CSE 486/586 Distributed Systems
Distributed Shared Memory

Steve Ko
Computer Sciences and Engineering
University at Buffalo

Overview

- Today: distributed shared memory, starting from some background on memory sharing
- Memory sharing for a single machine
  - Threads and processes
- Memory sharing for different machines
  - Threads and processes

Why Shared Memory?

- For sharing data
- There are two strategies for data sharing.
  - Message passing
  - Shared memory
- Message passing
  - Send/receive primitives
  - Explicit sharing → no synchronization (locks) necessary
- Shared memory
  - Memory read/write primitives (in your code, you could use regular variables)
  - Typically requires explicit synchronization (locks)
- Which is better?
  - Depends on your use case.
  - Multiple writers: perhaps message passing
  - (Mostly) read-only data: shared memory

Memory Sharing for Threads

- Threads belong to a single process, so all threads share the same memory address space.
- E.g., Java threads

```
class MyThread extends Thread {
        HashMap hm;
        MyThread(HashMap _hm ) {
                this.hm = _hm;
        }
        public void run() {
                …
                hm.put(key, value);
        }
}
```

```
HashMap hashMap = new HashMap();
MyThread mt0 = new MyThread(hashMap); // hashMap is shared
MyThread mt1 = new MyThread(hashMap);
mt0.start();
mt1.start();
```


Memory: Threads vs. Processes

- For threads, there's no special mechanism necessary to share memory.
  - Note: Languages like Java provide constructs to create thread-specific variables because by default memory is shared across different threads.
  - ThreadLocal for Java: if a shared object has a ThreadLocal variable, it will be specific to each thread.
- But, a process has its own address space, so by default, different processes do not share memory.
- Processes (on the same machine) can share memory regions with support from their OS.

Shared Memory on a Single Machine

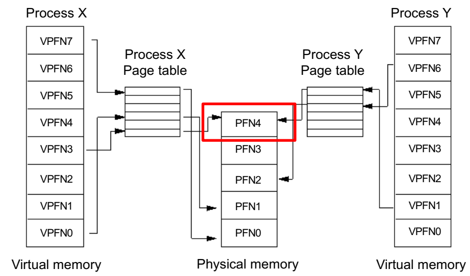
- Shared memory is part of IPC (Inter-Process Communication).
  - What are other IPC mechanisms?
  - Files, (domain) sockets, pipes, etc.
- Shared memory API (POSIX C)
  - shm_open(): create and open a new object, or open an existing object. The call returns a file descriptor.
  - mmap(): map the shared memory object into the virtual address space of the calling process.
  - …and others
- Semaphore API (POSIX C)
  - sem_open(): initialize and open a named semaphore
  - sem_wait(): lock a semaphore
  - sem_post(): unlock a semaphore
  - …and others

Shared Memory Example* (in C)

```
int main() {
  const char *name = "shared"; // shared with other processes
  int shm_fd;
  void *ptr;

  /* create the shared memory segment. name is shared. */
  shm_fd = shm_open(name, O_CREAT | O_RDWR, 0666);
  …
  /* now map the shared memory segment in the address space of
     the process */
  ptr = mmap(0,SIZE, PROT_READ | PROT_WRITE,
                  MAP_SHARED, shm_fd, 0);

  sprintf(ptr,"%s",message0);

  return 0;
}
```

*Adapted from http://www.os-book.com

Shared Memory Implementation

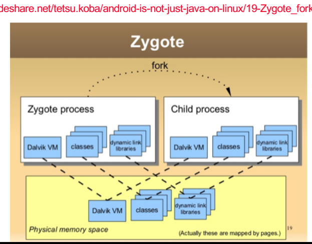


- VPFN: Virtual page frame number
- PFN: Physical page frame number
- Adapted from http://tldp.org/LDP/tlk/mm/memory.html

Shared Memory Use Case: Android

- All apps need framework API libraries, Java VM, etc.
  - Too expensive if all app processes have them in their memory space individually.
- Zygote: A process that starts everything else.
  - All app processes share memory with Zygote.

