Non-Uniform Memory Access (NUMA) Architectures
- Physical address space is statically partitioned among nodes
- Access to local memory much faster than remote memory
- For fast execution
  - Program should try to distribute work such that each processor uses mostly data from its local memory
- Optimizing programs for NUMA machines needs
  - Knowledge of static memory partitioning
  - Migrating part of data used by a processor to its local memory (unless cache is big enough)
- Would be easier if data can migrate automatically to local memory

Cache-Only Memory Architecture
- Programming model: Shared memory
- Physical design: Distributed Shared Memory
  - Each node holds a portion of the address space
- Key feature: Partitioning of data is dynamic
  - There is no fixed association between an address and a physical memory location
- Each node has “cache-only” memory
  - Acts like a big cache for the node
  - Holds a subset of the physical address space
  - Figure 1 shows UMA, NUMA and COMA

“Attraction” Memory
- Memory of the local node is organized as another cache level, called attraction memory
- Coherence protocol “attracts” data used by a processor to its attraction memory
- Virtual address is translated to a cache block or “item” identifier
- There is no mapping between the identifier and a physical memory
- But there is an association of the identifier to one or more items
- Association is determined using the cache tag

COMA Features
- Does not require static distribution of execution and memory usage
- Migration of data to the processor accessing the data is automatic
- For optimized NUMA programs, COMA runs with comparable speed
- Optimally runs non-optimized NUMA programs
- UMA programs runs well on COMA, but not necessarily on NUMA
- Performs better than NUMA when data migrates according to usage
- No need for programmer to migrate data to local memory

COMA Design Issues
- To avoid increasing memory cost, attraction memory needs to be built with ordinary DRAM
- Where do we put tags?
- Needs to find a home for blocks evicted from a cache
  - Complicates coherence protocol
  - Could result in deadlocks or livelocks
  - Needs total memory size to be bigger than “item” address space (otherwise, paging will be needed)
- Possible Implementation
  - Extend coherence protocol to find data on read miss and to handle replacement
  - Use directory protocol, where state is kept in home directory and data can move freely
Data Diffusion Machine (DDM)
- An implementation of COMA
- Relies on hierarchical network structure
- Large hierarchical machines can be built from small single-bus DDM machines
- Cache coherence protocol modeled after the Write-Once protocol (paper figure 2)

Minimal DDM
- A single bus connects the attraction memories (paper figure 3)
- Use split transaction bus
  - The bus is released between request and response
  - Requests are queued and tagged
- Single-bus DDM coherence protocol
  - Similar to write-once coherence protocol
    - But contains temporary state due to split transaction bus
  - Added support for replacement
    - Handles the attraction (read) and replacement when a set is full

DDM Cache Coherence States
- Invalid: Item not present (or has invalid data value)
- Exclusive: Only copy of item
- Shared: Attraction memory contains item, and other memories could possibly contain it
- Reading: waiting for data after issuing read request
- Waiting: waiting to become exclusive after issuing erase request (i.e., invalidate)
- Reading and Waiting: waiting for data value, will become exclusive later
- Answering: attraction memory has promised to answer a read request

DDM Bus (Network) Transactions
- Erase: Invalidate all other copies of item
- Exclusive: acknowledge an erase request
- Read: Read a copy of item
- Data: reply to earlier read with data value
- Inject: carry the only copy of data looking for a home
- Out: carry a data out of the subsystem and terminate when another copy is found
- State transition diagram: paper figure 4

Replacement
- Attraction memory may run out of space (no more invalid blocks)
- Replacement policy: try Shared items first
- Oldest Shared item may be selected for replacement
  - Generates an Out transaction
  - If Out sees an item in S, R, W, or RW, it does nothing
  - Otherwise, it is converted to Inject transaction
- If an item in Exclusive state is to be replaced
  - Protocol generates an Inject transaction
  - Inject transaction places item in any available I or S locations in other memories

Hierarchical DDM
- Removes the scalability limitation of a single shared bus
- Replaces top protocol with a directory
- The directory interfaces the local bus to a higher level bus
- It tracks all items in the attraction memories below
- Block diagram (paper figure 5)
- Directory architecture (paper figure 6)
- Multi-level read: Try first in local subsystem, then next higher directory etc. until a directory contains item
- Multi-level write: Erase all copies in local subsystem and the next higher directory etc. until all directories containing item are erased
- Replacement: Out and Inject transactions can move up the directory hierarchy
**DDM Prototype**
- Block diagram of a node: paper figure 10
- Remote delays in system: paper table 1
- For each item, we need to store
  - Address tag
  - State
- Memory overhead for a 32-processor DDM: 6%
- Memory overhead for a 256-processor DDM: 16% (due to multi-level directory hierarchy)
- R-NUMA (Falsafi & Wood) combines both ccNUMA and COMA to choose the best protocol for each memory page

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**Reading Assignment**
- Midterm on Monday
- Wednesday: