Distributed Shared Memory: Treadmarks

Origins of the idea

- N-way Multiprocessors are more expensive than N uniprocessors
  - expensive interconnect networks
  - smaller base to amortize costs
- Shared memory programming is easier than message passing
  - Up for debate now
- Hypothesis: we run parallel programs on a network of workstations more cheaply than on an SMP

Technology Motivation

- Low-latency networks (ATM) became available
- High performance workstations (Sparc, Alpha) also available
- Non-cache-coherent supercomputers could also do coherence in software
  - Intel Paragon
  - Thinking Machines CM-5

Origins of the Idea

- Kai Li, 1986: Ivy
  - Page-based DSM – uses MMU
  - Sequential consistency – same as SMPs
  - Looked at page assignment
    - do pages have a "home", and where
  - Page lookup
    - How do you find an up-to-date copy of a page?

Key concept

- SMP has shared *physical memory*
  - All processors can access the same DRAM
- DSM is shared *virtual memory*
  - OS coordinate access to provide illusion of shared physical memory
  - Can look like DRAM is a L-(2,3,4) cache of a larger address space

Other alternatives

- Remote reference
  - Provide commands to load/store to a remote machine
  - No cache coherence
- QUESTION: could you use a parallel programming language on Treadmarks?
    - if it is shared memory, probably yes, and if granularity matches

Advantages of DSM

- Normal shared memory programming techniques can be used
- Easily scalable, compared to traditional bus-connected shared memory multiprocessors
- Message passing is hidden from the user
- Can handle complex and large data bases without replication or sending the data to processes

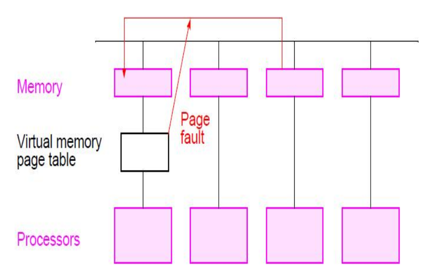
Disadvantages of DMS

- Lower performance than true shared memory multiprocessor systems
- Must provide for protection against simultaneous access to shared data
  - Locks, etc.
- Little programmer control over actual messages being generated
- Incur performance penalties when compared to message passing routines on a cluster

Follow-on work

- Many DSM systems
  - Munin
  - Midway
  - Blizzard/Typhoon (UW)

Page Based DSM System



Issues in DSM

- Granularity
  - What is unit of coherence?
    - page
    - cache line
    - word
    - object
- Consistency
  - When is the value of a write visible?
    - Immediately
    - After a lock is released
    - After a lock is released & acquired
- Location
  - How is data found?
    - Directory
    - Home nodes
- Protocol
  - How do you keep the number of messages low
- Implementation
  - Virtual memory – page faults
  - Binary instrumentation – edit instructions to perform access checks

Coherence methods

- Basic protocol: invalidation
  - Make sure only one copy of a piece of data is writable by taking "ownership" before writing
- Other option: update
  - Make changes locally and then send to other nodes
  - Benefit: avoids misses to fetch data after invalidation
- Challenge: when are the updates then visible to others?
  - Immediately: broadcast new data
  - Release: when lock released

Page ownership

- Locating owners:
  - Centralized: single node tracks owner of all pages
  - Distributed: ownership of different pages is tracked by different nodes
    - Fixed: mapping of addresses to directory is fixed
    - Dynamic: mapping of addresses to a directory is dynamic

TreadMarks approach

- User-mode only software
  - No kernel modifications
- Byte/word granularity
  - No dependence on language-level objects (e.g. structs, arrays)
- Uses VM hardware to detect reference to shared data
  - mprotect() pages to invalid, read-only, or read/write

Munin Implementation (I)

- Three kinds of variables:
  1. ***Ordinary variables:*** can only be accessed by the process that created them
  2. ***Shared data variables:*** should always be accessed from within critical regions
  3. ***Synchronization variables***:
     - locks, barriers or condition variables
     - must be accessed through special library procedures .

Munin Implementation (II)

- When a processor modifies shared data inside a critical region, all update messages are ***buffered*** and ***delayed*** until the processor leaves the critical region
- Processes accessing shared data variables outside critical regions do it at their own risks
  - Same as with shared memory model
  - Risk is higher

Basic

- Allocate shared memory using Tmk_malloc
- On access, check if local page is valid
  - If not, contact remote machines to get page or diffs to apply to local page to make it valid

Consistency in Treadmarks

- Consider two threads accessing shared data
  - Thread 1: lock(m); write(x); unlock(m)
  - Thread 2: does it need locks?
    - Answer: for correct synchronization, it does
  - Thread 2: lock(m); read(x); unlock(m)
  - Thread 3: read(local-z)
- When does the write to x need to be visible?
  - Immediately?
  - When lock m is released?
  - When lock m is acquired?
- To whom is the write to x visible
  - Everybody?
  - Thread 1? Thread 2? Thread 3?

