CSE 410: Systems Programming

Memory and Concurrency

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Memory and Concurrency

We have discussed shared state and concurrency.

However, the issues go deeper than that!

Shared state is in shared memory.

Memory has some confusing properties when it is shared.

How does memory become shared, anyway?

Types of Shared Memory

There are several “types” of shared memory in concurrent programming:

- Memory used by the same thread in the same process at different times (and maybe asynchronously)
- Memory used by different threads in the same process (maybe at the same time)
- Memory used by different processes (maybe at the same time)

The first is mostly non-problematic.

The second two require a little extra work.

Acquiring Shared Memory

Memory shared within a process requires no special setup.

Sharing memory between processes requires kernel assistance.

There are several methods for creating shared memory:

- Creating a shared mapping within a process before forking
- Attaching to a named mapping with `shm_open()`
- Attaching to a memory-mapped file

Consistency

Many problems with memory and concurrency are with consistency.

Within the dedicated computer model, we have expectations:

- Writing to a memory location is immediate
- Writes to a memory location are durable

With concurrent flows, these expectations can break.

We have already seen how to mitigate this with synchronization.

However, synchronization must control more than timing.

Temporal Synchronization

Up to now, we have thought of synchronization as a temporal construction:

- Operation o_1 occurs before operation o_2
- A sequence of operations is not interrupted

However, there are also spatial concerns.

- An operation is visible to another part of the system.

Caching

Modern computers have many layers of caching.

Some of these caches are shared, some are local:

- Local to a particular CPU core
- Local to a subset of cores
- Local to a process
- …

Writes to a local cache may not be visible to concurrent flows.

Why Cache?

Caches are used for performance reasons, in levels:

Level	*Type*	*Size*	*Access Time*
L0	CPU registers	O(100 B)	~0 clock cycles
L1	Level 1 cache	O(10 KB)	~1-5 clock cycles
L2	Level 2 cache	O(100 KB)	~10+ clock cycles
L3	Level 3 cache	O(1 MB)	~30+ clock cycles
L4	Main memory	O(10 GB)	~100+ clock cycles

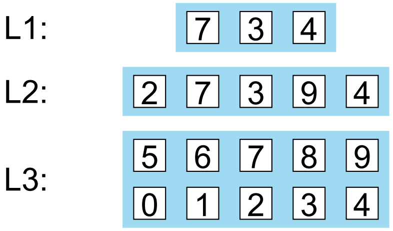
Lower levels are much faster but much smaller.

L0-L1 are often local to a core, L2-3 to a core or subset of cores. L4 is typically shared.[1]

[1] Architectures where it is not are called NUMA.

Caching Structure

Each level of cache stores blocks from the next level.



Block location and size may vary from level to level.

Reads come from the first level with the desired data.

Writes eventually propagate to all levels.

Write Propagation

The consistency problem comes from that eventually:
Writes eventually propagate to all levels.

If a cache is local to a core or set of cores, reads from other cores will not reflect its contents.

Consider registers: only one core sees them!

As previously discussed:

- Many operations (even instructions) have multiple steps
- Some of those steps are performed in registers

Write Propagation Problem

Consider:

- Core C_0 executes a write for memory location m
- The write is stored to C_0's L1 cache
- Core C_1 executes a read for memory location m
- The location m is not in C_1's L1 or L2
- C_1 reads m from shared L3
- C_0's L1 propagates m to C_0's L2
- C_0's L2 propagates m to the shared L3

Write Propagation II

Temporal synchronization can guarantee that a register is written to memory.

To guarantee it isn’t cached, we need memory barriers.

A memory barrier does one or more of:

- Blocks the current core until a write is visible to all cores
- Blocks the current core until all writes are visible
- Blocks all cores from accessing a location until a write is visible
- Prevents CPU instruction reordering from affecting this instruction
- …

Memory Barriers

Memory barriers are sometimes called memory fences.

Memory barriers are hardware functions.

Most processors have barrier instructions.

