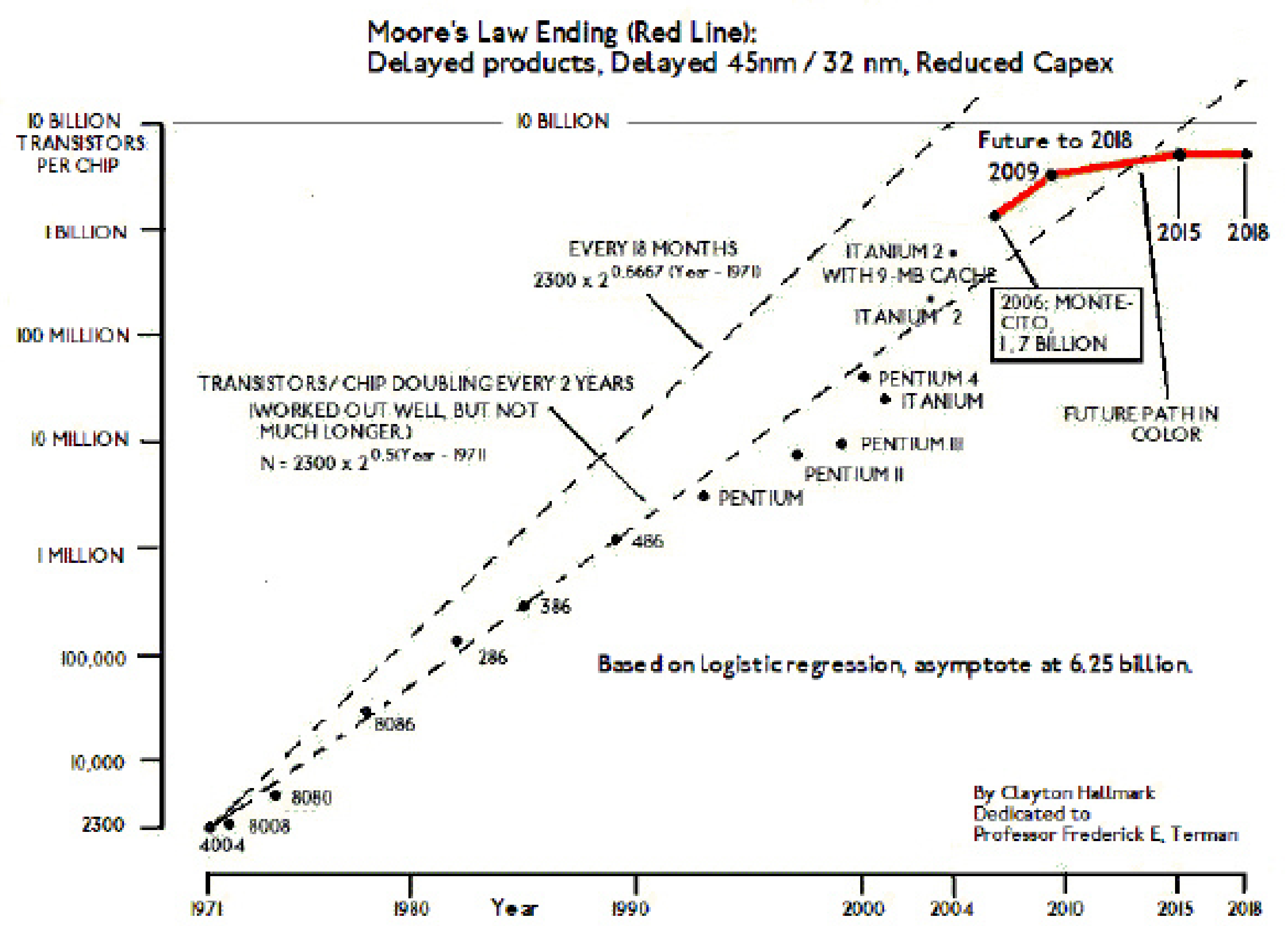
Slides borrowed liberally from past presentations from Deniz Altinbuken, Ana Smith, Jonathan Chang

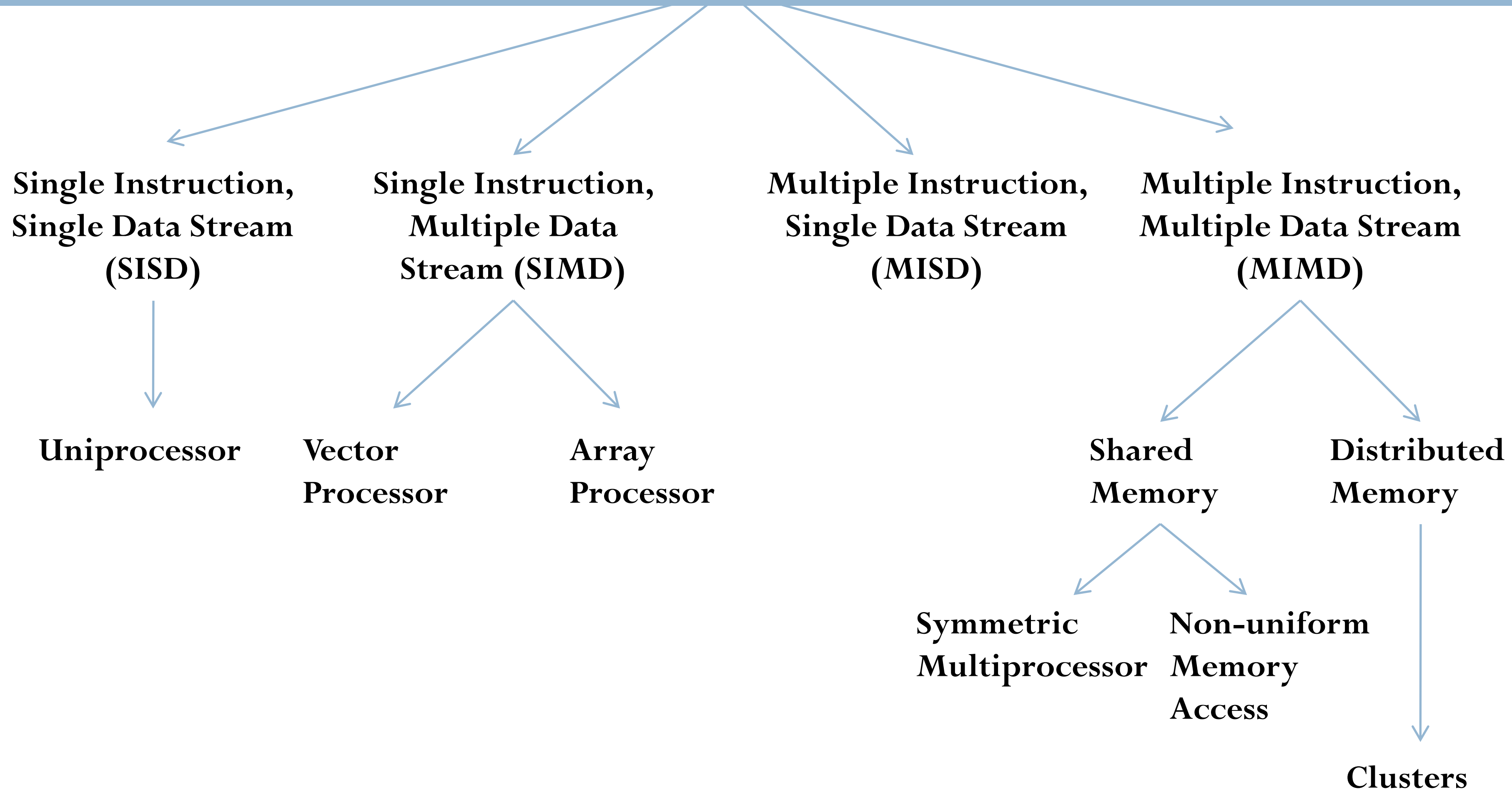
Overview

- Systems for heterogeneous multiprocessor architectures
- Disco (1997)
  - Smartly allocates shared-resources for virtual machines
  - Acknowledges NUMA (non-uniform memory access) architecture
  - Precursor to VMWare
- Barrelfish (2009)
  - Uses replication to decouple resources for virtual machines via MPI
  - Explores hardware neutrality via system discovery
  - Takes advantage of inter-core communication

End of Moore's Law?

