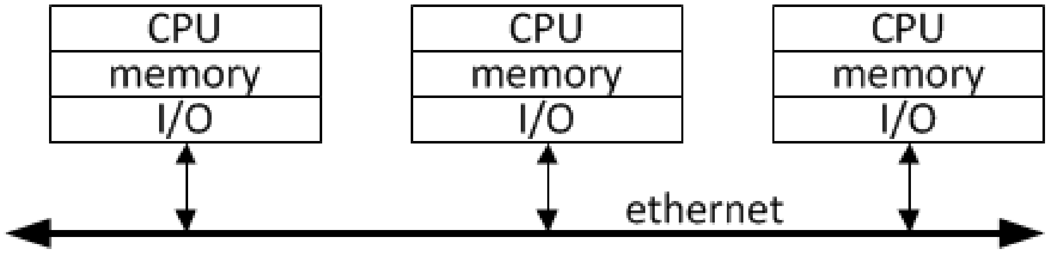
Multiprocessors

Loosely coupled [Multi-computer]



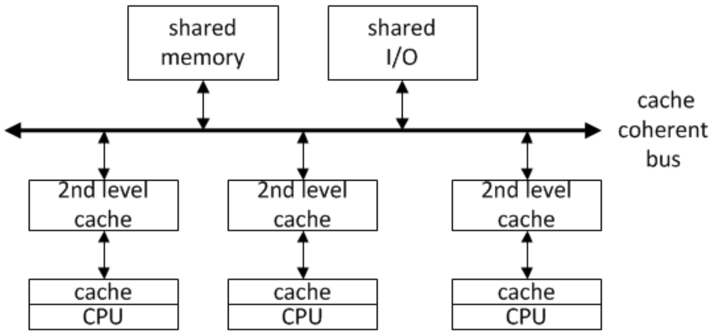
- each CPU has its own memory, I/O facilities and OS
- CPUs **DO NOT** share physical memory
- IITAC Cluster [in Lloyd building]

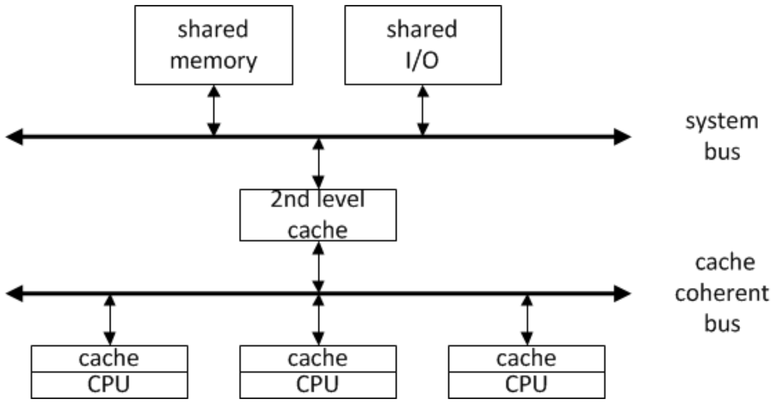
  346 x IBM e326 compute node each with 2 x 2.4GHz 64bit AMD Opteron 250 CPUs, 4GB RAM, …
  80GB SATA scratch disk, 2 x Broadcom BCM5704 Gbit Ethernet and PCI-X 10Gb InfiniBand connect
  2 x Voltaire 288 port InfiniBand switches + 512 port Gbit switch
  Debian [Linux]
  Theoretical peak performance 3.4TFlops [Linpac 2.7Tflops]
  ranked 345th most powerful supercomputer [in 2006]

- a distributed system, …

Multiprocessors

Tightly coupled [Multiprocessor]





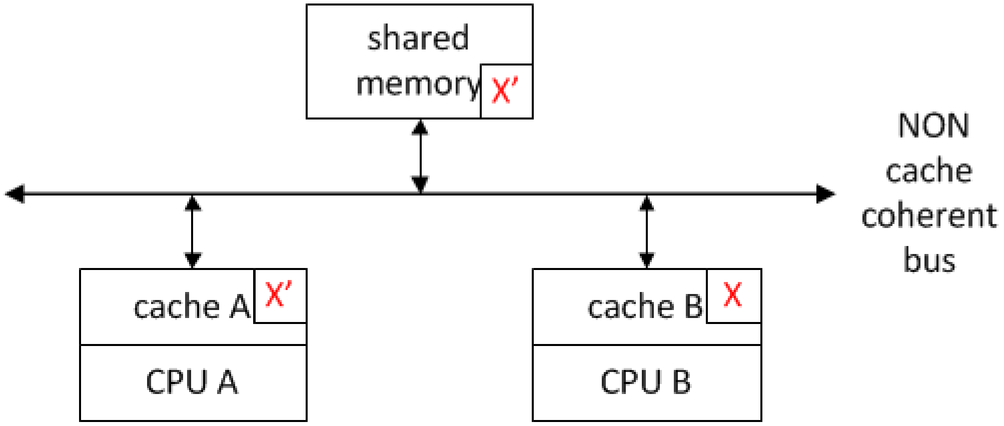
cache coherency can be handled by CPU

- CPUs physically share memory and I/O
- inter-processor communicate via shared memory
- symmetric multiprocessing possible [i.e. single shared copy of operating system]
- critical sections protected by locks/semaphores
- processes can easily migrate between CPUs