For example:

- `mfence` on x86-64
- `dmb` on ARM
- many atomic instructions

Write Propagation with Barriers

Consider:

- Core C_0 executes a write for memory location m
- The write is stored to C_0's L1 cache
- Core C_1 issues a barrier for all writes to m
- Core C_1 executes a read for memory location m
- Core C_1 blocks because C_0 is writing m
- C_0's L1 propagates m to C_0's L2
- C_0's L2 propagates m to the shared L3
- C_1 reads m from shared L3

Synchronization and Barriers

Synchronization primitives use memory barriers.

These functions, for example, all have barriers:

- `fork()`
- `pthread_mutex_lock()`
- `pthread_mutex_unlock()`
- `pthread_create()`
- `pthread_join()`
- ...

Basically all of the POSIX synchronization functions.

C and Memory Barriers

The C language makes very few guarantees regarding barriers.

C11 has some fence (barrier) operations.

C99 does not expose barriers.

In general libraries or OS functions (such as Pthreads) are required for thread-safe operation in C.

Some C compilers may provide barriers (*e.g.*, `__builtin_ia32_mfence()` in GCC).

Sharing Memory

So far, we have explored only one way to share memory: Threads within a process share all memory.

It is often useful to share memory in a controlled way.

For example:

- A typed data structure (such as a list or tree)
- A buffer of raw bytes
- A synchronization tool (such as a producer-consumer queue)
- …

Implicitly Shared Memory

Processes have a lot of implicitly shared memory:

- Shared libraries
- Executable images
- Kernel memory
- …

This memory is not obviously shared, however.

It is either read-only or hidden.

Explicitly Sharing Memory

A process can request explicit memory sharing.

That memory may be mutable and changes may be visible between processes.

Like all other resources, the kernel sets up shared memory.

POSIX systems offer two fundamental system calls (and three methods) for explicitly sharing memory:

- `mmap()` maps a file into memory, and changes to the file can be shared between processes
- `mmap()` can also be used to create an anonymous shared mapping shared between parent and child processes
- `shm_open()` opens a named shared memory region

`mmap()`

The `mmap()` system call is a Swiss-army knife of memory mapping tools.

It asks the kernel to manipulate the process virtual memory map.

Its analogue is `munmap()`.

It is quite complicated to use properly.

The original use of `mmap()` was to map a file into memory.

Memory mapped with mmap is preserved on `fork()`.

Using mmap()

```
#include <sys/mman.h>

void *mmap(void *addr, size_t len, int prot,
           int flags, int fd, off_t offset);
```

The only required (nonzero) arguments are `flags` and `fd`.

The arguments passed to mmap depend on what you do with it.

You don’t need to remember these details, but do learn the concepts!

Using mmap()

```
void *mmap(void *addr, size_t len, int prot,
           int flags, int fd, off_t offset);
```

The `flags` argument determines what kind of mapping is created.

It must include either `MAP_PRIVATE` or `MAP_SHARED`.

It may include many other options.

`MAP_ANONYMOUS`, in particular, means do not map a file.

Using mmap()

```
void *mmap(void *addr, size_t len, int prot,
           int flags, int fd, off_t offset);
```

The addr argument is the location in the virtual memory map where you would like the mapping to be placed.

It is often specified as zero, which lets the kernel decide.

Unless MAP_FIXED is passed to prot, this address is advisory.

Using mmap()

```
void *mmap(void *addr, size_t len, int prot,
           int flags, int fd, off_t offset);
```

The fd argument must be either:

- An open file descriptor
- -1

The open file descriptor specifies which file is to be mapped.

Using `mmap()`

```
void *mmap(void *addr, size_t len, int prot,
           int flags, int fd, off_t offset);
```

The `prot` argument determines the permissions of the mapping. It must be either `PROT_NONE` or a bitwise-or of:

- `PROT_READ`: the mapping is readable
- `PROT_WRITE`: the mapping is writeable
- `PROT_EXEC`: the mapping is executable

The selected protection must match the open fd mode.
(*E.g.*, an `O_RDONLY` file cannot be mapped `PROT_WRITE`.)