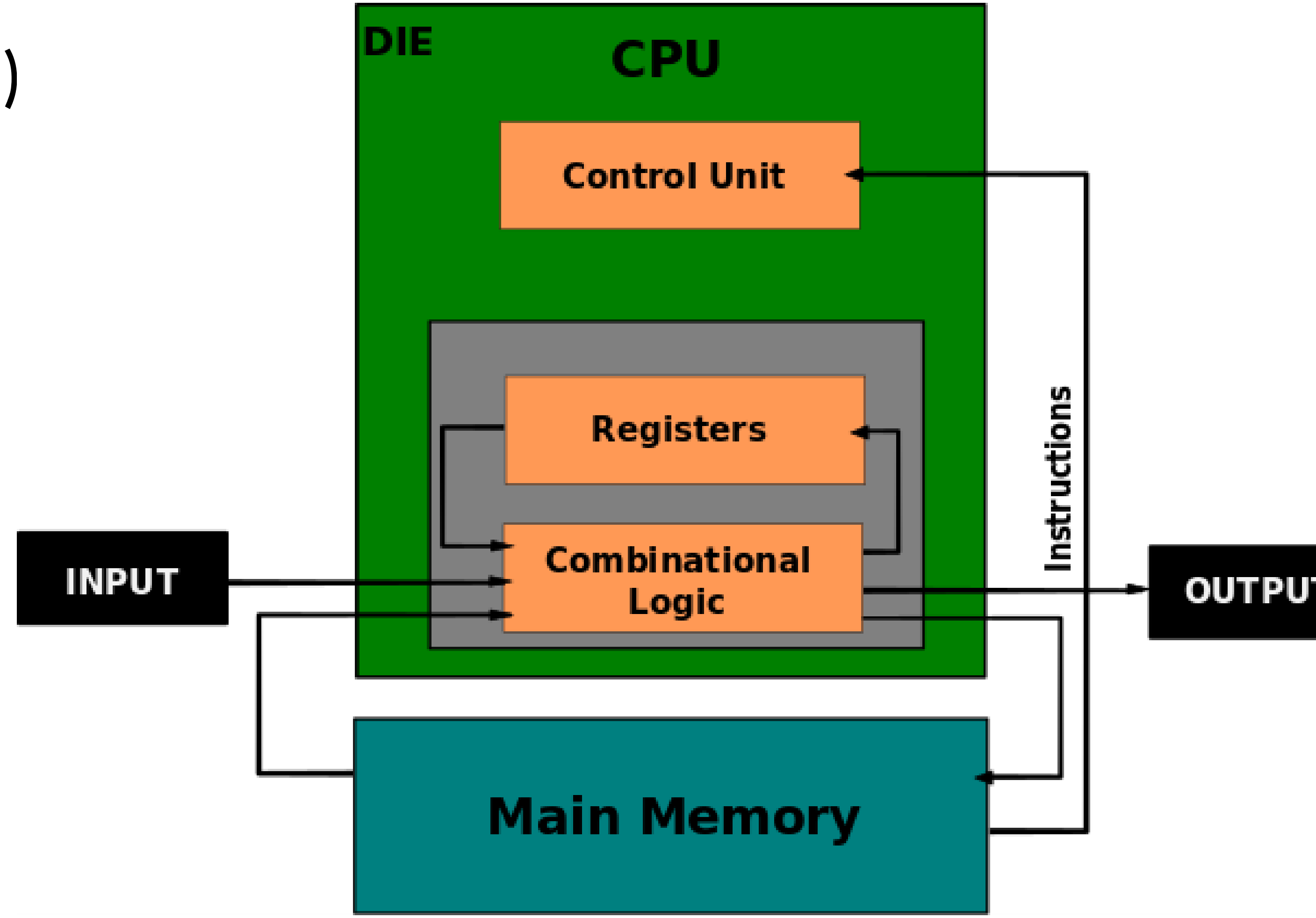


Processor Organizations



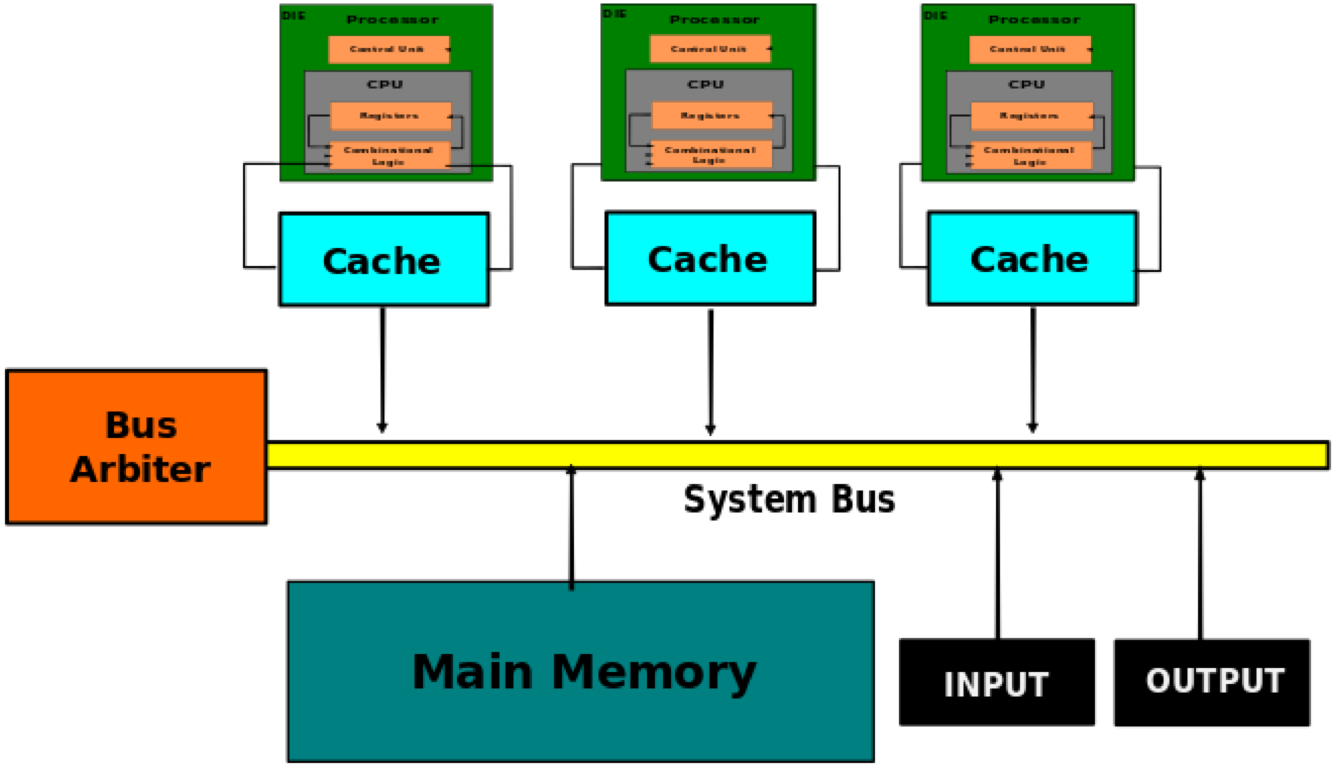
Evolution of Architecture (Uniprocessor)

- Von Neumann Design (~1960)
- # of Die = 1
- # of Cores/Die = 1
- Sharing=None
- Caching=None
- Frequency Scaling = True
- Bottlenecks
  - Multiprogramming
  - Main memory access



