Fast Non-Volatile Memories are Coming and We are Not Ready

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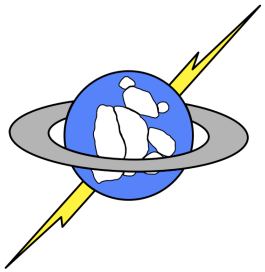

The Need for Fast Storage

- Humanity is generating data at an amazing rate
  - 5.6Exabytes in 2002
  - Estimated >> 45Exabytes in 2010
- Storage is not a problem
- Analysis is a problem
  - Unstructured data
  - Graph-based analyses
  - Interactive analysis

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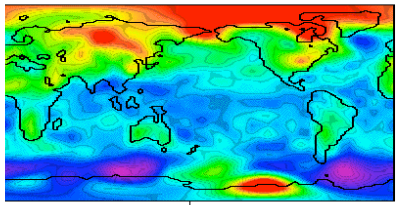
Save money. Live better.



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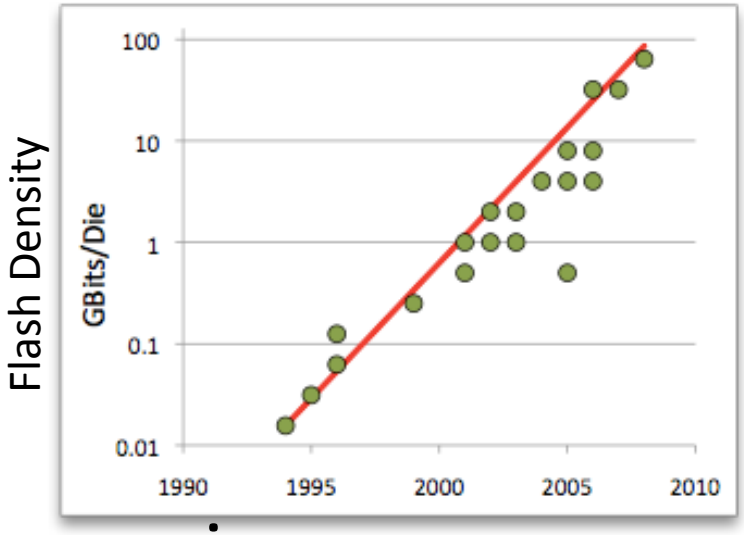
Non-volatile Memories

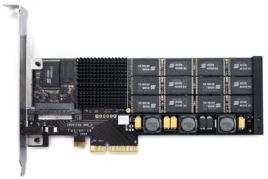
- NAND Flash is here!
  - Dense -> Cheap
  - Faster than disk (25-200us)
  - Reliability and scalability problems



- Storage class memories are coming
  - DRAM-like speed
  - Flash-like density
  - Phase change memory, spin torque transfer memory, the memristor, Race track memory

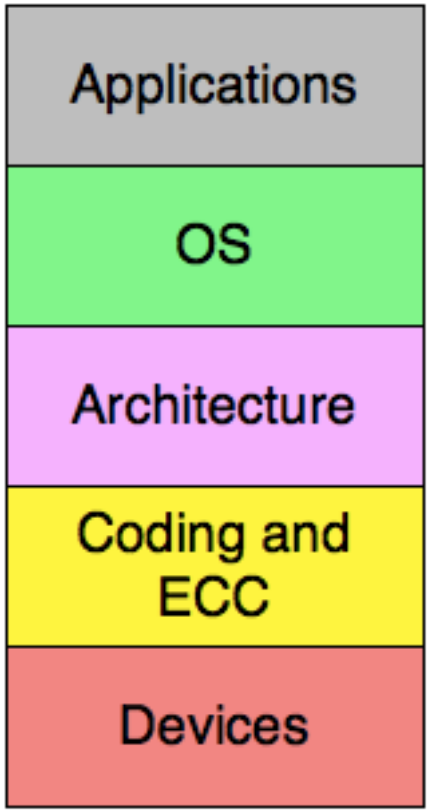
The Future of Storage

- Random 4KB Reads from user space

Hard Drives	PCIe-Flash 2007	PCIe-SCM 2013?	DDR-SCM 2016?	
				
Lat.: 7.1ms	68us	12us	6.5us	
BW: 2.6MB/s	250MB/s	1.3GB/s	6.5GB/s	
1x	104x	591x	1092x	= 2.2x/yr
1x	96x	500x	2600x	= 2.4x/yr

Hardware, OS, and Applications are unprepared

- Systems assume slow disk
  - IO stack and drivers are inefficient
  - IO interfaces (e.g., SATA) are slow.
- Large, unneeded, or unoptimized overheads
  - Misguided, disk-centric schedulers
  - Useless caching
- Avoid IO at all costs → enormous complexity
  - DB buffer managers
  - Sequential IO interfaces