Using mmap()

```
void *mmap(void *addr, size_t len, int prot,
           int flags, int fd, off_t offset);
```

`len` determines how many bytes of the file are mapped.

If a file is being mapped, `offset` determines the first byte of the file that is mapped.

It is common that `offset` must be a multiple of the system page size.

Example of mmap()

From your malloc project:

```
void *mapping =  mmap(NULL, size,
                      PROT_READ | PROT_WRITE,
                      MAP_PRIVATE | MAP_ANONYMOUS,
                      -1, 0);
```

- NULL addr because we don’t care
- readable, writeable mapping
- MAP_PRIVATE so the map is not shared, and MAP_ANONYMOUS because there’s no file
- fd is -1 because there’s no file
- The size is as requested, with no offset

Shared Mapping with mmap()

```
void *mapping = mmap(NULL, size,
                     PROT_READ | PROT_WRITE,
                     MAP_SHARED | MAP_ANONYMOUS,
                     -1, 0);
```

This mapping will be preserved across fork().

The memory will be at the same address in both processes.

POSIX semaphores created in the shared memory, or created in other memory, with `pshared = 1`, will synchronize processes.

Mapping a File

```
int fd = open("somefile", O_RDWR);
void *mapping = mmap(NULL, 4096,
                     PROT_READ | PROT_WRITE,
                     MAP_SHARED, fd, 0);
close(fd);
```

This maps the first 4 KB of `somefile` to the address `mapping`.

This mapping will be shared by all children of this process.

This mapping will be with shared with all processes mapping the same location in the same file.

Note that the file can be deleted after it is mapped.

Executable Loading with `mmap()`

Recall that executables on disk are mapped into memory.

This is accomplished using `mmap()`.

The various ELF sections are mapped appropriately:

- `.text` with `PROT_READ | PROT_EXEC`
- `.rodata` with `PROT_READ`
- `.data` with `PROT_READ | PROT_WRITE`

The text and read-only data can be `MAP_SHARED` to save RAM.

The BSS is an anonymous mapping using `MAP_ANONYMOUS` and `PROT_READ | PROT_WRITE`.

Shared Memory Without a File

Mapping a file to share memory can be convenient:

- It persists when no process is using it
- It persists between reboots
- It can be easily analyzed with standard utilities

Mappings can also be created without a file.

The `shm_open()` system call creates a file descriptor referencing a kernel memory buffer.

The filedescriptor returned by `shm_open()` is usable with `mmap()`.

shm_open()

```
#include <sys/mman.h>
#include <fcntl.h>

int shm_open(const char *name, int flags, int mode);
```

The `flags` and `mode` arguments are the same as `open()`.

The memory allocated by `shm_open()` lasts until either:

- It is removed with `shm_unlink()` and all processes have unmapped it
- The machine is rebooted

Example of shm_open()

```
int fd = shm_open("/shm_example", O_RDWR, 0600);
ftruncate(fd, 4096);
void *mapping = mmap(NULL, 4096,
                     PROT_READ | PROT_WRITE,
                     MAP_SHARED, fd, 0);
```

Any process attaching to `"/shm_example"` can share this memory.

Note the use of `ftruncate()` to set the size of the mapping.

In this case, only the creating user can open the memory.

Summary

- Caching and CPU architecture require more than just temporal synchronization
- Memory barriers force data visibility across cores
- Memory barriers are a hardware feature
- Caches are much faster than main RAM
- POSIX synchronization primitives use memory barriers
- Shared memory requires kernel assistance
- Files can be mapped into memory

References I

Required Readings

[1] Randal E. Bryant and David R. O’Hallaron. *Computer Science: A Programmer’s Perspective*. Third Edition. Chapter 6: Intro, 6.3; Chapter 9: 9.8. Pearson, 2016.

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