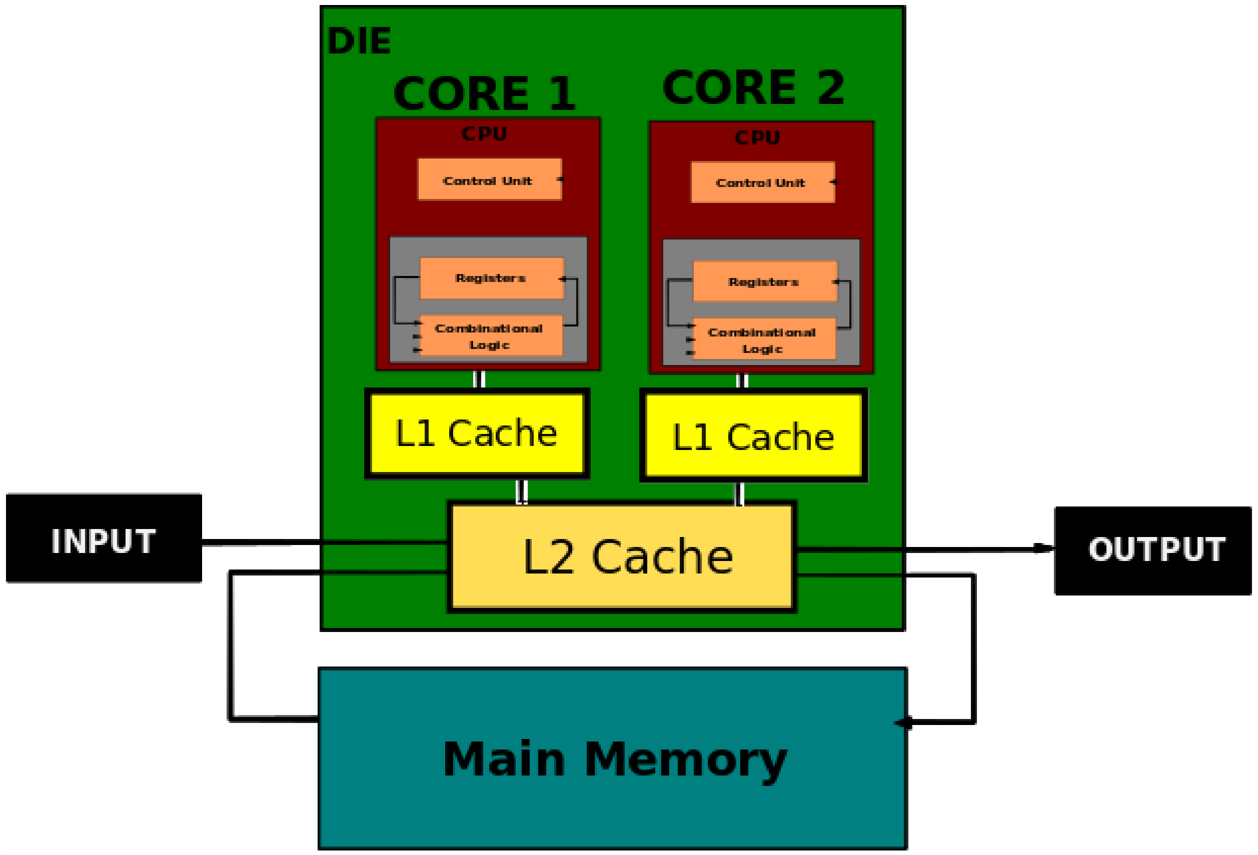
Evolution of Architecture (Multiprocessor)

- Super computers (~1970)
- # of Die = K
- # of Cores/Die = 1
- Sharing = 1 Bus
- Caching = Level 1
- Frequency Scaling = True
- Bottlenecks:
  - Sharing required
  - One system bus
  - Cache reloading



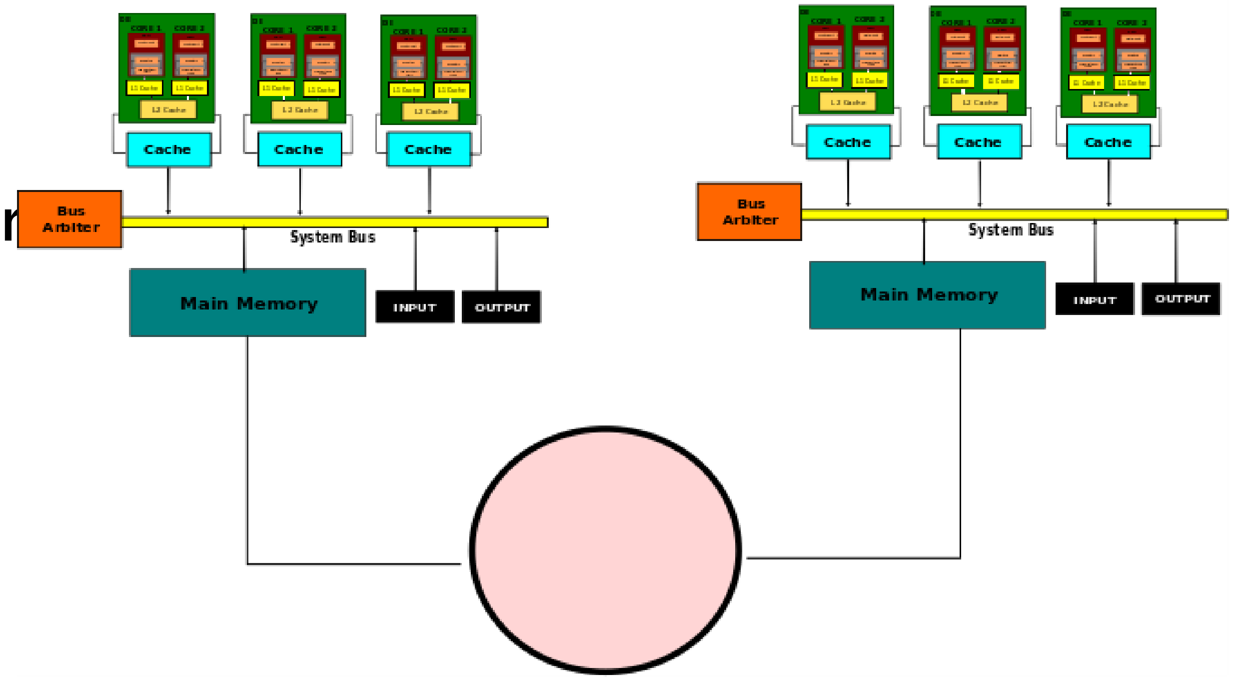
Evolution of Architecture (Multicore Processor)

- IBM's Power 4 (~2000s)
- # of Die = 1
- # of Cores/Die = M
- Sharing = 1 Bus, L2 cache
- Caching = Level 1 & 2
- Frequency Scaling = False
- Bottlenecks:
  - Shared bus & L2 caches
  - Cache-coherence



Evolution of Architecture (NUMA)

- Non-uniform Memory Access
- # of Die = K
- # of Cores/Die = variable
- Sharing = Local bus, local Memor
- Caching: 2-4 levels
- Frequency Scaling = False
- Bottlenecks:
  - Locality: closer = faster
  - Processor diversity



Challenges for Multiprocessor Systems

- Stock OS's (e.g. Unix) are not NUMA-aware
  - Assume uniform memory access
  - Requires major engineering effort to change this…
- Synchronization is hard!
  - Even with NUMA architecture, sharing lots of data is expensive

Doesn’t some of this sound familiar?...

- What about virtual machine monitors (aka hypervisors)?
- VM monitors manage access to hardware
  - Present more conventional hardware layout to guest OS’s
- Do VM monitors provide a satisfactory solution?

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  - Communication is still an issue
- Proposed solution: Disco (1997)

Multiprocessors, Multi-core, Many-core

- Goal: Taking advantage of the resources in parallel

What are critical systems design considerations

- Scalability
  - Ability to support large number of processors
- Flexibility
  - Supporting different architectures
- Reliability and Fault Tolerance
  - Providing Cache Coherence
- Performance
  - Minimizing Contention, Memory Latencies, Sharing Costs

Disco: About the Authors

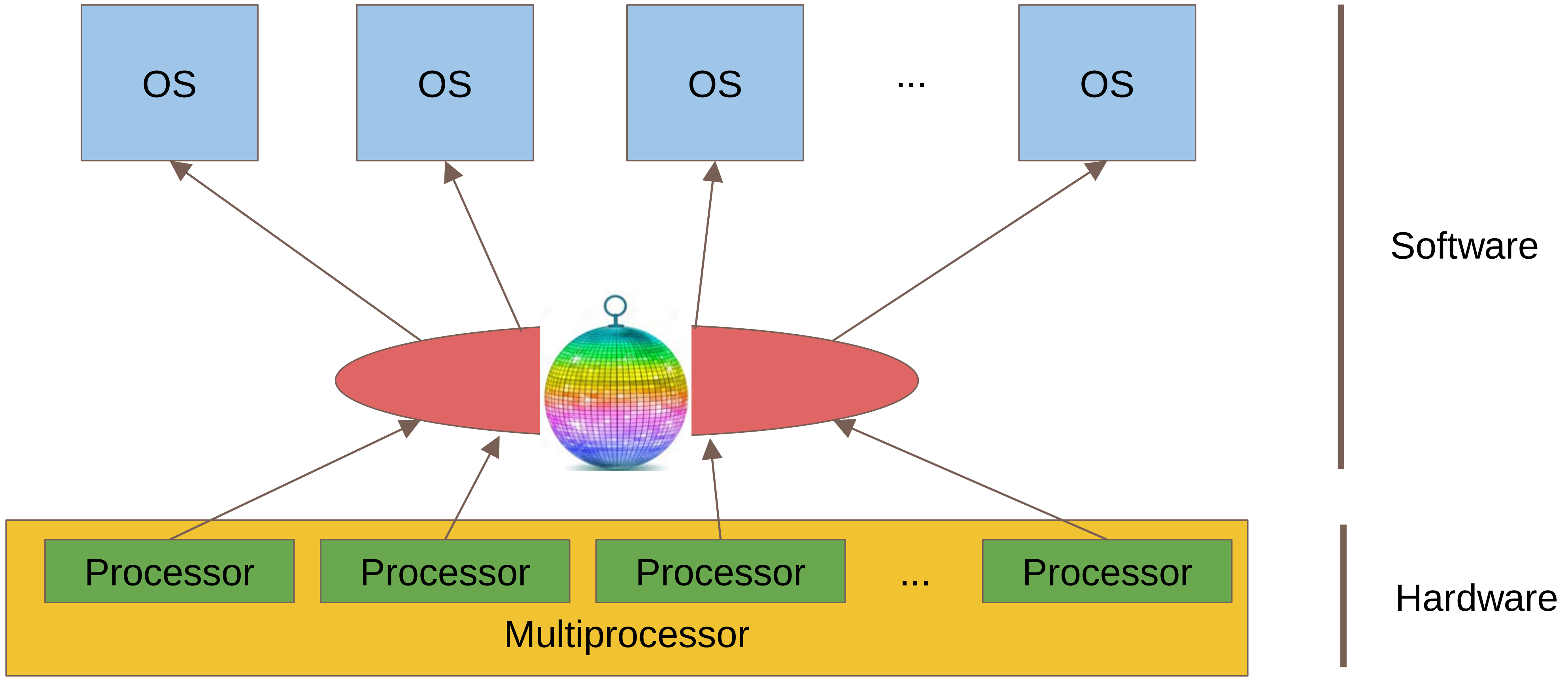
- Edouard Bugnion
  - Studied at Stanford
  - Currently at École polytechnique fédérale de Lausanne (EPFL)
  - Co-founder of **VMware** and **Nuova Systems** (now under Cisco)
- Scott Devine
  - Co-founded VMWare, currently their principal engineer
  - Not the biology researcher
  - Cornell alum!
- Mendel Rosenblum
  - Log-structured File System (LFS)
  - Another co-founder of VMWare