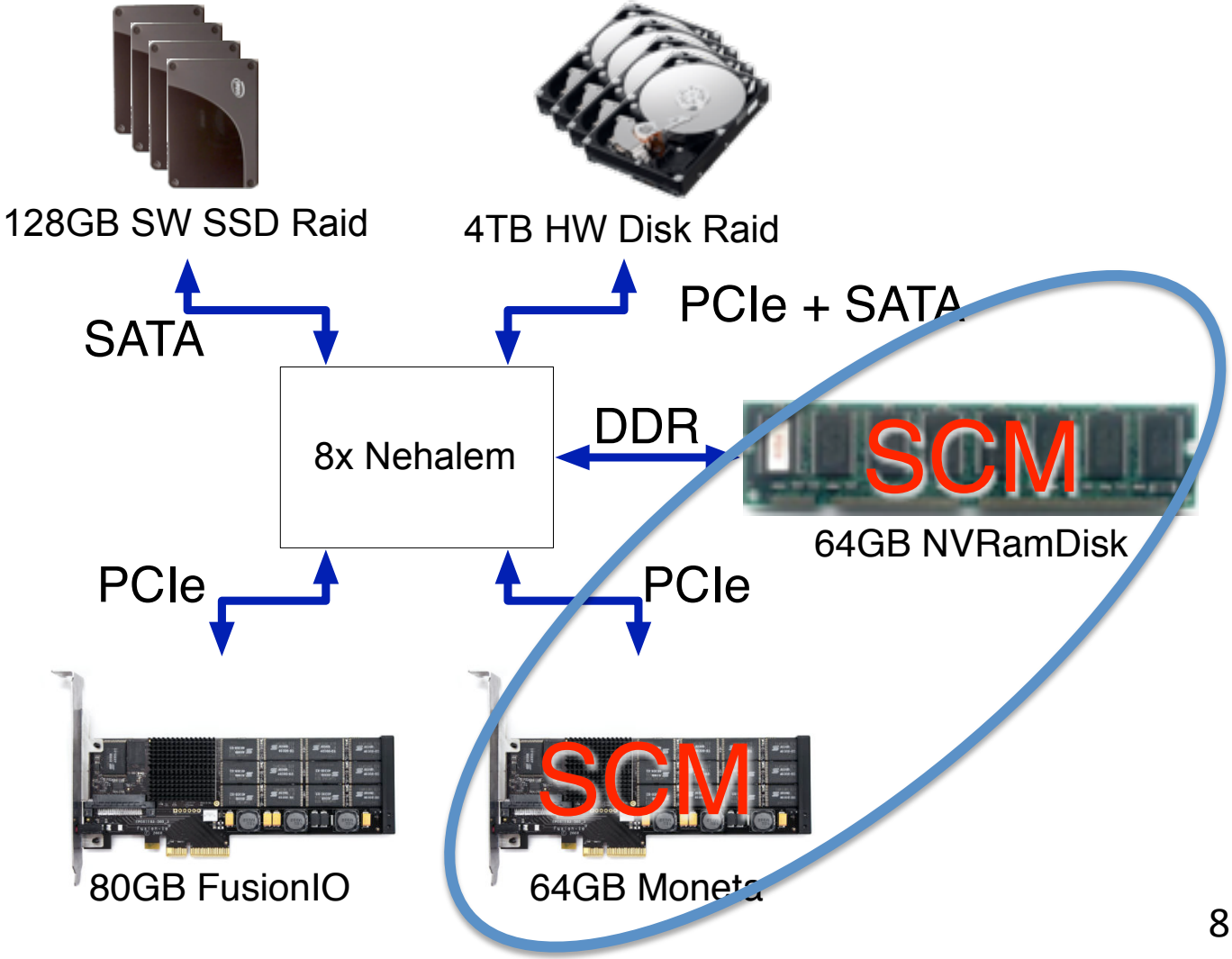
Today's Talk

Using the Moneta array to quantify the software problem

NV-heaps: Making the persistent objects safe and fast with SCM

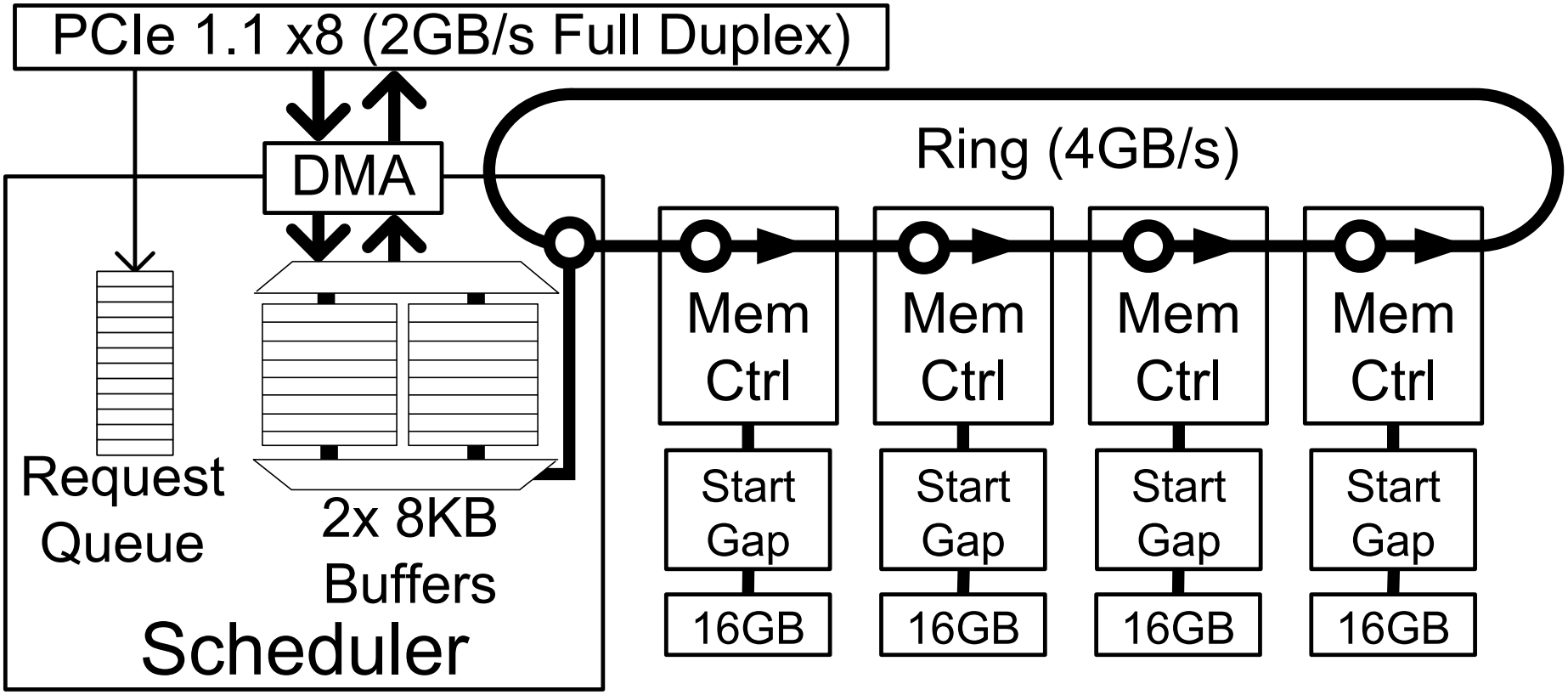
Can existing applications leverage the benefits of SCM?

Storage technologies under test



Moneta: PCIe-attached SCM

[To appear Micro 2010]



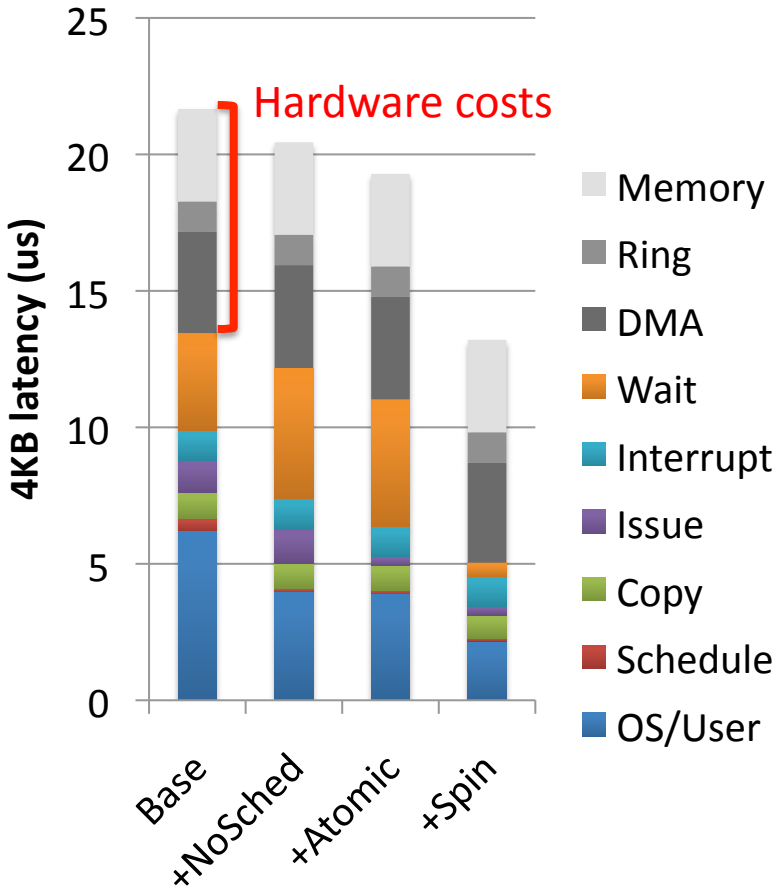
Built on the BEE3 FPGA prototyping platform