Multiprocessors

Multiprocessor Cache Coherency

- what's the problem? must guarantee that a CPU always reads the most up to date value of a *memory location*



1) CPU A reads location X, copy of X stored in cache A

2) CPU B reads location X, copy of X stored in cache B

3) CPU A writes to location X, X in cache and main memory updated [write-through]

4) CPU B reads X, BUT gets out of date [stale] copy from its cache B

Multiprocessors

Multiprocessor Cache Coherency…

- solutions based on *bus watching* or *snoopy* caches [yet again]
- *snoopy* caches watch all bus transactions and update their internal state according to a pre-determined cache coherency protocol
- cache coherency protocols given names eg. Dragon, **Firefly**, **MESI**, Berkeley, Illinois, **Write-Once** and **Write-Through** [will discuss protocols in bold]

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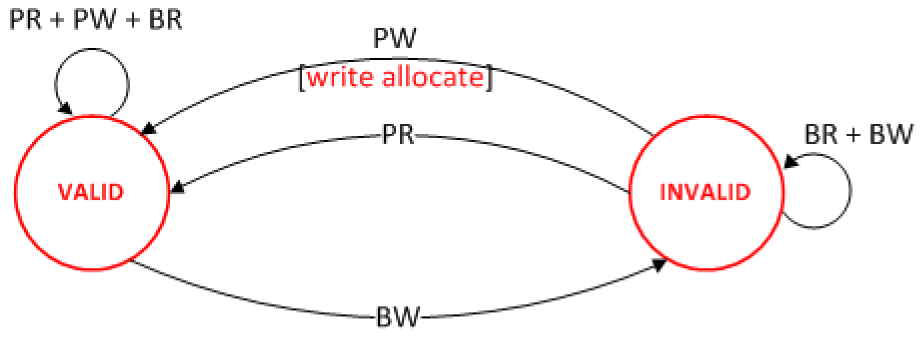
Write-Through Protocol

- key ideas
  - uses write-through caches
  - when a cache observes a bus write to a memory location it has a copy of, it simply invalidates the cache line [a write-invalidate protocol]
  - the next time the CPU accesses the same memory location/cache line, the data will be fetched from memory [hence getting the most up to date value]

Multiprocessors

Write-Through State Transition Diagram



PR	- processor read	BR	- observed bus read
PW	- processor write + write through	BW	- observed bus read

- each cache line is in either the VALID or INVALID state [if an address is not in the cache, it is captured by the INVALID state]
- PW ≡ processor write and write through to memory
- bus traffic ≈ Σ writes [writes ≈ 20% of memory accesses]
- straightforward to implement and effective for small scale parallelism [< 6 CPUs]