Disco: Goals

- Develop a system that can scale to multiple processors…
- …*without* requiring extensive modifications to existing OS's
  - Hide NUMA
- Minimize memory overhead
- Facilitate communication between OS's

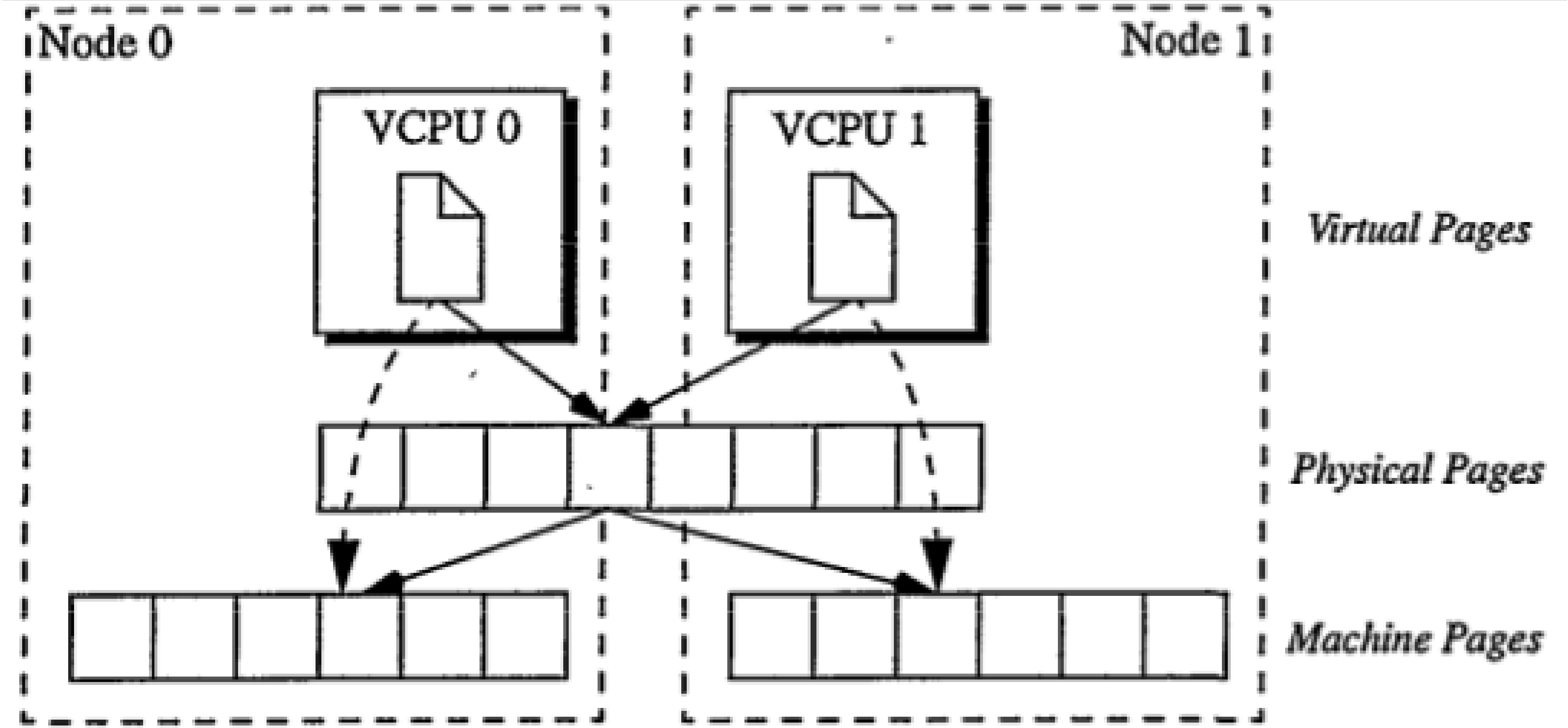
Disco: Achieving Scalability

- Additional layer of software that mediates resource access to, and manages communication between, multiple OS's running on separate processors



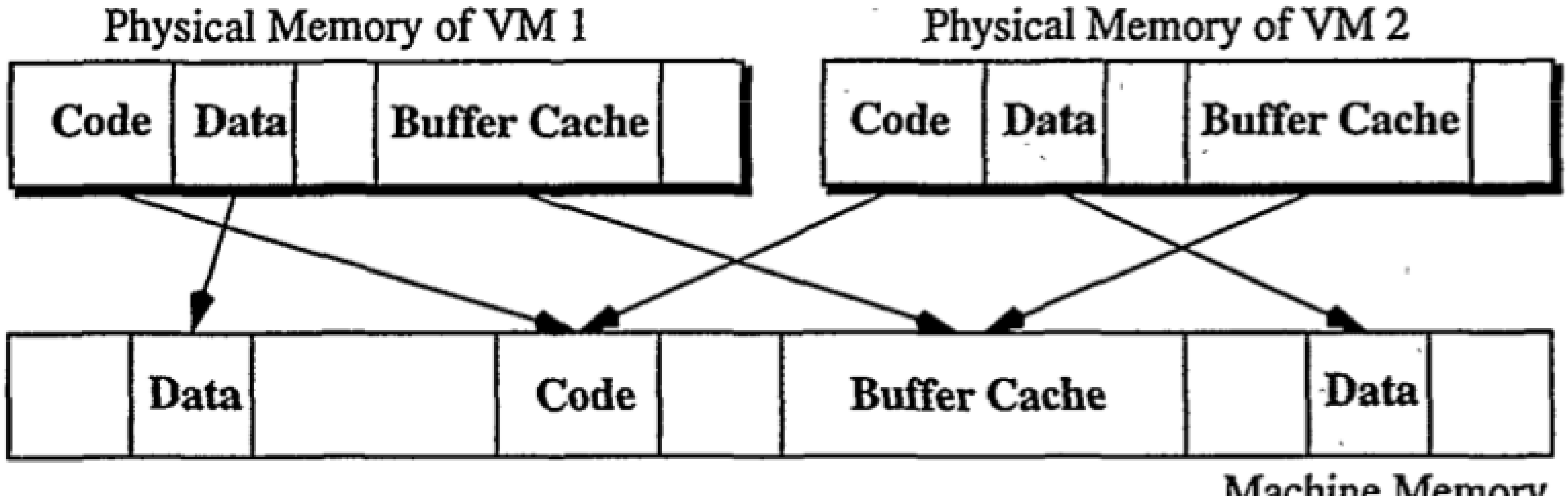
Disco: Hiding NUMA

- Relocate frequently used pages closer to where they are used



Disco: Reducing Memory Overhead

- Suppose we had to copy shared data (e.g. kernel code) for every VM
  - Lots of repeated data, and extra work to do the copies!
- Solution: copy-on-write mechanism
  - Disco intercepts all disk reads
  - For data already loaded into machine memory, Disco just assigns mapping instead of copying