Emulating fast NV memories in Moneta

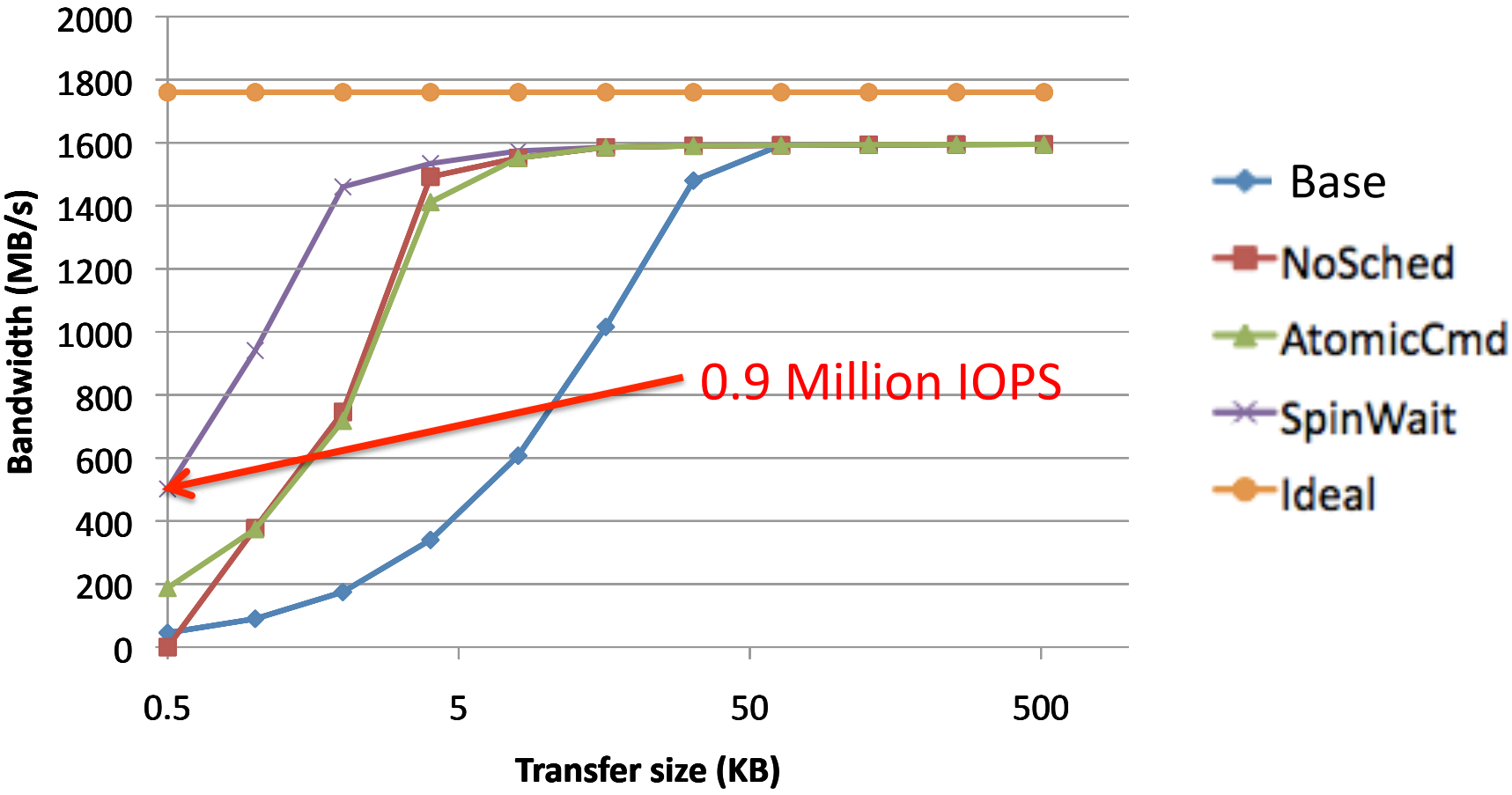
- Adjust DDR timings to match SCM projections
  - RAS-CAS Delay – read from the array
  - Post-write delay -- write to the array
  - Variable from DRAM times to microseconds.
- Wear-leveling – "Start-gap" [micro 2009]
- All the data here are for PCM
  - 67ns read
  - 215ns write

The Moneta software stack

- Optimizations
  - Baseline
  - No scheduler
  - Atomic command issue
  - Spin wait for completion
- Removed 2/3 of SW latency
- Removed all locks
- What remains?
  - Interrupt processing
  - Entering/leaving the kernel



The Moneta software stack



Emulating a NVRamDisk

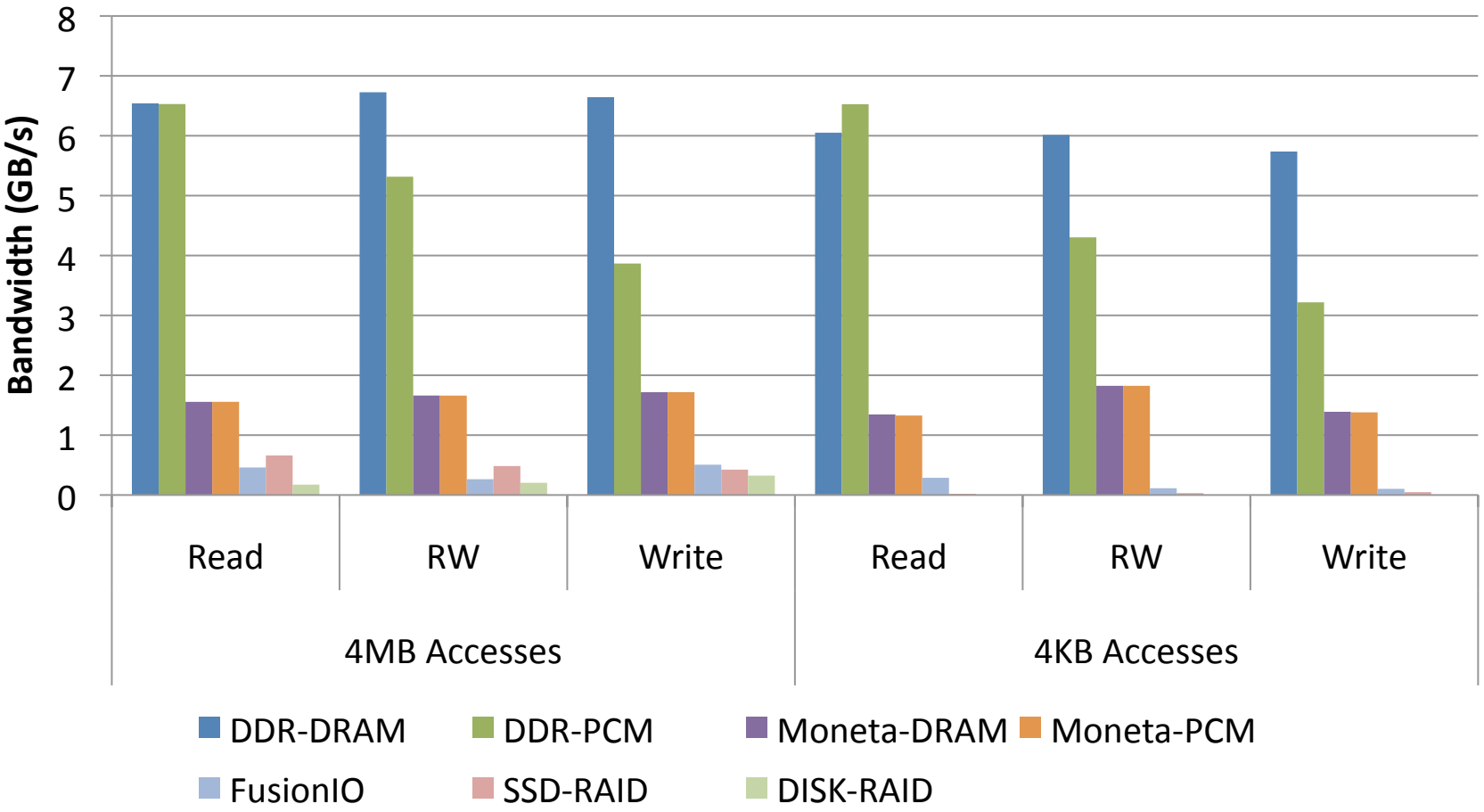
- NVRamDisk is an DDR3-attached array of SCM
- Modified Linux RamDisk Driver
  - Insert delays to model latency impact of SCM
  - By default, the driver is similar to spirit to the Moneta driver.

64GB NVRamDisk

Applications

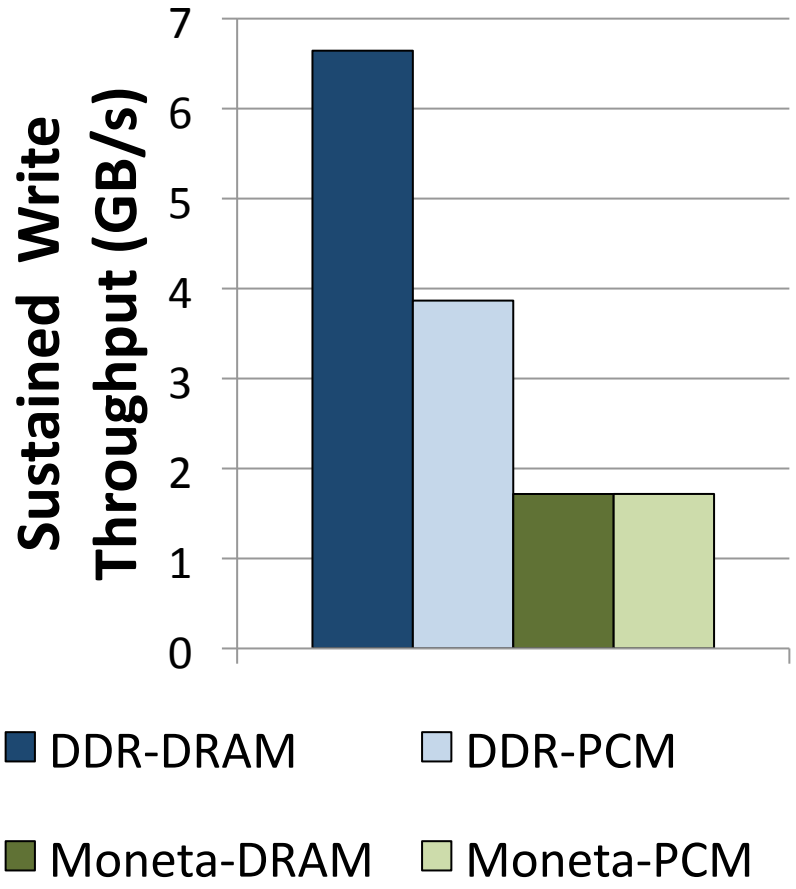
Name	Footprint	Description
Basic IO		
Raw IO	64 GB	Read, Write, read + write
File IO	64 GB	Read, Write, read + write
Database Applications		
Berkeley-DB Btree	16 GB	Transactional updates to btree key/value store
Berkeley-DB HashTable	16 GB	Transactional updates to hash table key/value store
BiologicalNetworks	35 GB	Biological database queried for properties of genes and biological-networks
PTF	50 GB	Palomar Transient Factory sky survey queries
Memory-hungry Applications		
DGEMM	21 GB	Matrix multiply with 30,000 x 30,000 matrices
NAS Parallel Benchmarks	8-35 GB	7 apps from NPB suite modeling scientific workloads