Image source: https://www.slideshare.net/tetsu.koba/android-is-not-just-java-on-linux/19-Zygote_forkZygote_process_Child_process



CSE 486/586 Administrivia

- PA3 grades will be posted today.
- PA4 deadline: 5/10
  - Please start early. The grader takes a long, long time.
- Survey & course evaluation
  - Survey: https://forms.gle/eg1wHN2G8S6GVz3e9
  - Course evaluation: https://www.smartevals.com/login.aspx?s=buffalo
- If both have 80% or more participation,
  - For each of you, I'll take the better one between the midterm and the final, and give the 30% weight for the better one and the 20% weight for the other one.
  - (Currently, it's 20% for the midterm and 30% for the final.)
- No recitation today; replaced with office hours

Distributed Shared Memory

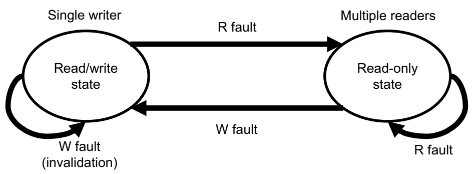
- We will discuss two cases.
  - DSM for processes
  - DSM for threads
- DSM for processes: different processes running on different machines sharing a memory page.
- The shared memory page is replicated and synchronized across different machines.
  - However, replication is not the goal (e.g., we're not keeping replicas to deal with failures).
- A generic way of doing this is at the OS layer.
  - Similar to the diagram on slide #8, but with processes on different machines

DSM Synchronization Options

- Write-update
  - A process updates a memory page.
  - The update is multicast to other replicas.
  - The multicast protocol determines consistency guarantees (e.g., FIFO-total for sequential consistency).
  - Reads are cheap (always local), but writes are costly (always multicast).
- Write-invalidate
  - Two states for a shared page: read-only or read & write
    - » Read-only: the memory page is potentially replicated on two or more processes/machines
    - » Read & write: the memory page is exclusive for the process (no other replica)
  - If a process intends to write to a read-only page, an invalidate request is multicast to other processes.
  - Later writes can take place without communication (cheap).
  - Writes are only propagated when there's a read by another process (cheap for write, costly for read).
  - But a write can be delayed by invalidation (costly for write).

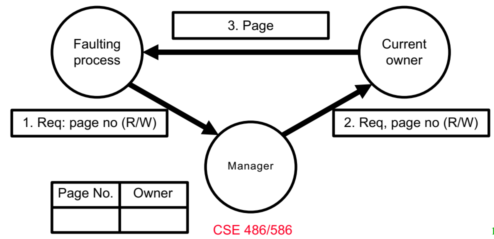
Write Invalidate Protocol Example

- Note: R fault and W fault can occur at any process



Example System: Ivy

- Implements a write-invalidation protocol
  - Owner of a page: the process with the most up-to-date
  - Copyset of a page: the processes with a replica
  - A centralized manager maintains ownership info.

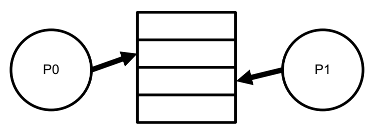


Granularity Problem

- Let's assume that we operate at the page-level.
  - (But other implementations also have similar problems.)
  - Just as a reference, a Linux memory page is 4KB.
- Problem
  - When two processes (on two different machines) share a page, it doesn't always mean that they share everything on the page.
  - E.g., one process reads from and writes to a variable X, while the other process reads from and writes to another variable Y. If they are in the same memory page, the processes are sharing the page.

Granularity Problem

- True sharing
  - Two processes share the exact same data.
- False sharing
  - Two processes do not share the exact same data, but they access different data from the same page.