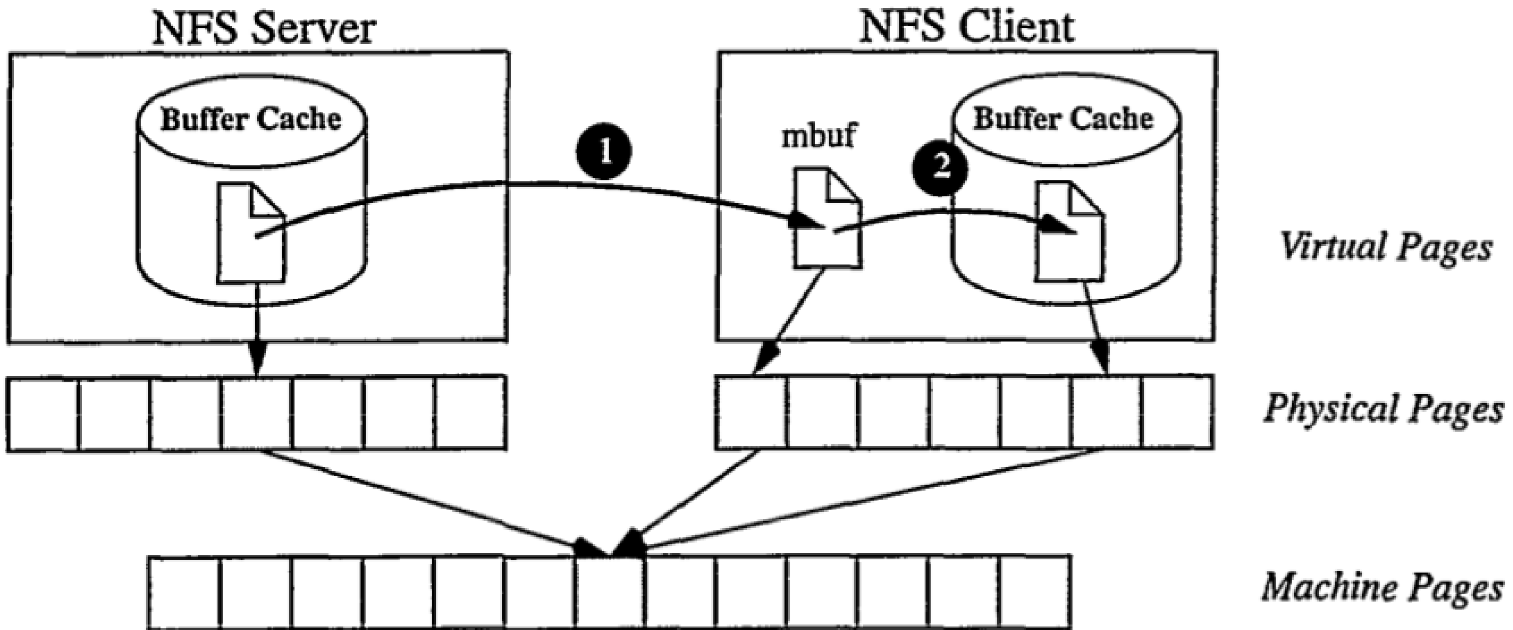


Disco: Facilitating Communication

- VM's share files with each other over NFS
- What problems might arise from this?

Disco: Facilitating Communication

- VM's share files with each other over NFS
- What problems might arise from this?
  - Shared file appears in both client and server's buffer!
- Solution: copy-on-write, again!
  - Disco-managed network interface + global cache



Disco: Evaluation

- Evaluation goals:
  - Does Disco achieve its stated goal of achieving scalability on multiprocessors?
  - Does it provide effective reduction in memory overhead?
  - Does it do all this without significantly impacting performance?

- Evaluation methods: benchmarks on (simulated) IRIX (commodity OS) and SPLASHOS (custom-made specialized library OS)
  - Needed some changes to IRIX source code to make it compatible with Disco
  - Relocated IRIX kernel in memory, hand-patched hardware abstraction layer (HAL)
  - Is this cheating?

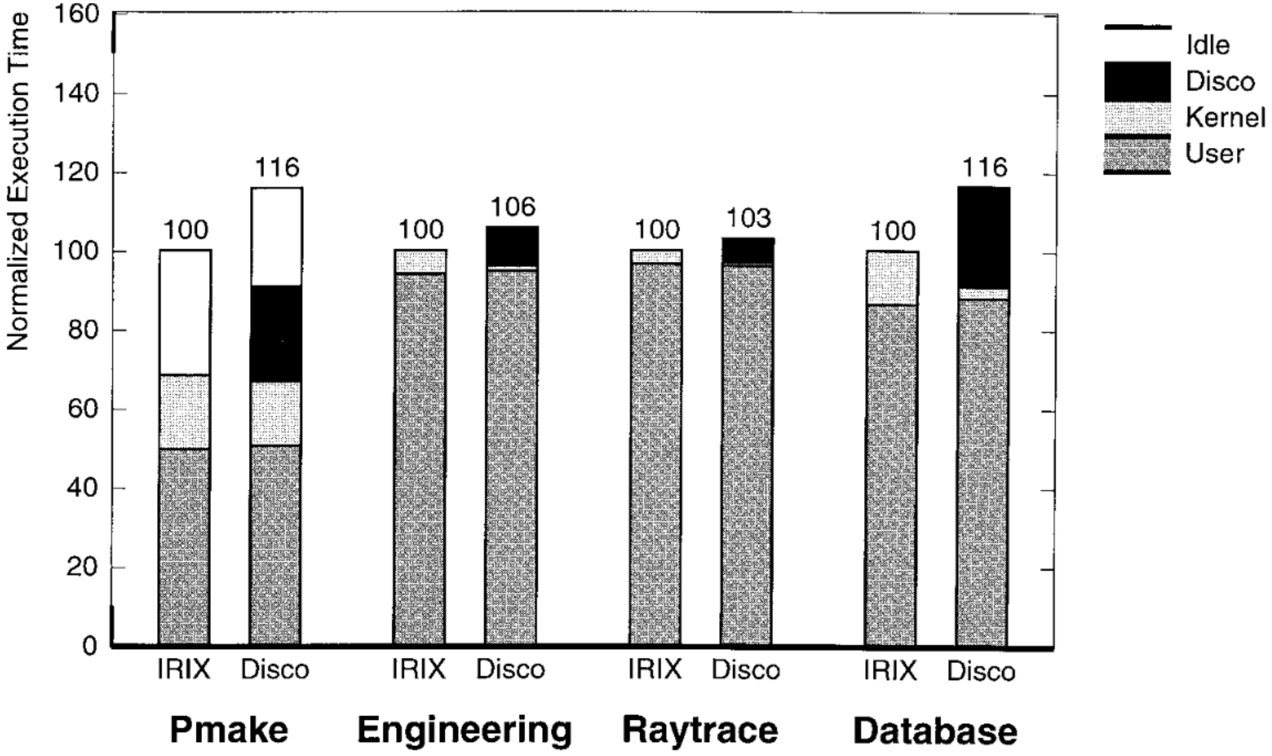
Disco: Evaluation Benchmarks

- The following workloads were used for benchmarking:

Workload	Environment	Description	Characteristics	Execution Time
Pmake	Software Development	Parallel compilation (-J2) of the GNU chess application	Multiprogrammed, short-lived, system and I/O intensive processes	3.9 sec
Engineering	Hardware Development	Verilog simulation (Chronologics VCS) + machine simulation	Multiprogrammed, long running processes	3.5 sec
Splash	Scientific Computing	Raytrace from SPLASH-2	Parallel applications	12.9 sec
Database	Commercial Database	Sybase Relational Database Server decision support workload	Single memory intensive process	2.0 sec

