Distributed Systems

Distributed Shared Memory

Paul Krzyzanowski
pxk@cs.rutgers.edu

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Motivation

SMP systems

- Run parts of a program in parallel
- Share single address space
  - Share data in that space
- Use threads for parallelism
- Use synchronization primitives to prevent race conditions

Can we achieve this with multicomputers?

- All communication and synchronization must be done with messages

Distributed Shared Memory (DSM)

Goal: allow networked computers to share a region of virtual memory

- How do you make a distributed memory system appear local?
- Physical memory on each node used to hold pages of shared virtual address space. Processes address it like local memory.

Take advantage of the MMU

- Page table entry for a page is valid if the page is held (cached) locally
- Attempt to access non-local page leads to a **page fault**
- **Page fault handler**
  - Invokes DSM protocol to handle fault
  - Fault handler brings page from remote node
- Operations are transparent to programmer
  - DSM looks like any other virtual memory system

Simplest design

Each page of virtual address space exists on only *one* machine at a time

-no caching

Simplest design

<u>On page fault:</u>

- Consult central server to find which machine is currently holding the page
- **Directory**

<u>Request the page from the current owner:</u>

- Current owner invalidates PTE
- Sends page contents
- Recipient allocates frame, reads page, sets PTE
- Informs directory of new location

Problem

Directory becomes a bottleneck

- All page query requests must go to this server

Solution

- **Distributed directory**
- Distribute among all processors
- Each node responsible for portion of address space
- Find responsible processor:
  - hash(*page#*) mod *num_processors*

Distributed Directory

P0

Page	Location
0000	P3
0004	P1
0008	P1
000C	P2
…	…

P1

Page	Location
0001	P3
0005	P1
0009	P0
000D	P2
…	…

P2

Page	Location
0002	P3
0006	P1
000A	P0
000E	--
…	…

P3

Page	Location
0003	P3
0007	P1
000B	P2
000F	--
…	…

Design Considerations: granularity

- Memory blocks are typically a multiple of a node's page size to integrate with VM system
- Large pages are good
  - Cost of migration amortized over many localized accesses
- BUT
  - Increases chances that multiple objects reside in one page
    - Thrashing
      (page data ping-pongs between multiple machines)
    - False sharing
      (unrelated data happens to live on the same page, resulting in a need for the page to be shared)

Design Considerations: replication

What if we allow copies of shared pages on multiple nodes?

- Replication (caching) reduces average cost of read operations
  - Simultaneous reads can be executed locally across hosts
- Write operations become more expensive
  - Cached copies need to be invalidated or updated
- Worthwhile if reads/writes ratio is high

Replication

Multiple readers, single writer

- One host can be granted a **read-write** copy
- **Or** multiple hosts granted **read-only** copies

Replication

Read operation:

If page not local

- Acquire read-only copy of the page
- Set access writes to read-only on any writeable copy on other nodes

Write operation:

If page not local or no write permission

- Revoke write permission from other writable copy (if exists)
- Get copy of page from owner (if needed)
- Invalidate all copies of the page at other nodes

Full replication

Extend model

- Multiple hosts have read/write access
- Need multiple-readers, multiple-writers protocol
- Access to shared data must be controlled to maintain consistency

Dealing with replication

- Keep track of copies of the page
  - Directory with single node per page not enough
  - Keep track of **copyset**
    - Set of all systems that requested copies
- On getting a request for a copy of a page:
  - Directory adds requestor to copyset
  - Page owner sends page contents to requestor
- On getting a request to invalidate page:
  - Directory issues invalidation requests to all nodes in copyset and wait for acknowledgements

How do you propagate changes?