- False sharing problems
  - Write-invalidate: unnecessary invalidations
  - Write-update: unnecessary data transfers

Granularity Problem

- Bigger page sizes
  - Better handling for updates of large amounts of data (good)
  - Less management overhead due to a smaller number of units/pages to handle (good)
  - More possibility for false sharing (bad)
- Smaller page sizes
  - The opposite of the above
  - If there is an update of a large amount of data, it'll be broken down to many small updates, which leads to more network overhead (bad)
  - A smaller page size means more pages, which leads to more management overhead, i.e., more tracking of reads and writes (bad)
  - Less possibility of false sharing (good)

Thrashing

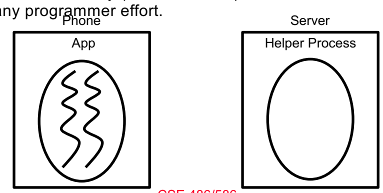
- Thrashing could happen with write-invalidate protocols.
- *Thrashing is said to occur when DSM spends an inordinate amount of time invalidating and transferring shared data compared with the time spent by application processes doing useful work.*
- This occurs when several processes compete for a data item or for falsely shared data items.

Thrashing

- Common scenario: producer-consumer pattern
  - Data is produced by a process and used by another process.
  - The producer will keep invalidating the consumer & the consumer will keep transferring data from the producer.
  - Write-update is better for this pattern.
- Solutions to thrashing
  - Manual avoidance: a programmer avoids thrashing patterns.
  - Timeslicing: once a process gains a write access to a page, it retains it for a period of time. Other processes' read/write requests are buffered during that period.

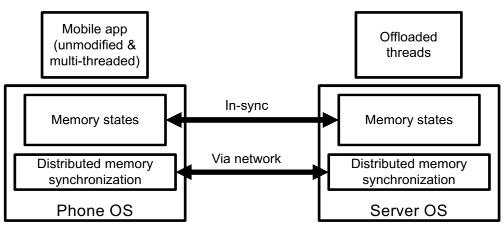
DSM for Threads

- Memory sharing among threads on different machines.
- Use case: code (thread) offloading from a smartphone to a server
  - Low-power smartphones augmented by high-power servers (computation & energy)
  - It's done already (cloud backend), but DSM allows it without any programmer effort.



Example: Comet*

- Comet allows thread offloading for Android apps in Java
- Comet synchronizes the entire Java VM state.



*https://www.usenix.org/conference/osdi12/technical-sessions/presentation/gordon

Java Code Execution Background

- Memory: program code, stack, heap, & CPU state
- Stack & heap
  - Generally, the program stack handles statically allocated objects & method call return addresses.
  - The heap is used for dynamically allocated objects.

```
public class Ex {
  public void method() {
        int i = 0; // stack
        HashMap hm = new HashMap(); // heap
  }
}
```

- CPU state
  - Android Java VM uses registers for instruction execution.
  - The program counter (PC) points to the next instruction to execute.
- For program execution, Java VM has an execution loop.
  - Fetches the next instruction that the PC points to.
  - Executes the new instruction
  - While executing, it uses registers, the stack, and the heap.

Comet Thread Migration

- Comet completely synchronizes VMs on both sides (phone & server).
  - In Java, everything you need for program execution is stored in memory.
  - Program code, stack, heap, & CPU state
  - DSM can synchronize these.
- Any side can execute a thread, since they both know everything necessary for program execution.
  - The PC is synchronized, so both sides know the next instruction to execute.
  - The registers are synchronized, so they both know the CPU state.
  - The stack & the heap are synchronized, so they know the memory state.

Summary

- Memory sharing among threads
  - By default, they share the same address space
- Memory sharing among processes
  - Shared memory API & semaphore API
  - Virtual-physical memory mapping implements this.
- Memory sharing across machines
  - Write-update
  - Write-invalidate
- Memory sharing across threads on different machines
  - Use case: code offloading

Acknowledgements

- These slides contain material developed and copyrighted by Indranil Gupta (UIUC).