Disco: Impact on Performance

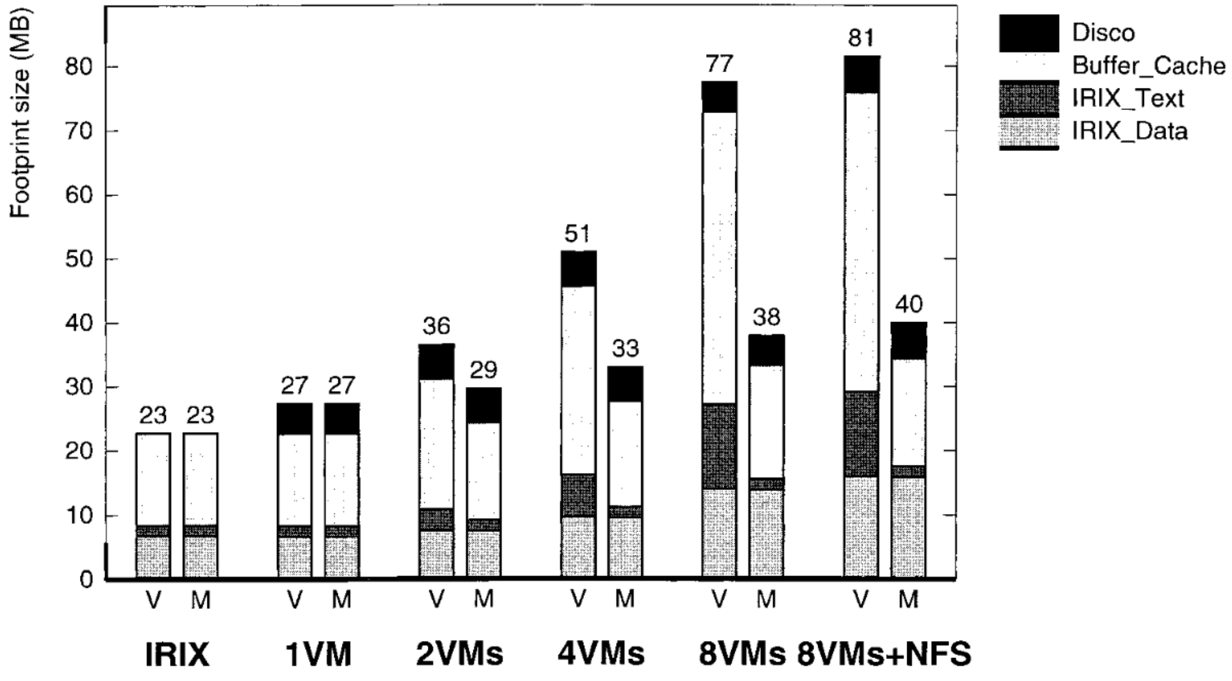
- Methodology: run each of the 4 workloads on a uniprocessor system with and without Disco, measure difference in running time



- What could account for the difference between workloads?

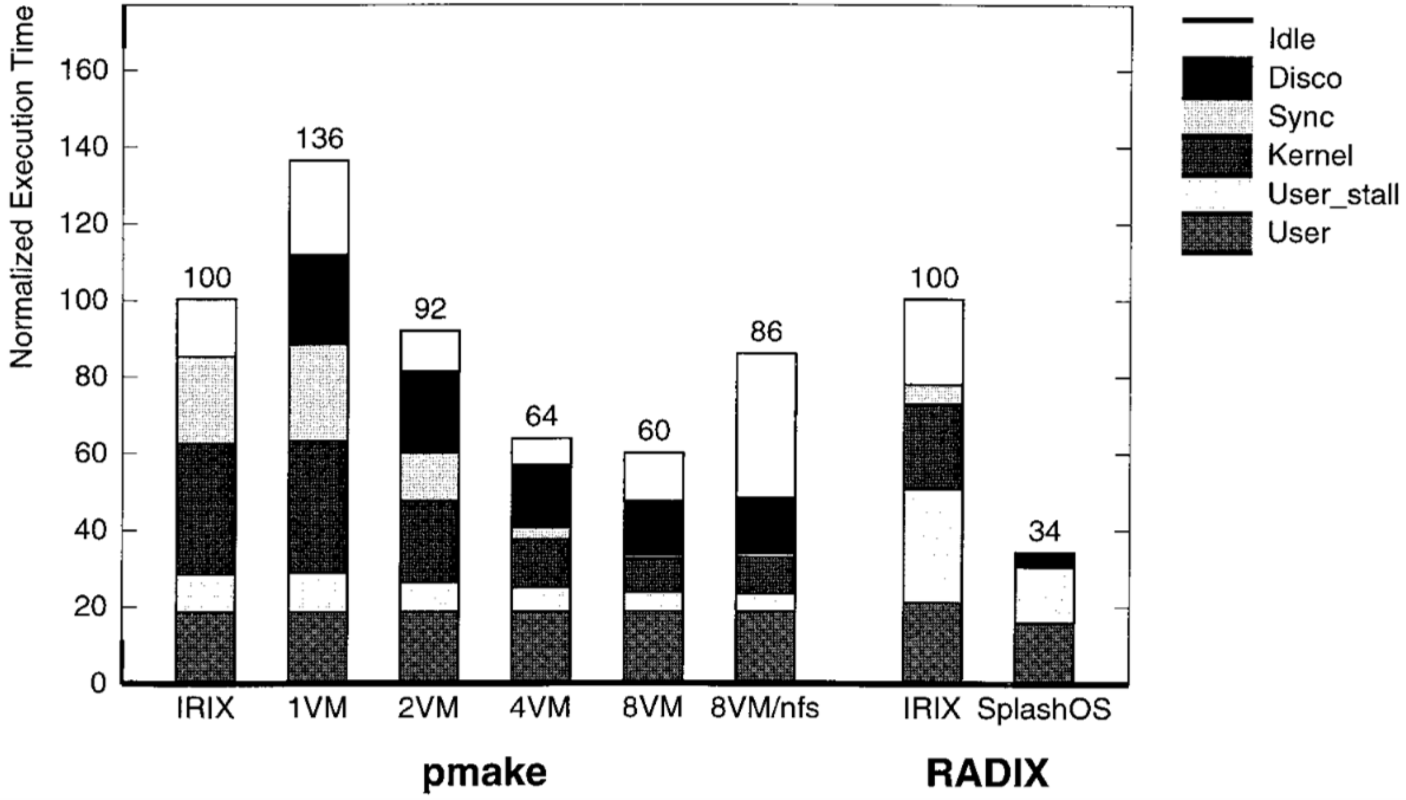
Disco: Measuring Memory Overheads

- Methodology: run the pmake workload on stock IRIX and on Disco with varying number of VMs
- Measurement: memory footprint in virtual memory (V) & actual machine memory (M)



Disco: Does It Scale?

- Methodology: run pmake on stock IRIX and on Disco with varying number of VM's and measure execution time
- Also compare radix sort performance on IRIX vs SPLASHOS



Disco: Takeaways

- Virtual Machine Monitors are a feasible tool to achieve scalability on multiprocessor systems
  - Corollary: scalability does not require major changes
- The disadvantages of virtual machine monitors are not intractable
  - Before Disco, overhead of VMs and resource sharing were big problems

Disco: Questions

- Does Disco achieve its goal of not requiring major OS changes?
- How does Disco compare to microkernels? Advantages/disadvantages?
- What about to Xen / other virtual machine monitors?

10 Years Later…

- Multiprocessor → Multicore
- Multicore → Many-core
- Amdahl's law limitations

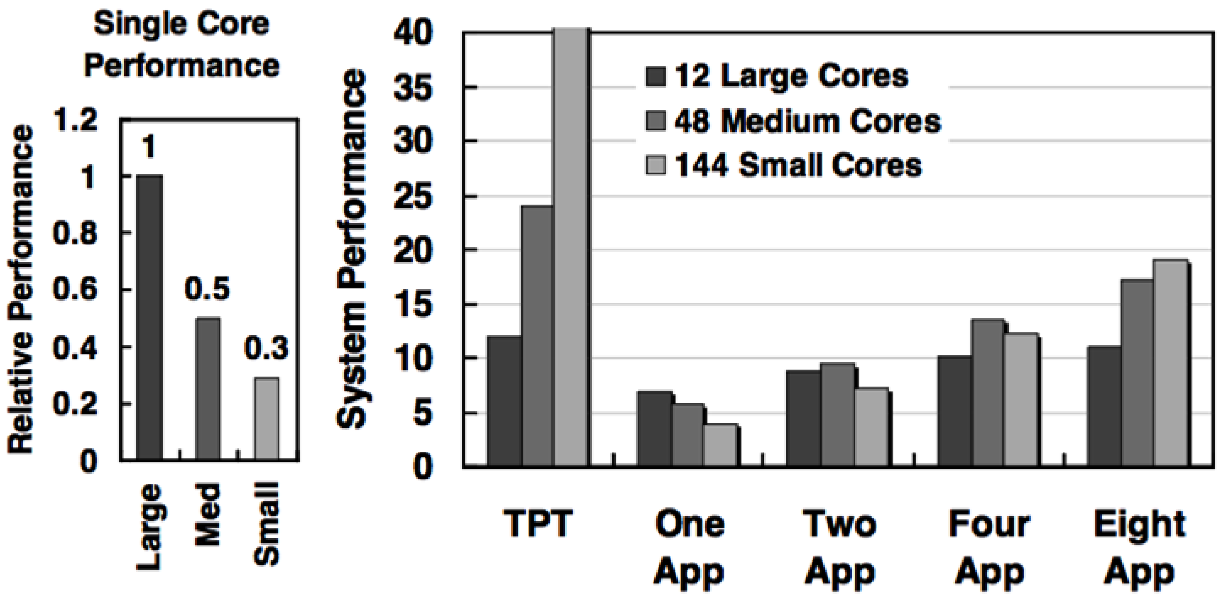
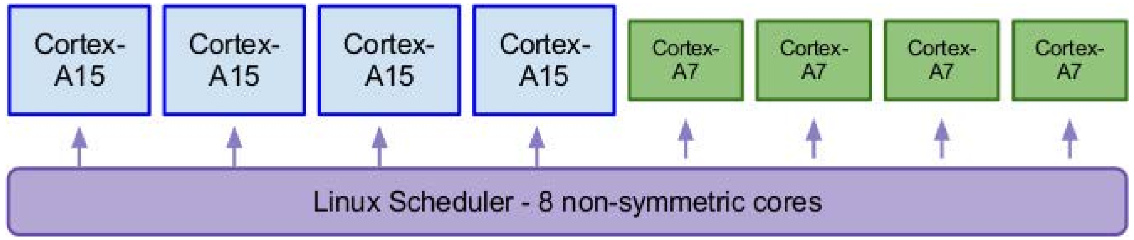