Multiprocessors

Write-Once Protocol

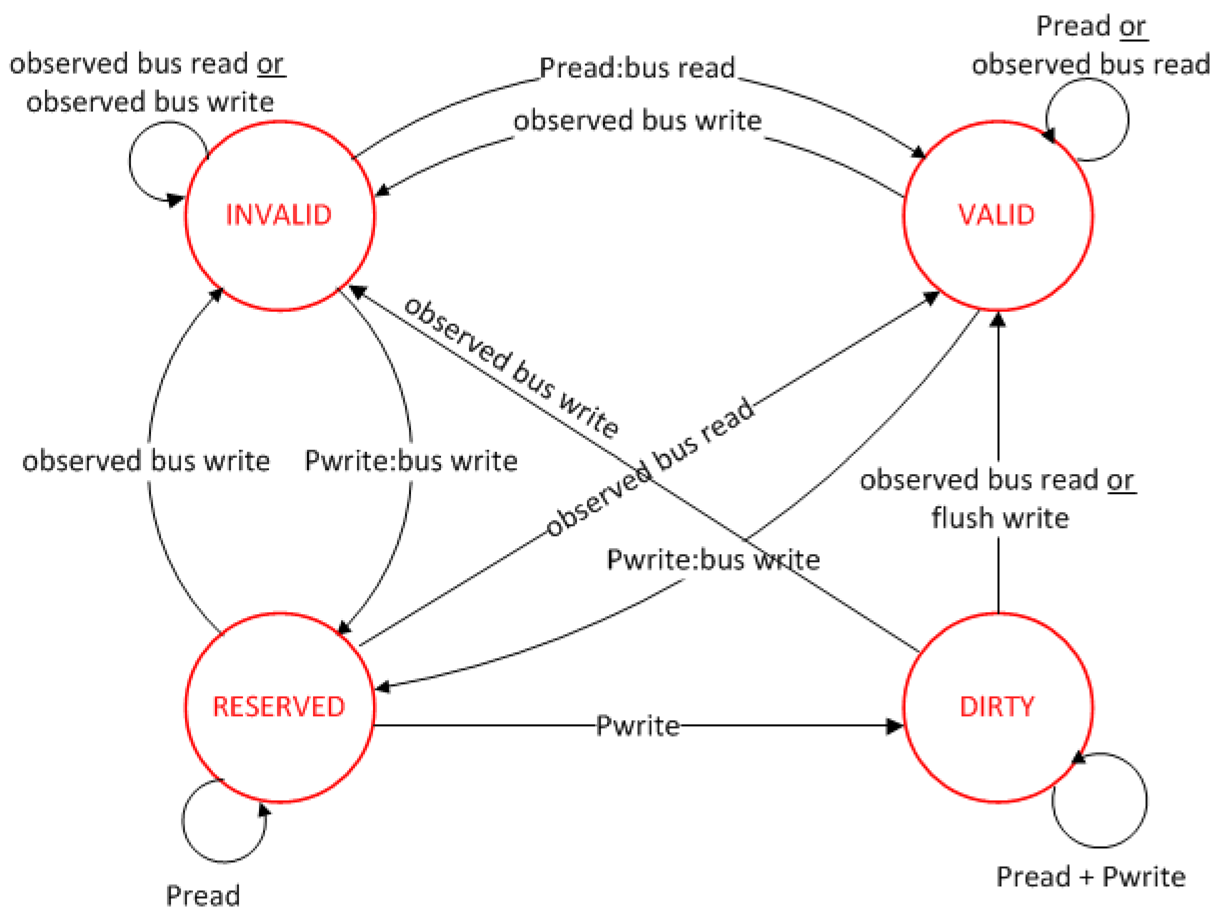
- uses write-back caches [to reduce bus traffic]

  BUT still uses a write-invalidate protocol

- each cache line can be in one of 4 states:

  - **INVALID**
  - **VALID**: cache line in <u>one or more</u> caches, cache copies $\equiv$ memory
  - **RESERVED**: cache line in one cache ONLY, cache copy $\equiv$ memory
  - **DIRTY**: cache line in one cache ONLY and it is the ONLY up to date copy [memory copy out of date / stale]

Write-Once State Transition Diagram



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Write-Once Protocol...

- key ideas
  - write-through to VALID cache lines
  - write back (local write) to RESERVED/DIRTY cache lines [as we know cache line in one cache ONLY]
- when a memory location is read initially, it enters the cache in the VALID state
- a cache line in the VALID state changes to the RESERVED state when written for the first time [hence the name write-once]
- a write which causes a transition to the RESERVED state is written through to memory so that all other caches can observe the transaction and invalidate their copies if present [cache line now in one cache ONLY]

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Write-Once Protocol...

- subsequent writes to a RESERVED cache line will use write-deferred cycles and the cache line marked as DIRTY as it is now the only up to date copy in the system [memory copy out of date]

- caches must monitor bus for any reads or writes to its RESERVED and DIRTY cache lines

  - if a cache observes a read from one of its RESERVED cache lines, it simply changes its state to VALID

  - if a cache observes a read from one of its DIRTY cache lines, the cache must intervene [intervention cycle] and supply the data onto the bus to the requesting cache, the data is <u>also</u> written to memory and the state of both cache lines are changed to VALID

  - NB: behaviour on an observed write [DIRTY => INVALID]