Raw Bandwidth

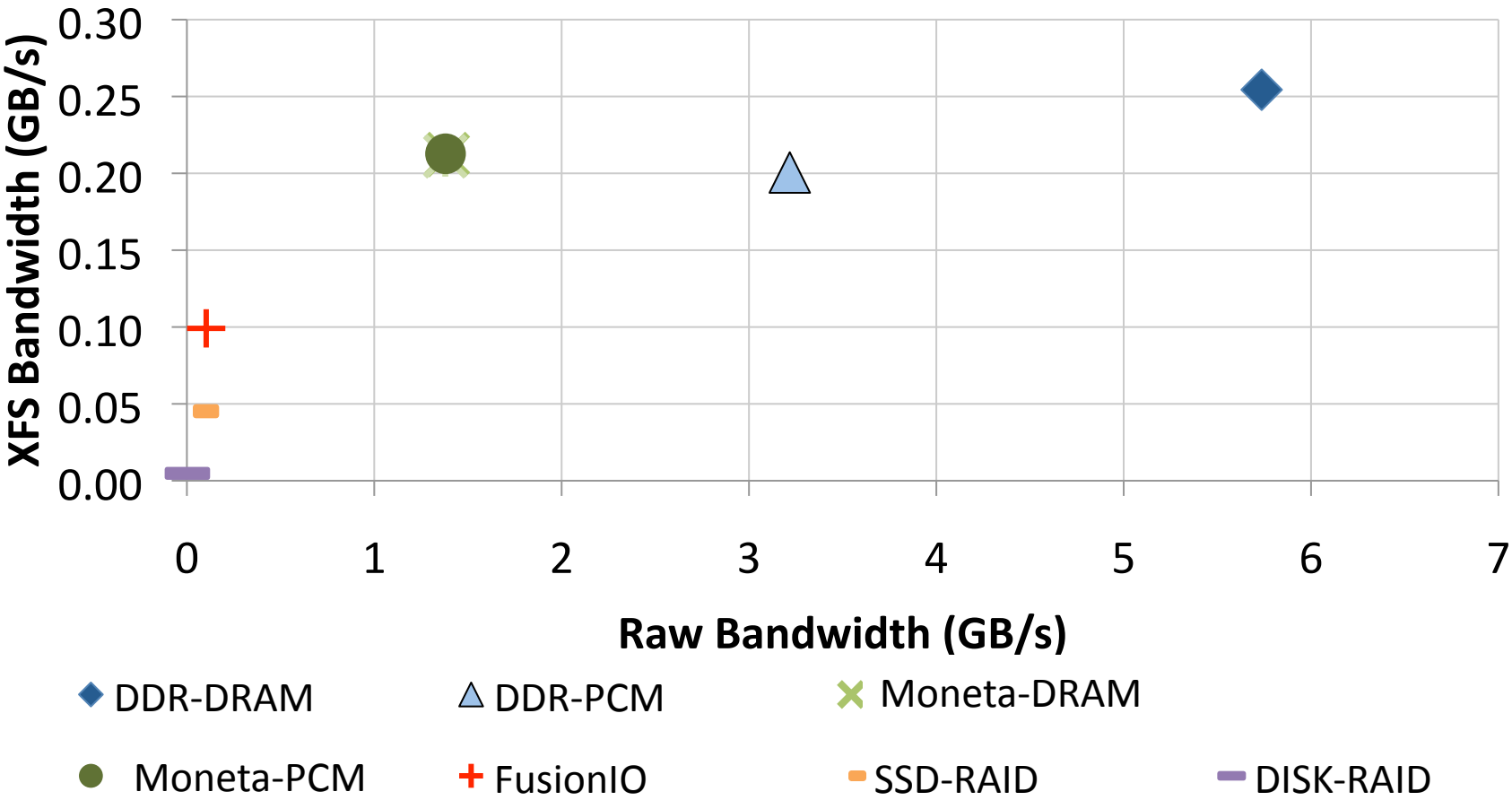


Latency Hiding

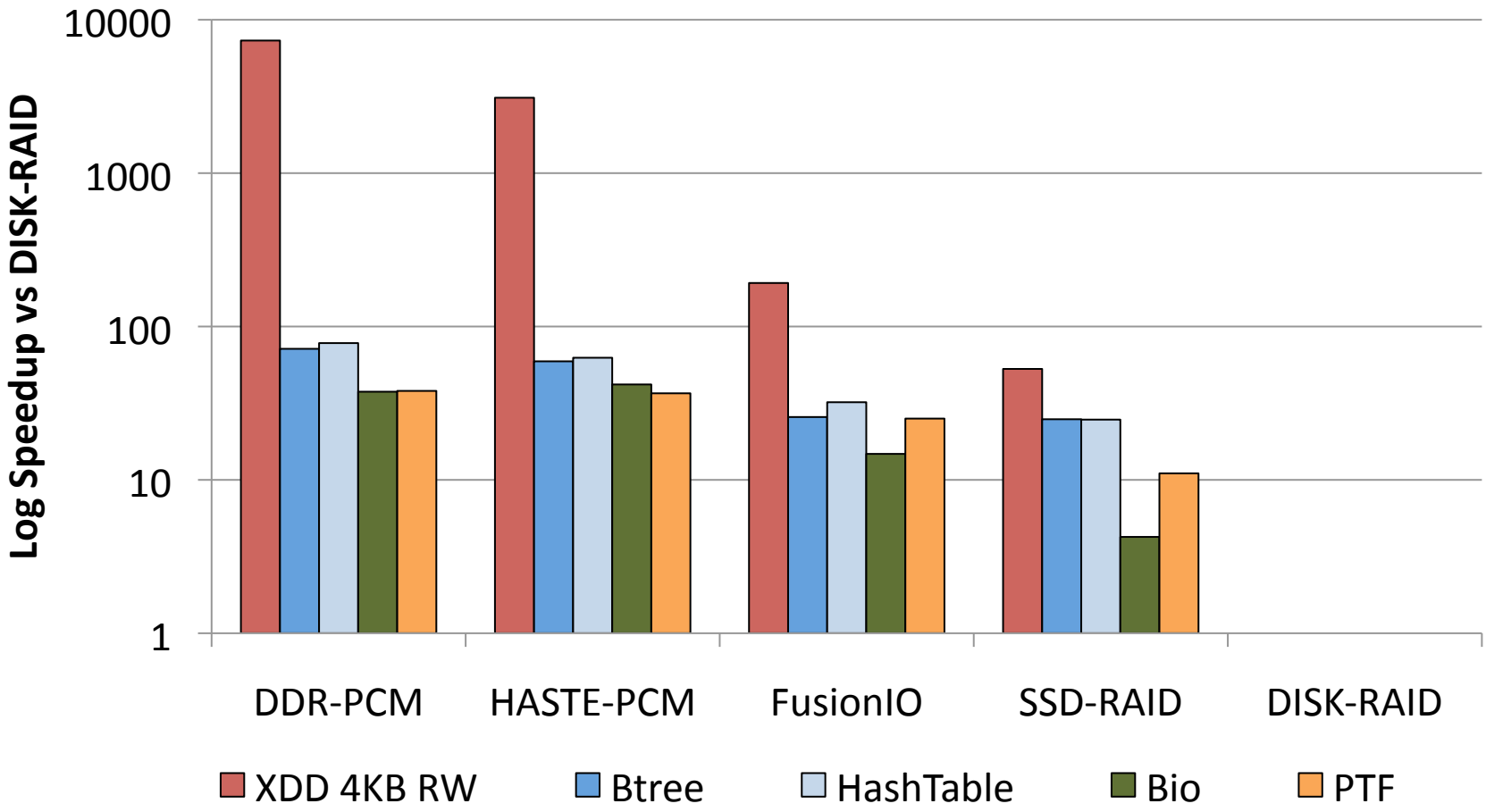
- Latency impacts DDR more
  - 64 byte requests
  - 128 for an 8KB transfer
  - Fine-grain bus contention
- Moneta hides latency well
  - 8KB requests
  - 1 for an 8KB transfer
  - Bus contention occurs once.