Lazy release consistency

- Observation: correctly synchronized programs don't have data races
  - All access to shared state are ordered with Lamport's happens-before and **synchronization instructions**
    - Locks, barriers
  - Two conflicting accesses to a variable by different threads must have a sync operation between the to specify the order
- Conflicts = 2 accesses, one is a write

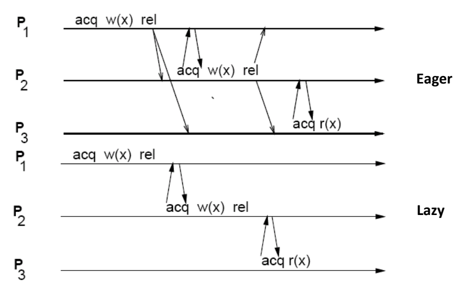
Is LR-C a good idea

- Is it important to support buggy programs?
  - The alternative approaches (sequential consistency) were many times slower
  -

LR-C

- Updates are only "Tracked" while holding a lock
  - assumes no shared data written without lock
- Updates made while holding one lock are propagated to the next holder of the lock
  - Not known until lock acquired, so …
- Updates are propagated from releaser to acquirer of a lock and acquire time

Eager Vs. Lazy RC



Pros and Cons?

Example

- Thread 1: lock(m); write(x); unlock(m);
- Thread 2: lock(m); read (x); unlock(m);
  - Thread 1 remembers the x was written
    - Invalidates X on other processors
  - When thread 2 acquires m, it must contact thread 1 to get the lock. It goes back to thread 1 to get any pages invalidated

Problems with LR-C

- Publication
  - Write an object privately
  - Acquire lock
  - Add to list
  - Release lock
- In LR-C, writes to object occur without lock, are never propagated

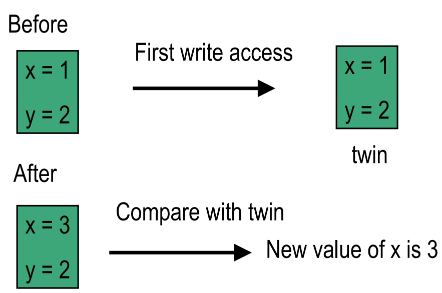
Multiple Writers

- What if two language-objects reside on the same page?
  - If page-based coherence, have *false sharing*:
    - access to one will invalidate access to the other
    - pages ping-pong back and forth between processors

WRITE-SHARED PROTOCOL (I)

- Designed to fight false sharing
- Uses a ***copy-on-write*** mechanism
- Whenever a process is granted access to write-shared data, the page containing these data is marked ***copy-on-write***
- First attempt to modify the contents of the page will result in the creation of a copy of the page modified (the ***twin***).

Example



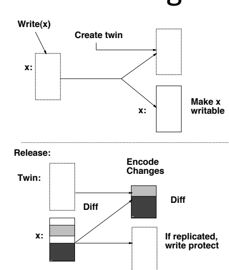
WRITE-SHARED PROTOCOL (II)

- At release time, the DSM will perform a ***word by word*** comparison of the page and its twin, store the diff in the space used by the twin page and notify all processors having a copy of the shared data of the update
- A runtime switch can be set to check for conflicting updates to write-shared data.

Treadmarks solution

- Assume program is correctly synchronized
  - 2 threads holding different locks will not update the same range of bytes
- Track byte-level modification to pages
  - On write, create a *twin page*. On release, diff original page and twin to create a list of bytes that changed
  - On fault of invalid page, get diffs from all nodes that wrote to it

Twinning



Multiple-writers example

- int x,y; // on same page
- Thread 1: lock(m1); write(x); unlock(m1);
  - Invalidates other copies
- Thread 2: lock(m2); write(y); unlock(m2);
  - concurrent; QUESTION: How get a page here?
  - non-blocking: copies page from thread 1
- Thread 3: lock(m1); read(x); unlock(m1);
  - Gets diffs from thread 1, thread 2

Persistent Challenges

- Hot pages cause a lot of coherence traffic
  - NOTE: Same is true within a machine
  - QUESTION: what can be done?
    - ANSWER: rewrite application (data partitioning)
- Fine-grained vs coarse grained
  - Fine grained may work on reliable, fast network (e.g. TM CM-5)
  - Coarse grained only possibility for workstations
- Fault tolerance
  - People have combined with STM
- SMP nodes
  - only a load-balance problem, but system still works (as it operates on VM)

Kai Li's take on DSM

- As a product/feature, it went nowhere
  - Hard to reason about failure
  - Works best for coarse-grained programs, which aren't that hard to write in other ways
  - Overheads are pretty high
- As a test bed, it was useful
  - Developed novel consistency semantics (lazy release consistency)
  - scalable coherence protocols

Willy Zaenepoel's Take

- DSM and P2P (and probably TM) are cousins
  - High implementation complexity leads to lots of papers
  - Research drove towards fine-grained DSM (see Shasta), but fine-grained inherently performs poorly on a cluster
    - More problems with fine grained, so more solutions and more papers
- Reality: DSM only works for coarse grained data, large chunks of contiguous data

Willy on P2P

- Decentralized is harder/more complex than centralized
  - P2P tries to make this a feature, yet few real applications demand true decentralization except illegality
  - But this yields more research papers
- P2P problems
  - Hard to find data (Chord)
  - Hard to secure (Sybil attack, no root of trust)
  - Hard to write programs
  - These all lead to more papers
- Real benefits of P2P: content distribution
  - Solved by BitTorrent, not P2P research
- P2P has low impact
  - What are the natural uses of decentralized systems?