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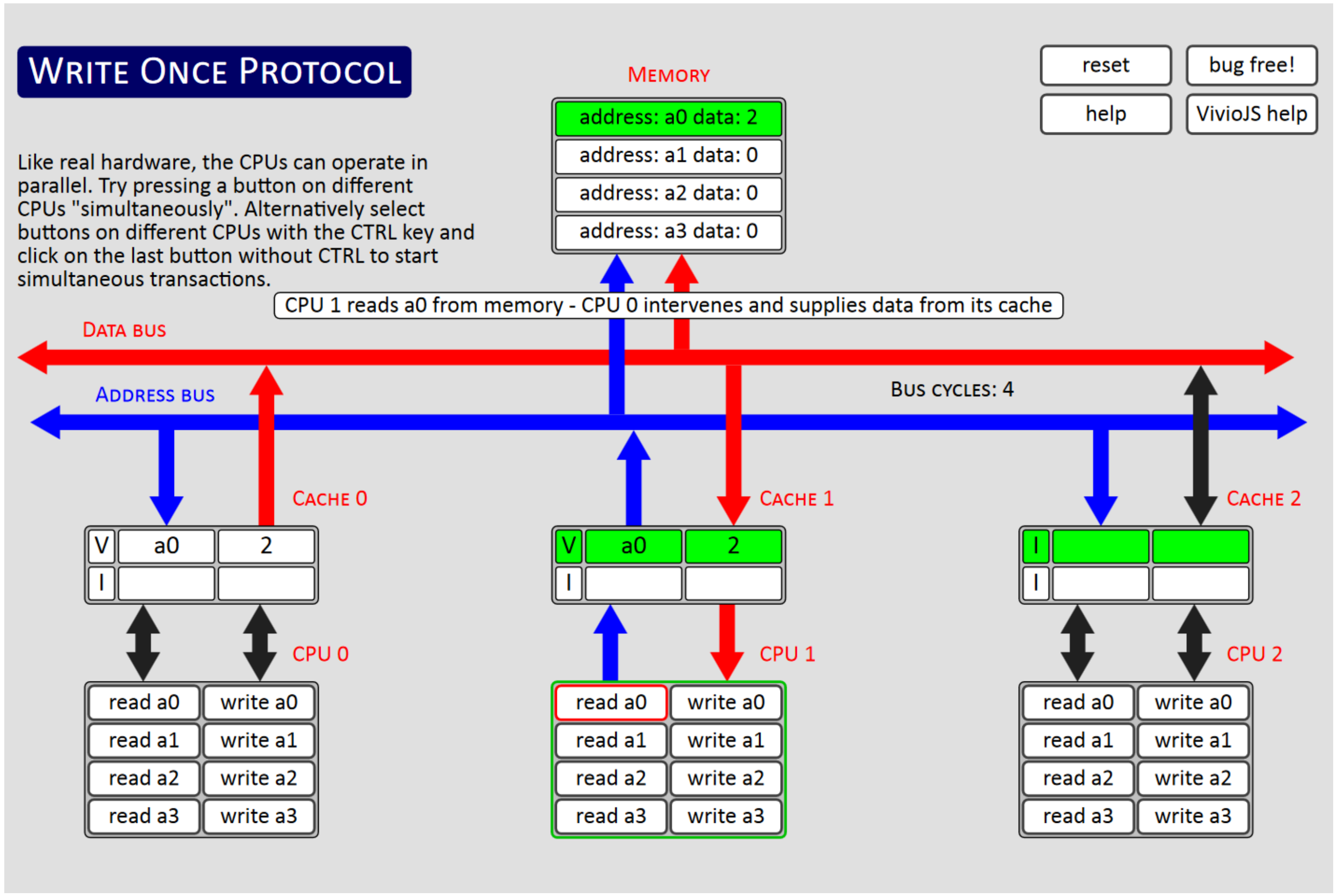
Write-Once Protocol...

- try the Vivio cache coherency animation



Like real hardware, the CPUs can operate in parallel. Try pressing a button on different CPUs "simultaneously". Alternatively select buttons on different CPUs with the CTRL key and click on the last button without CTRL to start simultaneous transactions.

CPU 1 reads a0 from memory - CPU 0 intervenes and supplies data from its cache

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Firefly Protocol

- used in the experimental Firefly DEC workstation

  DEC ≡ Digital Equipment Corporation

- each cache line can be in one of 4 states:
  - ~Shared & ~Dirty [Exclusive & Clean]
  - ~Shared & Dirty [Exclusive & Dirty]
  - Shared & ~Dirty [Shared & Clean]
  - Shared & Dirty [Shared & Dirty]
- NB: there is NO INVALID state

Multiprocessors

Firefly Protocol…

- key ideas
  - a cache knows if its cache lines are shared with other caches [may not actually be shared but that is OK]
  - when a cache line is read into the cache the other caches will assert a common SHARED bus line if they contain the same cache line
  - writes to exclusive cache line are write-deferred
  - writes to shared cache lines are write-through and the other caches which contain the same cache lines are updated together with memory [write-update protocol]
  - when a cache line ceases to be shared, it needs an extra write-through cycle to find out that the cache line is no longer shared [SHARED signal will not be asserted]
  - sharing may be illusory e.g. (i) processor may no longer be using a *shared* cache line (ii) process migration between CPUs [sharing with an old copy of itself]