- Send entire page
  - Easiest, but may be a lot of data
- Send differences
  - Local system must save original and compute differences

Home-based algorithms

Home-based

- A node (usually first writer) is chosen to be the **home** of the page
- On *write*, a non-home node will send changes to the home node.
  - Other cached copies invalidated
- On *read*, a non-home node will get changes (or page) from home node

Non-home-based

- Node will always contact the directory to find the current owner (latest copy) and obtain page from there

Consistency Model

Definition of when modifications to data may be seen at a given processor

Defines
how memory will appear to a programmer

Places restrictions on what values can be returned by a *read* of a memory location

Consistency Model

Must be well-understood

- Determines how a programmer reasons about the correctness of a program

- Determines what hardware and compiler optimizations may take place

Sequential Semantics

Provided by most (uniprocessor) programming languages/systems

Program order

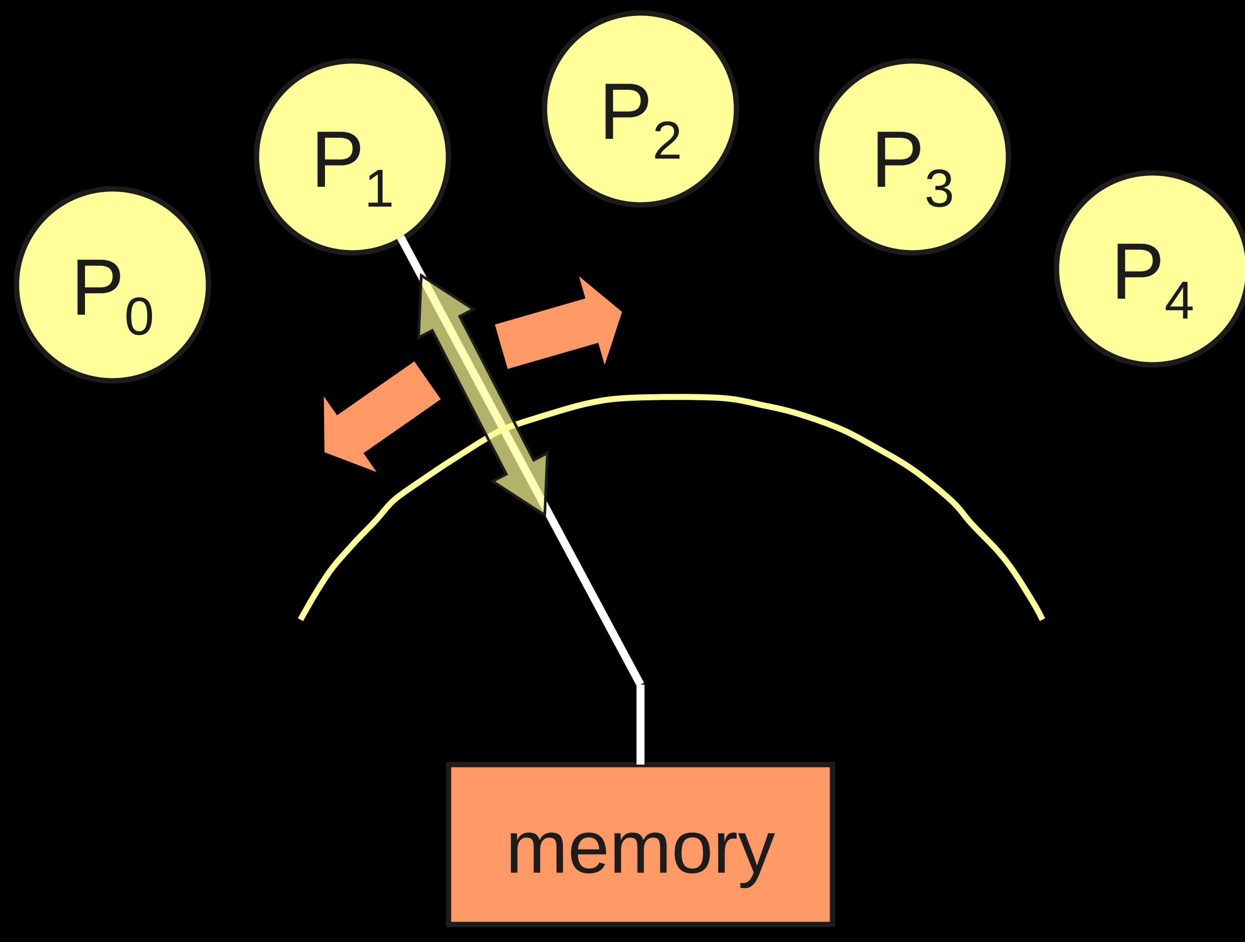
> *The result of any execution is the same as if the operations of all processors were executed in <u>some</u> sequential order **and** the operations of each individual processor appear in this sequence in the order specified by the program.*
>
> *— Leslie Lamport*