File System Performance



Database Performance



SCMs will make fast IO a software problem

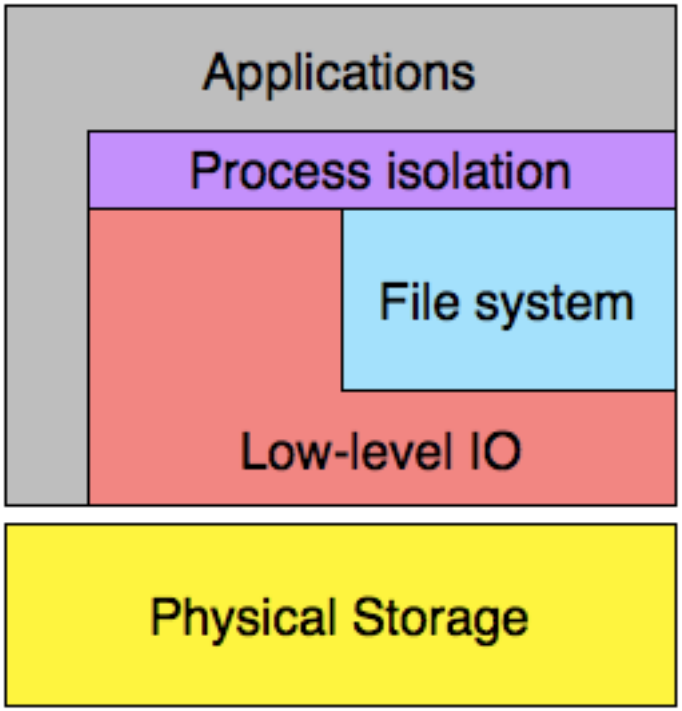
- Optimizing the driver helps a great deal, but costs remain
  - Entering the kernel
  - Interrupt processing
- The file systems destroys SCM performance
- End-to-end application benefits are small
- Research problems abound!!!

Today's Talk

The Moneta array and quantifying the software problem

NV-heaps: Making the persistent objects safe and fast with SCM

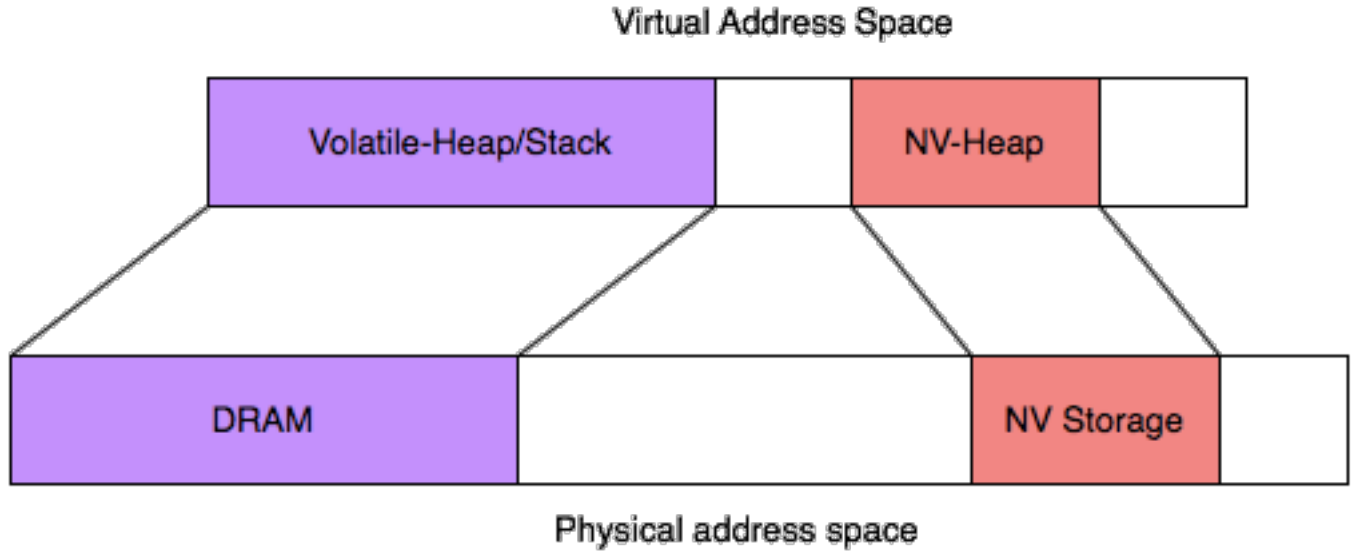
SCM is a *memory.* Why should we treat it like disk?



Expose SCM memory like DRAM and give programmers the tools to use it like DRAM.

Exposing NVM Raw Storage

- Byte-addressable NV memories allow for direct access via load/store instructions.
- Access it with loads and stores.



Two Classes of Persistent Object Systems

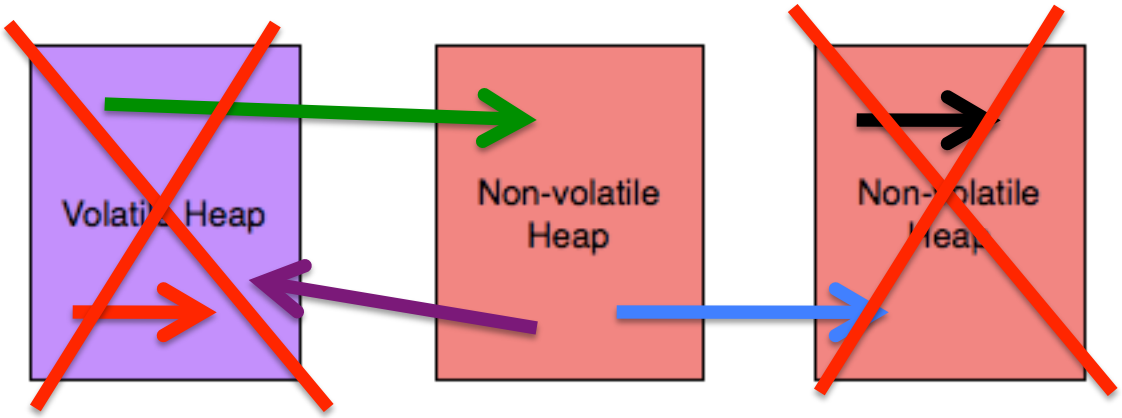
- Assume slow storage but provide strong safety guarantees
  - Database frontends – Java Persistence, C# LINQ
  - Object-oriented databases (Thor, Objectstore, Texas, Quickstore)
  - Single-level stores (as400, Opal, etc.)
  - Orthogonally persistent Java
- Assume fast storage and leave everything up to the programmer
  - Rio Vista (battery backed DRAM)
  - Recoverable Virtual memory (RVM)

The Dangers of NV Memory

- All existing programming errors are still possible
  - Memory leaks
  - Multiple-frees
  - Locking errors
- Rebooting/restarting won't help.
- Average programmers cannot get this stuff right
- System support can make it easier
  - Garbage collection
  - Transactions

New Kinds of Bugs

- Multiple heaps means 5 types of pointers
  - V-to-V – Normal pointers
  - V-to-NV – Useful
  - NV-to-V – inherently unsafe
  - Inter-heap NV-to-NV – Inherently unsafe
  - Intra-heap NV-to-NV – Necessary



Existing Primitives are Error Prone

```
Insert(Object * a, List<Object> * l)
{
...
}
```

- Is `a` volatile? Is `L`? Are they in the same heap?
- One wrong call causes permanent corruption

Memory Management, Locking, and Persistent Objects

- Non-GC Memory management and locking disciplines are well-known sources of errors
- Both rely on a program-wide invariant that is…
  - Not specified in the source
  - Not enforced by the system.
- The NV pointer safety relies on a similar invariant.
- Programmers will get it wrong

Getting it Right: BPFS

- BPFS [Condit et. al. 2009]
  - Transactional file system for byte-addressable NV memory

A useful persistent object system for SCMs must be both fast *and* safe.