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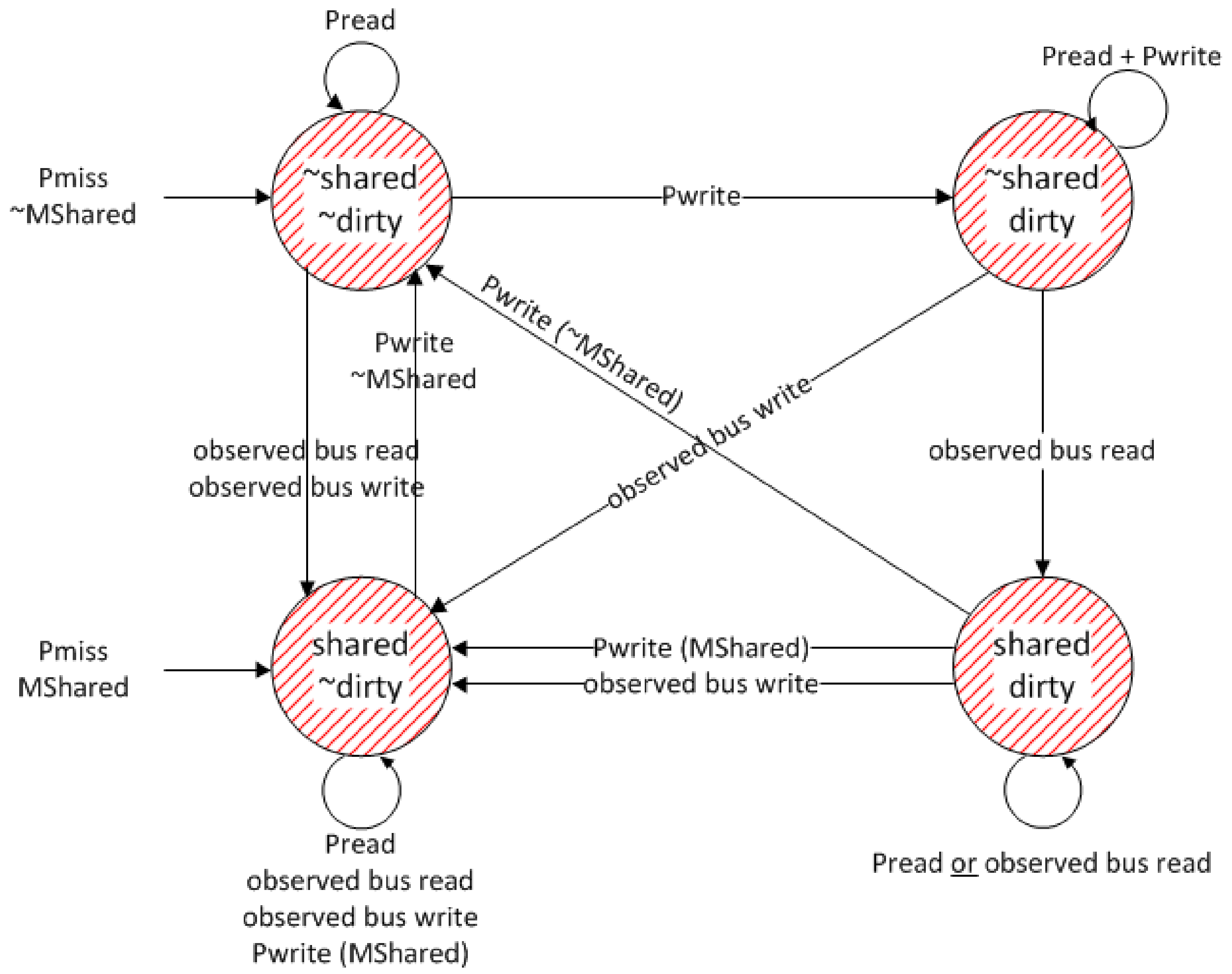
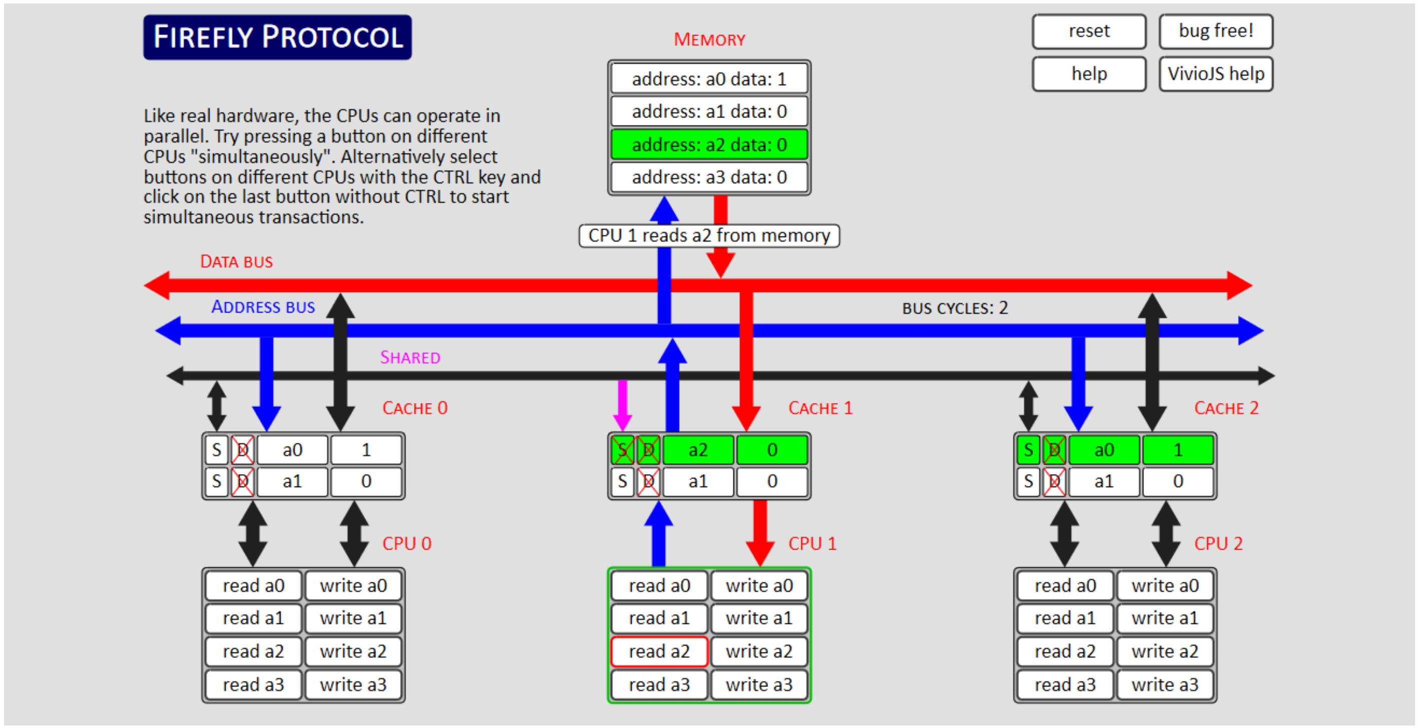
Firefly State Transition Diagram