Sequential Semantics

Requirements:

- All memory operations must execute one at a time
- All operations of a single processor appear to execute in program order
- Interleaving among processors is OK

Sequential semantics



Achieving sequential semantics

Illusion is efficiently supported in uniprocessor systems

- Execute operations in program order when they are to the same location or when one controls the execution of another
- Otherwise, compiler or hardware can reorder

Compiler:

- Register allocation, code motion, loop transformation, …

Hardware:

- Pipelining, multiple issue, VLIW, …

Achieving sequential consistency

Processor must ensure that the previous memory operation is complete before proceeding with the next one

Program order requirement

- Determining completion of *write* operations
  - get acknowledgement from memory system
- If caching used
  - Write operation must send *invalidate* or *update* messages to all cached copies
  - ALL these messages must be acknowledged

Achieving sequential consistency

All writes to the same location must be visible in the same order by all processes

Write atomicity requirement

- Value of a *write* will not be returned by a *read* until all updates/invalidates are acknowledged
  - hold off on read requests until write is complete
- Totally ordered reliable multicast

Improving performance

Break rules to achieve better performance

- But compiler and/or programmer should know what's going on!

Goals:

- combat network latency
- reduce number of network messages

Relaxing sequential consistency

- Weak consistency models

Relaxed (weak) consistency

Relax program order between all operations to memory

- Read/writes to different memory operations can be reordered

Consider:

- Operation in critical section (shared)
- One process reading/writing
- Nobody else accessing until process leaves critical section

No need to propagate writes sequentially *or at all* until process leaves critical section

Synchronization variable (barrier)

- Operation for synchronizing memory
- All local writes get propagated
- All remote writes are brought in to the local processor
- Block until memory synchronized

Consistency guarantee

- Access to synchronization variables are sequentially consistent
  - All processes see them in the same order
- No access to a synchronization variable can be performed until all previous writes have completed
- No read or write permitted until all previous accesses to synchronization variables are performed
  - Memory is updated during sync

Problems with sync consistency

- Inefficiency
  - Are we synchronizing because the process finished memory accesses or is about to start?
- On a sync, systems must make sure that:
  - All locally-initiated writes have completed
  - All remote writes have been acquired

Can we do better?

Separate synchronization into two stages:

1. acquire access

   Obtain valid copies of pages

2. release access

   Send invalidations or updates for shared pages that were modified locally to nodes that have copies.

```
acquire(R)    // start of critical section
Do stuff
release(R)    // end of critical section
```

Eager Release Consistency (ERC)

Getting Lazy

The *release* operation requires:

- Sending invalidations to copyset nodes
- **And** waiting for all to acknowledge

Do not make modifications visible globally at release

On *release*:

- Send invalidation only to directory
  or send updates to home node (owner of page)

On *acquire*: this is where modifications are propagated

- Check with directory to see whether it needs a new copy
  - Chances are not every node will need to do an acquire

Reduces message traffic on releases

Lazy Release Consistency (LRC)

Finer granularity

Release consistency

- Synchronizes *all* data
- No relation between lock and data

Use object granularity instead of page granularity

- Each variable or group of variables can have a synchronization variable
- Propagate only writes performed in those sections
- Cannot rely on OS and MMU anymore
  - Need smart compilers

Entry Consistency

The end.