- Well worth the effort – write once, use many times
- 3 PhDs/persistent data structure does not scale.

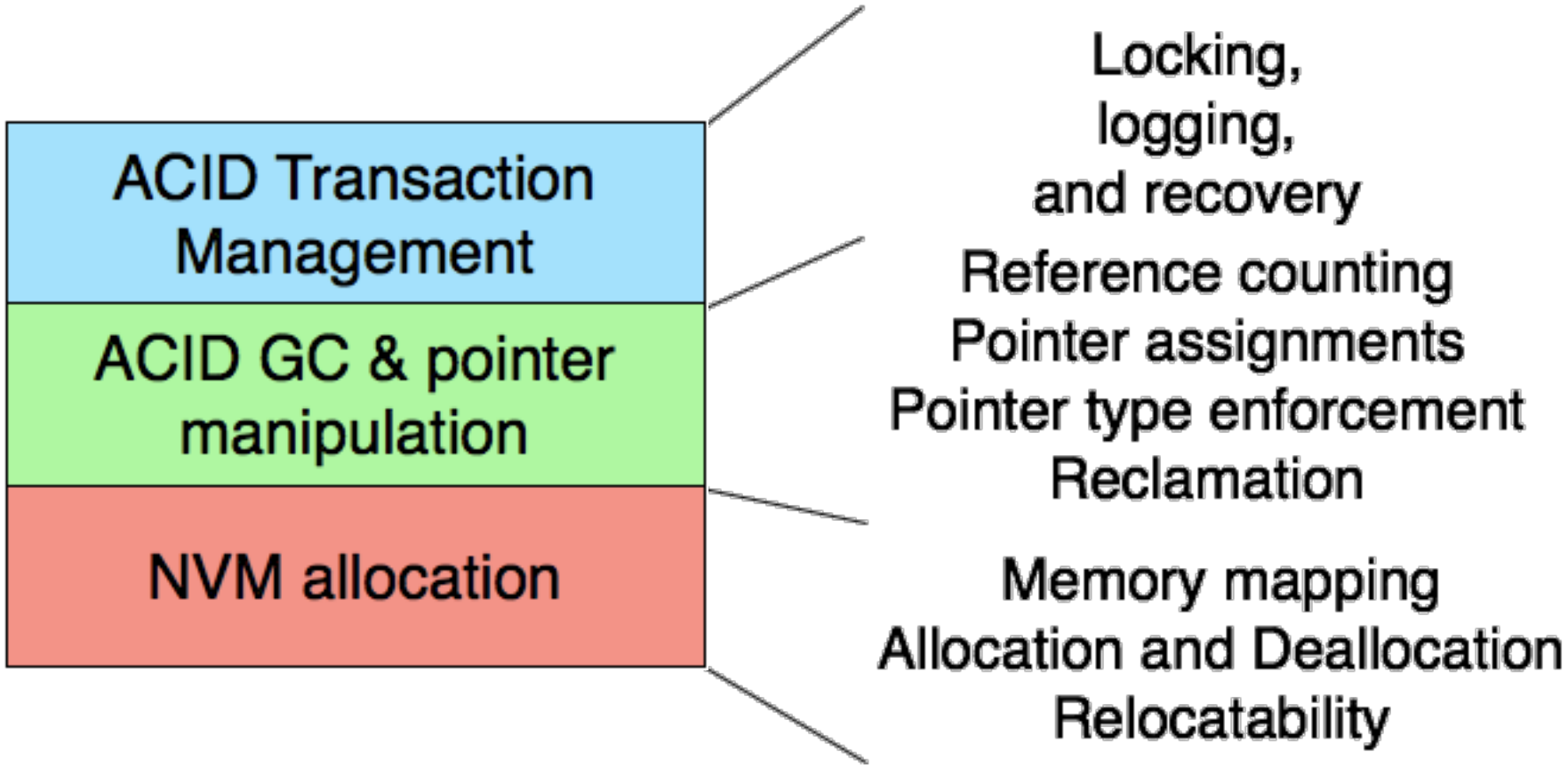
NV-heaps: Safe Persistent Objects

- Safety First
  - Garbage collection
  - Transactions
  - Pointer safety
- Expose raw SCM performance.
- Scalability
  - Volatile storage requirement is constant and small.
  - Operations are O(touched data) not O(storage size)
- Easy to use
  - All of the above
  - Leverage existing file systems and tools.
  - Intuitive separation between V and NV data.

```
class NVList : public NVObject {
  DECLARE_POINTER_TYPES(NVList);
public:
  DECLARE_MEMBER(int, value);
  DECLARE_PTR_MEMBER(NVList::NVPtr, next);
};

void remove(int k)
{
  NVHeap * nv = NVHOpen("foo.nvheap");
  NVList::VPtr a =
            nv->GetRoot<NVList::NVPtr>();
  AtomicBegin {
    while(a->get_next() != NULL) {
      if (a->get_next()->get_value() == k) {
        a->set_next(a->get_next()->get_next());
      }
      a = a->get_next();
    }
  } AtomicEnd;
}
```

Implementing NV-heaps



The NV-heap Allocator

- Raw allocation and de-allocation
  - Per-thread free lists
  - Fixed-sized, write-ahead logging for durability.
  - Assignment is part of allocation
  - Epoch barriers for consistency [Condit et. al.,2009]
- Mapping
  - “Execute in place” support in Linux
  - Relative pointers for relocation

Garbage Collection and Pointer Safety

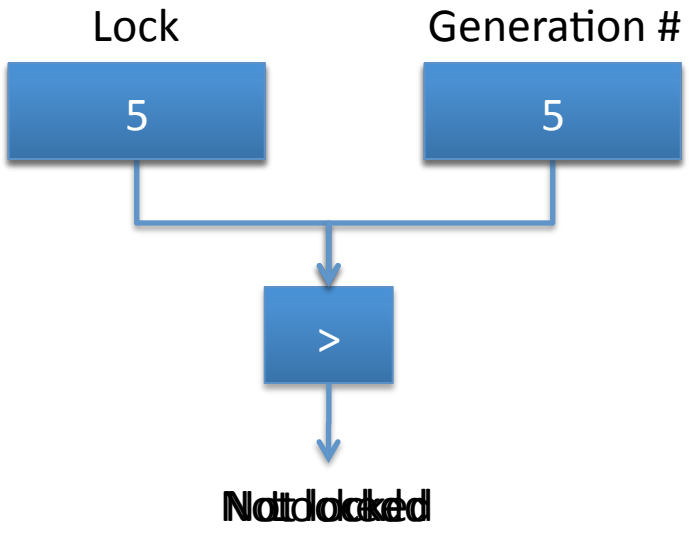
- Reference-counting GC
  - Per-object locks protect reference counts
  - Weak references for cycles
- Dynamic type system prevents dangerous NV pointers.
  - Wide pointers allow run-time checks on assignments
  - A static type systems is also possible.

Scalable locking for NV-heaps

- NV-heaps require per-object locks
- Volatile locks don't scale
  - V storage rises with NV-heap size.
- Simple non-volatile locks don't scale
  - On recovery, all locks need to be released
  - Recovery time scales with NV-heap size

Generational NV Locks

- Every NV-heap has a generation number
- A generational lock is an integer
  - If the integer > generation #, the lock is held
  - Atomic incr/decr acquires/releases
- Opening an NV-heap increments the generation number, freeing all the locks.



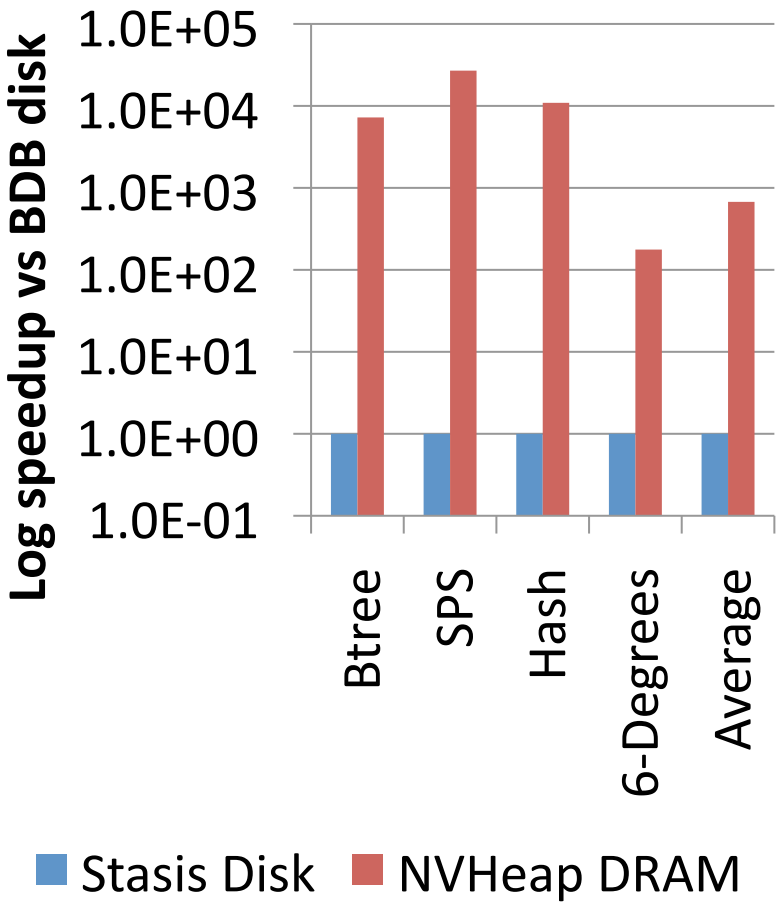
General, ACID Transactions

- Software transactional memory system
  - Object-based undo logging
  - Eager conflict detection with locks and version numbers
  - Flattens nested transactions.
- Logging
  - Per-thread NV write logs and V read logs
  - Using GC objects and pointers.

Evaluation Methodology

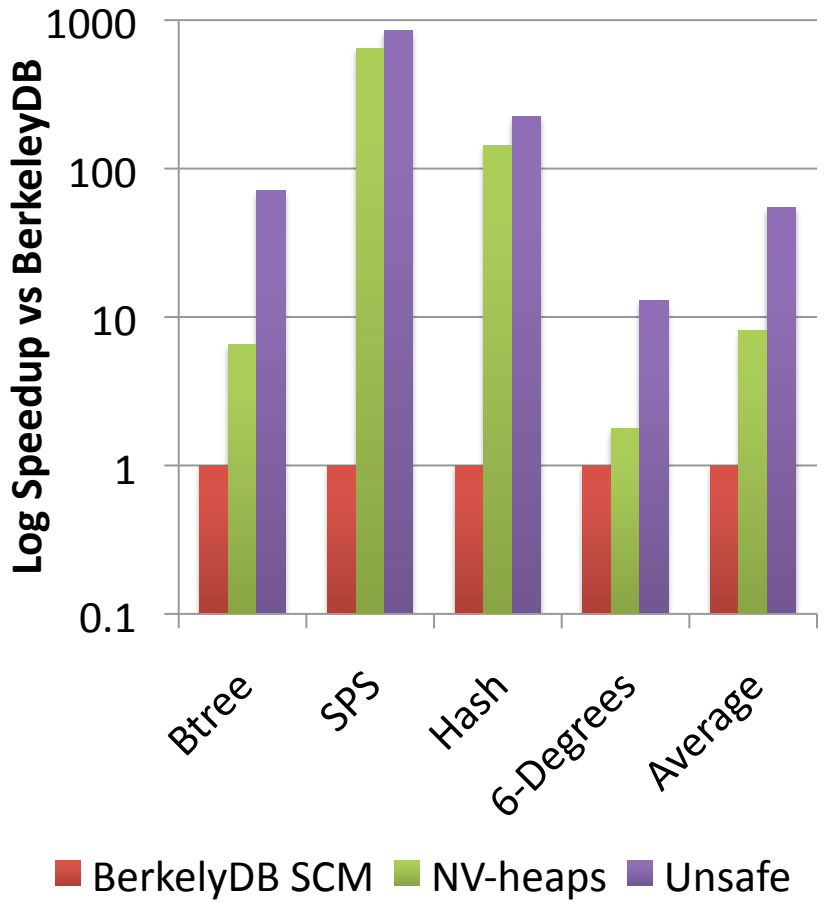
- Similar to NVRamDisk
  - But there's no driver interaction in the common case
  - Emulate SCM with profiling and simulation
- Four workloads
  - Swaps per second
  - Btree
  - Hash Table
  - Six Degrees of separation
- Three other systems
  - Stasis [Sears, et. al., 2006]
  - Berkeley DB – Native implementations
  - Rio Vista-like interface: "Unsafe"

Speedup vs Disk



- 170-30,000x faster than disk
- Raw performance gap: 10,000x

Direct access and the cost of safety



- 8x faster than BDB
  - The benefit of direct access!
- 7x slower than "Unsafe"
  - The cost of safety.

Conclusion

- Software is not ready for SCM
  - Old “optimizations” are wasted effort
  - Moneta shows that redesigning existing software can fix some of this
- NV-heaps can do better by rethinking the abstractions
  - Provide safe, easy to use, persistent objects
  - 7x overhead vs raw SCM
  - Very large application-level improvements

Thanks!

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Questions?