Multiprocessors

Firefly Protocol...

- try the Vivio cache coherency animation



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Firefly Protocol…

- as there is NO INVALID state
  - at reset the cache is placed in a *miss* mode and a bootstrap program fills cache with a sequence of addresses making it consistent with memory [VALID state]
  - during normal operation a location can be displaced if the cache line is needed to satisfy a miss, BUT the protocol never needs to a invalidate cache line
- how is the Shared & Dirty state entered?
  - asymmetrical behaviour with regard to updating memory [avoids changing memory cycle from a read cycle to a write cycle mid cycle]
- try the vivio animation

Multiprocessors

MESI Cache Coherency Protocol

- used by Intel CPUs

- very similar to write-once, BUT uses a *shared* bus signal [like Firefly] so cache line can enter cache and be placed directly in the shared or exclusive state
- a write-invalidate protocol

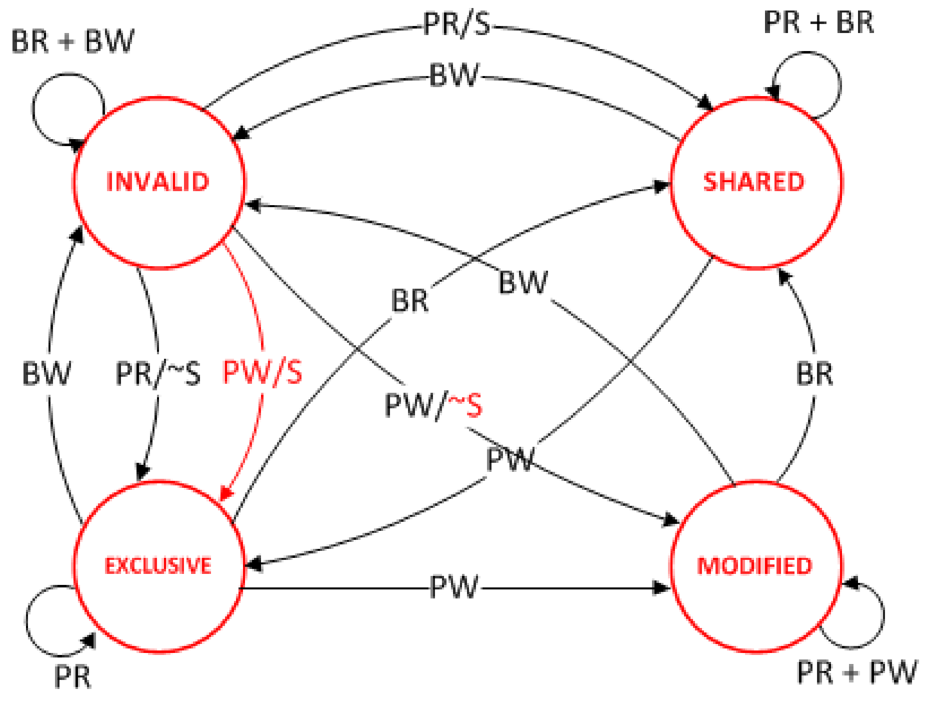
MESI states compared with Write-Once states