Figure 6: Performance of Large, Medium, and Small Cores



Big.Little heterogeneous multi-processing

From Disco to Barrelfish

Shared Goals	**Disco (1997)**	**Barrelfish (2009)**
Better VM Hypervisor	Make VMs scalable!	Make VMs scalable!
Better communication	VM to VM	Core to Core
Reduced overhead	Share redundant code	Use MPI to reduce wait
Fast memory access	Move memory closer	Distribute multiple copies

Barrelfish: Backdrop

"Computer hardware is diversifying and changing faster than system

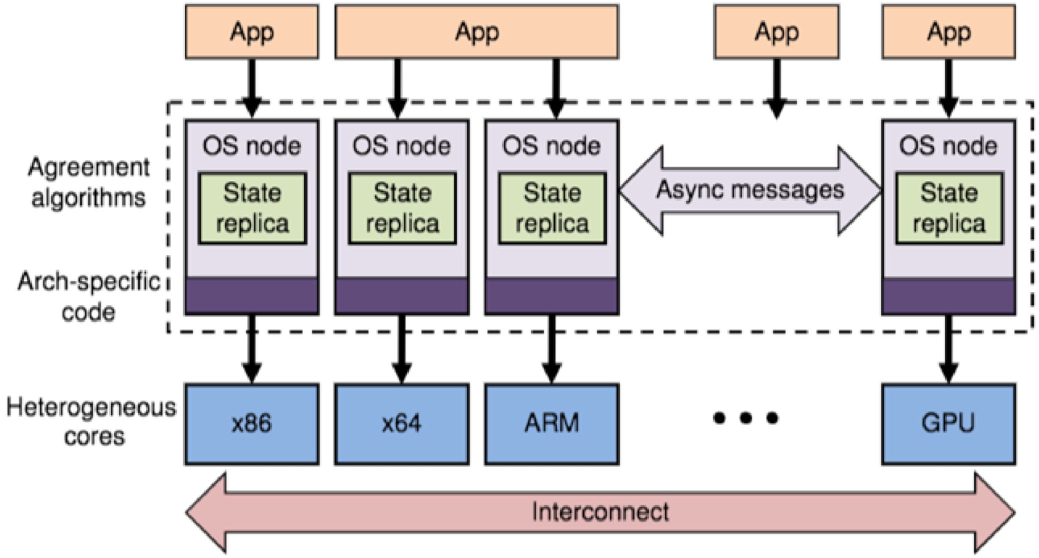


Figure 1: The multikernel model.

- 12 years later, still working with heterogeneous commodity systems
- Assertion: Sharing is bad; cloning is good.

About the Barrelfish Authors

- Andrew Baumann
  - Currently at Microsoft Research
  - Better resource sharing (COSH)
- Paul Barham
  - Currently at Google Research
  - Works on Tensorflow
- Pierre-Evariste Dagand
  - Formal verification systems
  - Domain specific languages
- Tim Harris
  - Microsoft Research → Oracle Research
  - “Xen and the art of virtualization” co-author

About the Barrelfish Authors

- Rebecca Isaacs
  - Microsoft Research → Google →Twitter
- Simon Peter
  - Assistant Professor, UT Austin
- Timothy Roscoe
  - Swiss Federal Institute of Technology in Zuri
- Adrian Schüpbach
  - Oracle Labs
- Akhilesh Singhania
  - Oracle

Barrelfish: Goals

- Design scalable **memory management**
- Design VM Hypervisor for **multicore** systems
- Handle **heterogenous** systems

Barrelfish: Goals → Implementation (Multikernel)

- **Memory Management:** State replication *instead of* sharing
- **Multicore:** Explicit inter-core communication
- **Heterogeneity:** Hardware Neutrality

Barrelfish: Implementation for Memory Management

- Monitors & CPU drivers
  - User-level code performs virtual memory management (end-to-end)
  - CPU driver checks only that operations are correct (end-to-end)
  - Capability copying & retyping (abstraction)
- Shared address spaces
  - Trade-off between replicated and shared hardware pages (Corey)
  - OS allowed to select spatio-temporal scheduling policy (end-to-end)

Barrelfish: Implementation for Multicore

- Cache-coherence costly, so supplement it with direct communication
- **Intercore** instead of **interprocess** communication
- Local shared cache-line

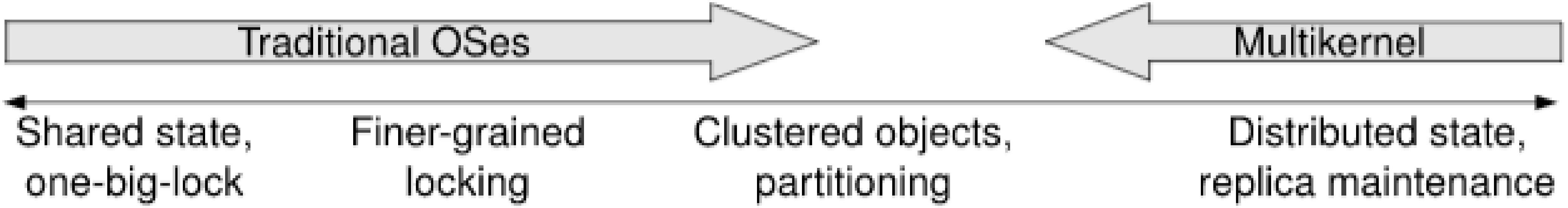


Figure 4: Spectrum of sharing and locking disciplines.

Barrelfish: Implementation for Heterogeneity

- Monitors
  - Single-core, user-space processes
  - Runs the agreement protocol that synchronizes system state
- CPU-driver
  - Authorization & process scheduling
  - Heavily customized for hardware/processors

Barrelfish: Implementation for Heterogeneity

- Knowledge and policy engine
  - System knowledge based used to map hardware to first-order logic
  - Good for creating cache/topology aware networks
- Experiences
  - CPU/monitor driver division → non-optimal performance, good engineering
  - Network stack insufficient

Barrelfish: Evaluation Goals

- **Memory management** operations
- **Overhead** of message-passing
- **CPU**-intensive operations
- **I/O** testing for async overhead

Barrelfish: Goals → Experiments

- **Memory management:** TLB shootdown
- **Overhead:** synchronous programs, polling & interrupts
- **CPU:** CPU-bound applications
- **I/O:** IP Loopback, Database, Web-server

Barrelfish: Evaluation for Memory Management

- **Task:** TLB shootdown
- **Difficulty:** Requires global coordination
- **Result:** NUMA-aware & plain multicast win

- **Question:**

  Is reliance on hardware knowledge problematic given the overhead of system discovery or hand-coding?

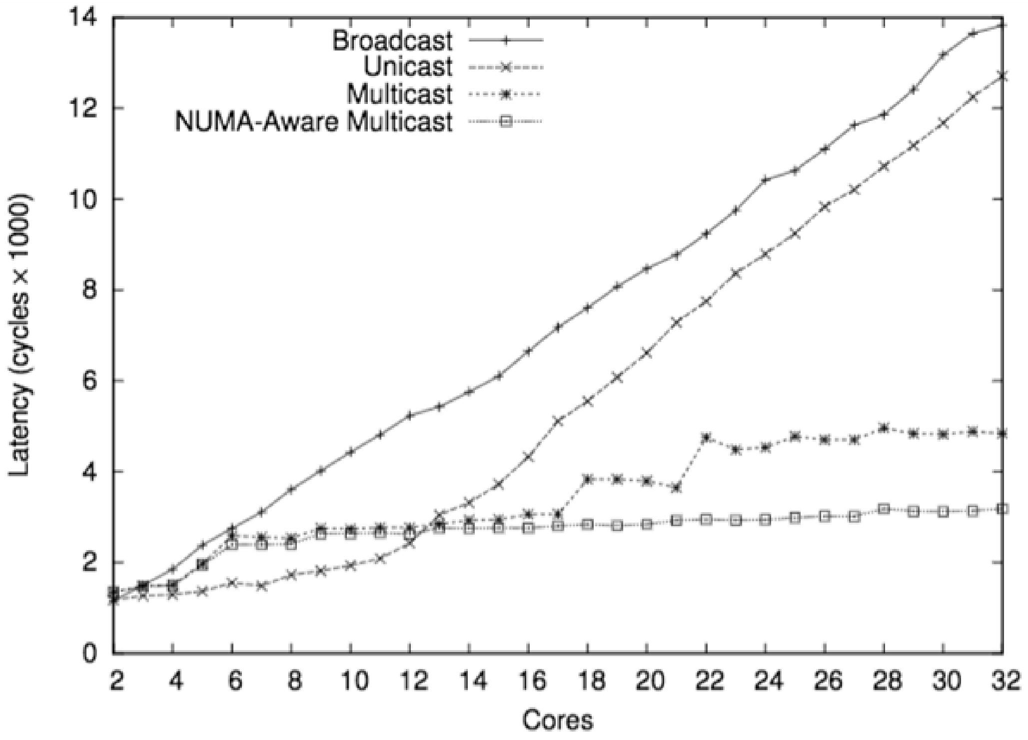


Figure 6: Comparison of TLB shootdown protocols

Barrelfish: Evaluation for Overhead

- **Task:** Two-phase commit, polling & interrupts
- **Difficulty:** Message-passing requires more polling and interrupts
- **Result:** Current hardware is good enough

