Memory Consistency

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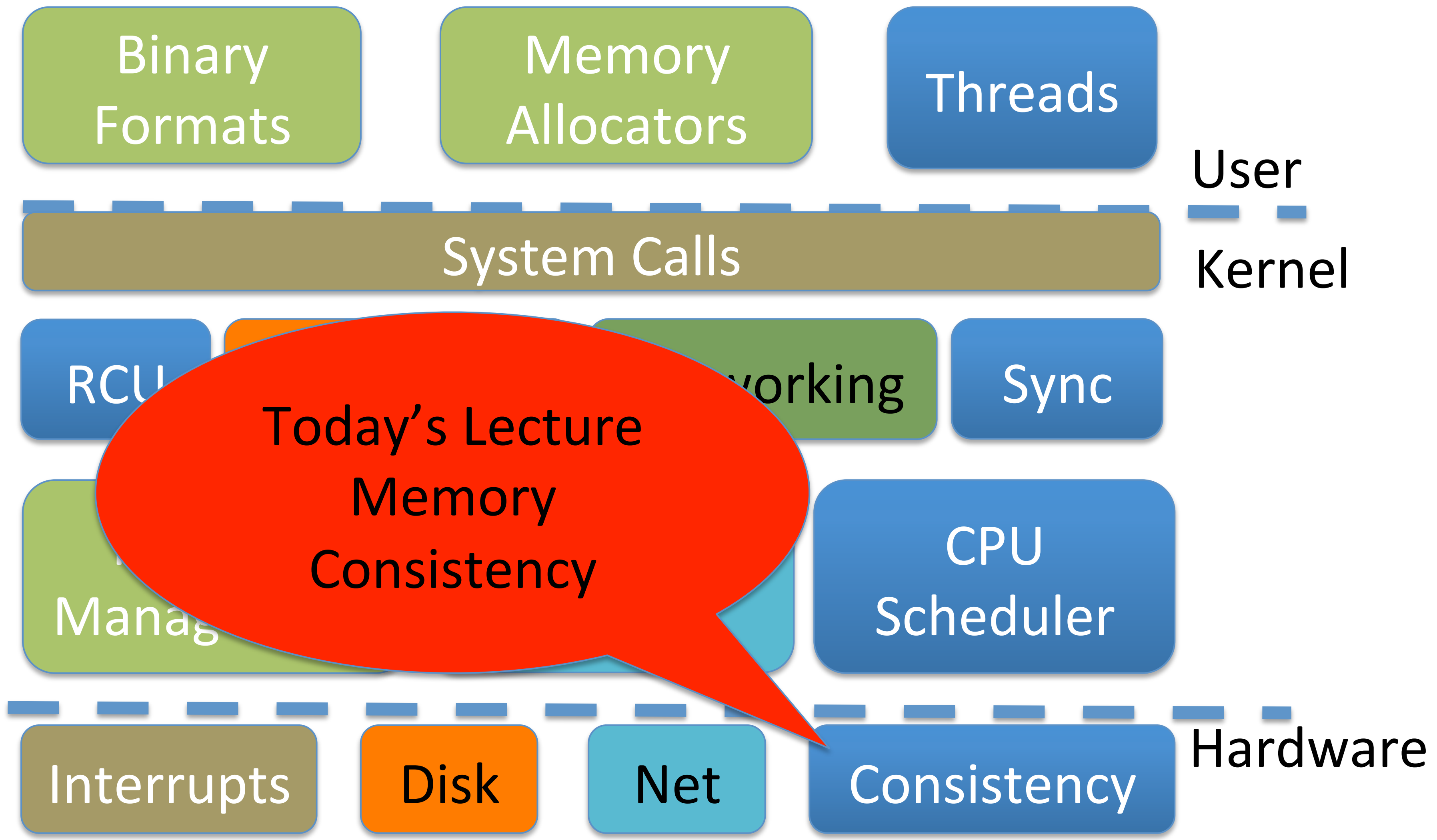
Logical Diagram



Difficult topic

- Memory consistency models are difficult to understand
  - Knowing when and how to use memory barriers in your programs takes a long time to master
- I read the long version of this paper about once a year
  - Started in graduate architecture, still mastering this
- Even if you can't master this material, it is worth conveying some intuitions and getting you started on the path
  - Multi-core programming is increasingly common

Background

- In the 90s, people were figuring out how to build and program shared memory multi-processors
- Several hardware and compiler optimizations that worked well on single-CPU systems were causing “heisen-bugs” in correct parallel code
  - Disabling all optimizations made this code correct, but slow
- Various consistency models strike different balances between optimization and programmability