- Modified ≡ dirty
- Exclusive ≡ reserved
- Shared ≡ valid
- Invalid ≡ invalid

- what is the difference between the MESI and Write-Once protocols?
- cache line may enter cache and be placed directly in the Exclusive [reserved] state
- "write-once" write-through cycles no longer necessary if cache line is Exclusive
- try the Vivio animation

Multiprocessors

MESI State Transition Diagram

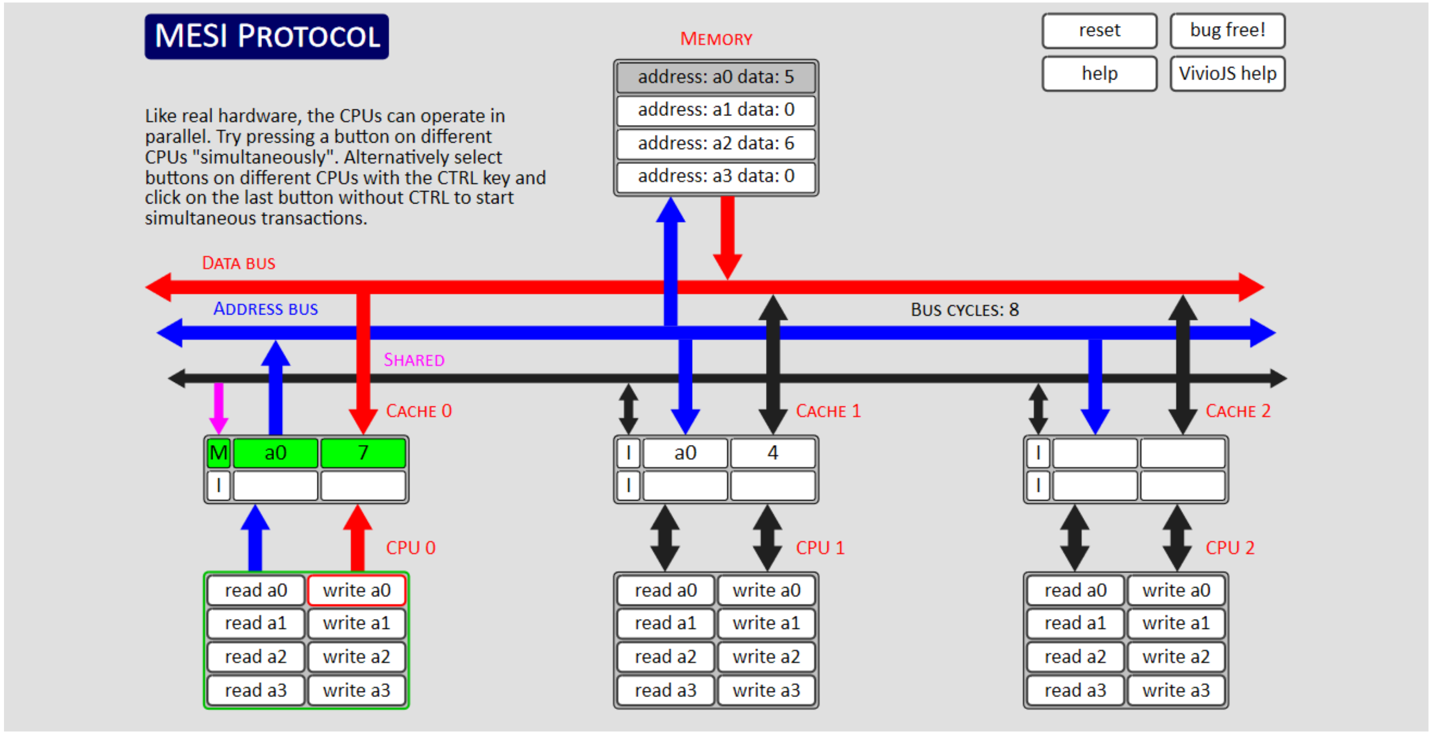


PR	= processor read	BR	= observed bus read
PW	= processor write	BW	= observed bus read
S/~S	= shared/NOT shared		

Multiprocessors

MESI Protocol…

- try the Vivio cache coherency animation



address: a0 data: 5
address: a1 data: 0
address: a2 data: 6
address: a3 data: 0

Like real hardware, the CPUs can operate in parallel. Try pressing a button on different CPUs "simultaneously". Alternatively select buttons on different CPUs with the CTRL key and click on the last button without CTRL to start simultaneous transactions.