$$overhead = \begin{cases} t & \text{if } t \leq P, \\ P + C & \text{otherwise.} \end{cases}$$

– and the latency of the message is:

$$latency = \begin{cases} 0 & \text{if } t \leq P, \\ C & \text{otherwise.} \end{cases}$$

- **Question:** TLB fills, costs. Fair?
- **Question:** How might these results change with hardware? And application?

Barrelfish: Evaluation for Overhead

- **Task:** IP Loopback Tests
- **Difficulty:** Reading/writing sockets on local computer
- **Results:** Barrelfish moderately outperforms Linux

	Barrelfish	Linux
Throughput (Mbit/s)	2154	1823
Dcache misses per packet	21	77
source → sink HT traffic* per packet	467	657
sink → source HT traffic* per packet	188	550
source → sink HT link utilization	8%	11%
sink → source HT link utilization	3%	9%

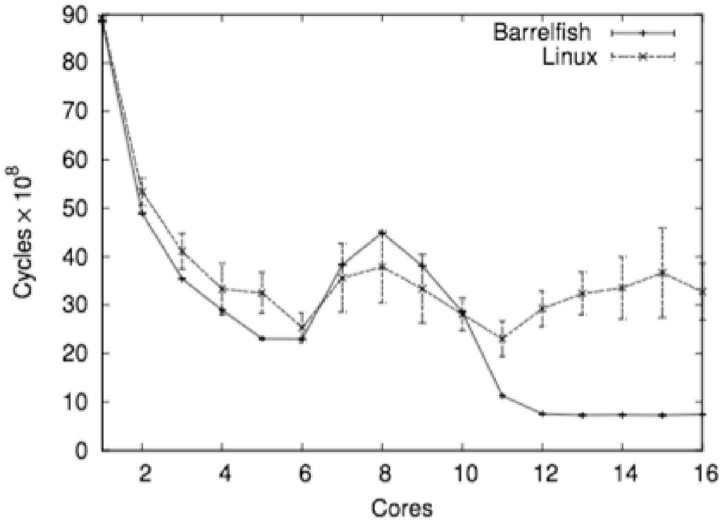
* HyperTransport traffic is measured in 32-bit dwords.

Table 4: IP loopback performance on 2×2-core AMD

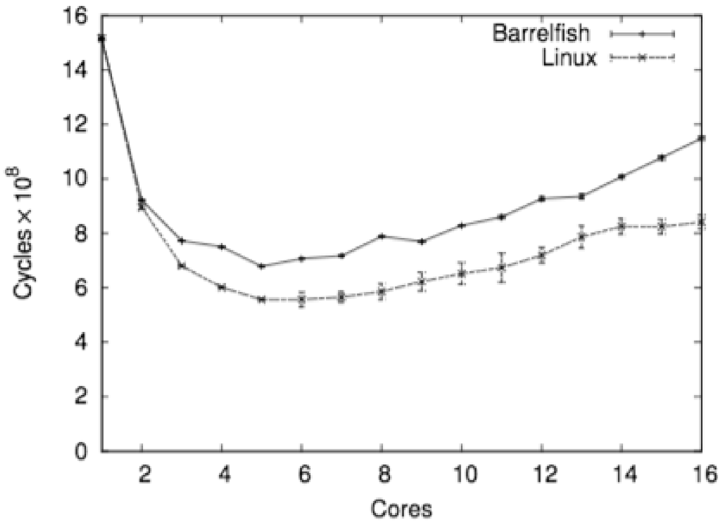
Barrelfish: Evaluation for CPU

- **Task:** Compute-bound (CPU heavy) workloads
- **Difficulty:** Large shared-address spaces, parallel code
- **Result:** Barrelfish not great, but comparable to Linux

- **Question:**
  Consistency > raw performance gains?



(a) OpenMP conjugate gradient (CG)



(c) OpenMP integer sort (IS)

Barrelfish: Evaluation for I/O

- **Task(s):** Web-server and relational database setup
- **Difficulty:** I/O traditional bottleneck
- **Approach:** Message-passing/distributed systems
- **Result:** Twice as many requests per second vs. lighttpd on Linux

- **Question:** Does load pattern matter for comparison?

- **Question:** Sufficient comparison for SQLite DB test?

Barrelfish: Summary

- Authors opinions
  - Building an operating from scratch is difficult
  - Barrelfish performs well given its relative underdevelopment
- Still actively developed
  - http://www.barrelfish.org/download.html
  - Not quite VMWare though!
- Message-passing elegant but perhaps not more efficient
- Interesting use of system discovery
- Evaluations
  - Very synthetic, no money-graph
  - Peppered with microbenchmarks, needs better macro-evaluation
  - TLB shootdown, I/O results better than compute-bound results

Barrelfish: Questions

- Is message-passing a viable alternative to a shared-data approach?
- What applications would this system be best for?
- Were the evaluations thorough and realistic enough?

Takeaways

- Efficient VM monitor software critical
  - Rapidly changing computer architectures → the-floor-is-lava
  - Commodity and personal computing have increasing numbers of cores and processors
- Improving VM performance possible if…
  - Resources are shared even more (Disco)
  - Resources are replicated and synced (Barrelfish)
- Best of Disco
  - Don't hide power: recognition of ccNUMA advantages
  - Get it right: Disco clearly beats out competitors
- Best of Barrelfish
  - Reuse good ideas: distributed systems for many-core computers
  - Abstraction: System discovery

Thank You!

References

Baumann, Andrew, Paul Barham, Pierre-Evariste Dagand, Tim Harris, Rebecca Isaacs, Simon Peter, Timothy Roscoe, Adrian Schüpbach, and Akhilesh Singhania. "The multikernel: a new OS architecture for scalable multicore systems." In *Proceedings of the ACM SIGOPS 22nd symposium on Operating systems principles*, pp. 29-44. ACM, 2009.

Borkar, Shekhar. "Thousand core chips: a technology perspective." In *Proceedings of the 44th annual Design Automation Conference*, pp. 746-749. ACM, 2007.

Boyd-Wickizer, Silas, Haibo Chen, Rong Chen, Yandong Mao, M. Frans Kaashoek, Robert Morris, Aleksey Pesterev et al. "Corey: An Operating System for Many Cores." In *OSDI*, vol. 8, pp. 43-57. 2008.

Bugnion, Edouard, Scott Devine, Kinshuk Govil, and Mendel Rosenblum. "Disco: Running commodity operating systems on scalable multiprocessors." *ACM Transactions on Computer Systems (TOCS)* 15, no. 4 (1997): 412-447.

Perspective

- Virtualization: creating a illusion of something
- Virtualization is a principle approach in system design
  - OS is virtualizing CPU, memory, I/O …
  - VMM is virtualizing the whole architecture
  - What else? What next?

Next Time

- Project: next step is the Survey Paper due next Friday
- MP1 Milestone #3 due Monday
- Read and write a review:
  - ***Required*: Shielding Applications from an Untrusted Cloud with Haven.** Andrew Baumann and Marcus Peinado and Galen Hunt. *In the 11th USENIX Symposium on Operating Systems Design and Implementation (OSDI)*. Broomfield, CO, October 2014, pp. 267—283.
  - ***Optional*: Logical Attestation: An Authorization Architecture For Trustworthy Computing.** Emin Gun Sirer, Willem de Bruijn, Patrick Reynolds, Alan Shieh, Kevin Walsh, Dan Williams, and Fred B. Schneider. *In Proceedings of the Symposium on Operating Systems Principles (SOSP)*, Cascais, Portugal, October 2011.