Cache 0		
M	a0	7
I		

Cache 1		
I	a0	4
I		

Cache 2		
I		
I		

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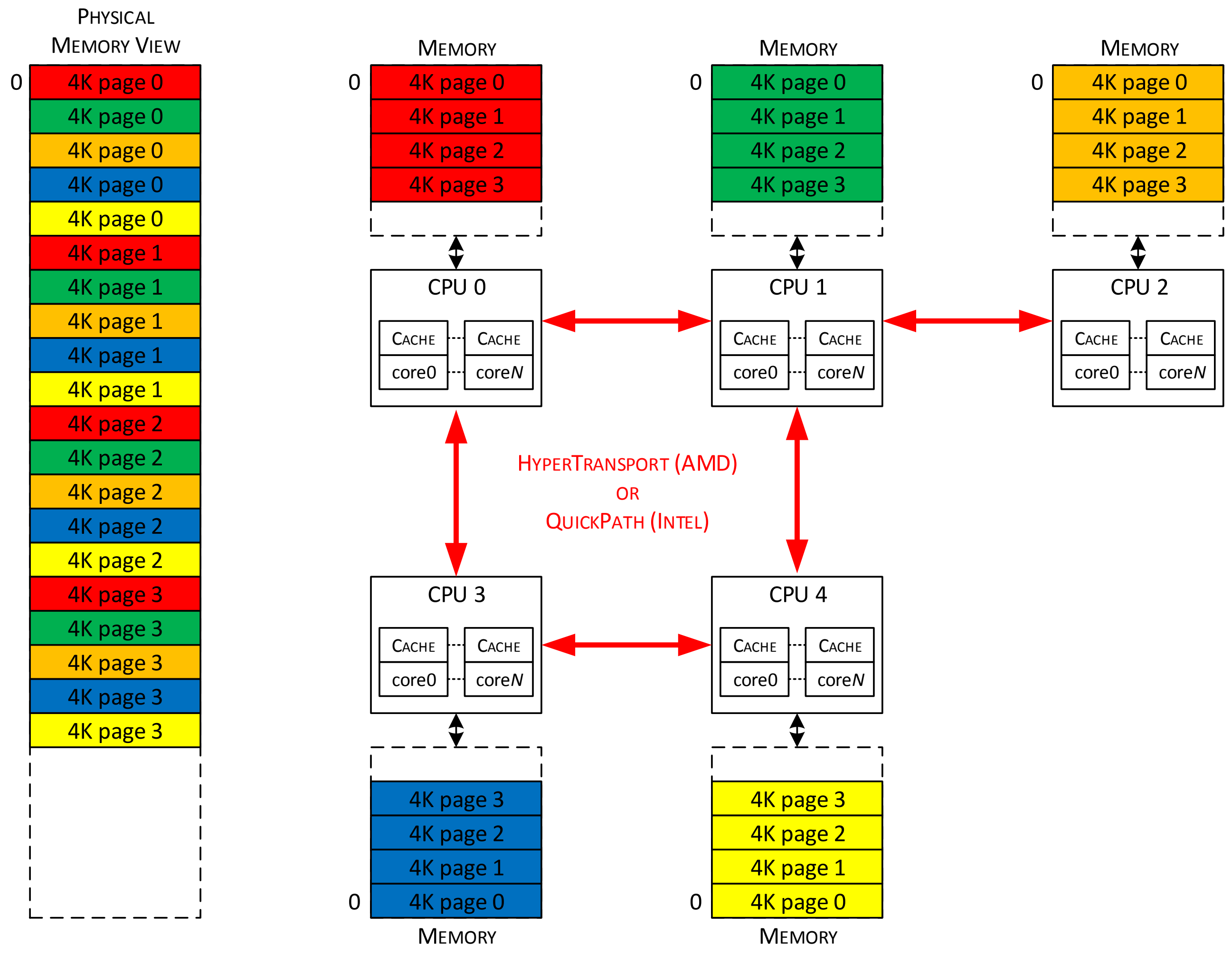
What's next?



Multiprocessors

What's next?...

- network of multiprocessors
- shared bus removed as it is a bottleneck
- physical memory interleaved between CPUs
- given a physical address, it is straightforward to determine to which CPU the memory is attached
- high speed point-to-point links between CPUs [Intel QuickPath and AMD HyperTransport]
- if a CPU accesses non local memory, request sent via high speed point-to-point links to correct CPU which accesses its local memory and returns the data
- System can be view as a large shared memory multiprocessor
- point-to-point protocol supports cache-coherency [Intel MESIF and AMD MOESI]

Multiprocessors

Summary

- you are now able to:
  - explain the cache coherency problem
  - describe the operation of the write-through, write-once, Firefly and MESI cache coherency protocols
  - predict the cache behaviour and bus traffic for a sequence of CPU "memory" accesses in a multiprocessor with a cache coherent bus
  - evaluate the cost updating shared data