Simple example

```
/* Pre condition: flag = 0 */
x = a + b
flag = 1
```

a isn't in the cache yet.
(or ALU is busy, etc)

This line is independent of the one above.
Execute first, since result is identical

Extended to multi-processors

/* Pre condition: flag = 0 */

<u>Thread 1</u>

```
x = a + b
flag = 1
```

<u>Thread 2</u>

```
while ( ! flag ) { 1; }
val = x
```

flag is acting as a barrier to synchronize read of x after x was written

Distinction

- Compiler/CPU can figure out when instructions can be safely reordered within a given thread
- Hard to figure out when the order is meaningful to coordinate with other threads
- If you want optimizations (and you do), programmer MUST give hardware and compiler some hints
  - Hard to design hints that average programmer can successfully give the hardware

Definitions

- Cache coherence: The protocol by which writes to one cache invalidate or update other caches
- Memory consistency model: How are updates to memory published from one CPU to another
  - Reordering between CPU and cache/memory?
  - Are cache updates/invalidations delivered atomically?
    - Coherence protocol detail that impacts consistency
- Distinction between coherence and consistency muddled

Intuition

- On a bus-based multi-processor system (nearly all current x86 CPUs), a write to the cache immediately invalidates other caches
  - Making the write visible to other CPUs
- But, the update could spend some time in a write buffer or register on the CPU
- If a later write goes to the cache first, these will become visible to another CPU out of program order

Sequential Consistency

- Simplest possible model
- Every program instruction is executed in order
  - No buffered memory writes
- Only one CPU writes to memory at a time
  - Given a write to address x, all cached values of x are invalidated before any CPU can write anything else
- Simple to reason about

Sequential is too slow

- CPUs want to pipeline instructions
  - Hide high latency instructions
- Sequential consistency prevents these optimizations
- And these optimizations are harmless in the common case

Relaxed consistency

- If the common case is that reordering is safe, make the programmer tell the CPU when reordering is unsafe
  - Details of the model specify what can be reordered
  - Many different proposed models
- **Barrier (or fence)**: common consistency abstraction
  - Every memory access before this barrier must be visible to other CPUs before any memory access after the barrier
  - Confusing to use in practice

Total Store Order (TSO)

- Model adopted in nearly all x86 CPUs
- All stores leave the CPU in program order
- CPU may load "ahead" of an unrelated store
  - Ex: x = 1; y = z;
  - CPU may load z from memory before x is stored
  - CPU may not reorder load and store of same variable
- Atomic instructions are treated like a barrier

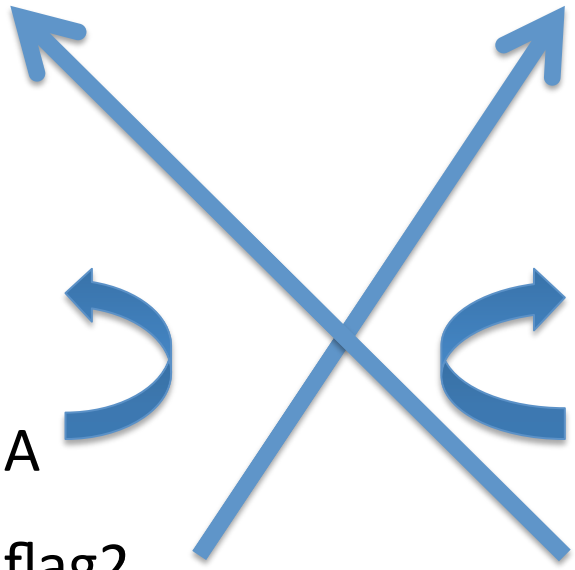
TSO benefits

- Since nearly all locks involve an atomic write, the CPU will never reorder a critical region with a lock
  - If you use locks, you rarely need to worry about consistency issues
- When do you worry about memory consistency?
  - Custom synchronization / lock-free data structures
  - Device drivers

5a Example

Reorder Load of R2, R4 ahead of stores

* Pre condition: A= flag1 = flag2 = 0 */



Both CPUs forward write of A internally before globally visible

Thread 1	Thread 2
flag1 = 1	flag2 = 1
A = 1	A = 2
Register1 = A	Register3 = A
Register2 = flag2	Register4 = flag1

Register 1 = 1, R2 = 0, R3 = 2, R4 = 0

5a Example + barriers

/* Pre condition: A= flag1 = flag2 = 0 */

Thread 1	Thread 2
flag1 = 1	flag2 = 1
A = 1	A = 2
barrier	barrier
Register1 = A	Register3 = A
Register2 = flag2	Register4 = flag

Store A must be visible before flag reads

Flag writes must be globally visible before A is written (TSO)

Must be a sequential ordering of store A's

A = 2 and R2 = 0 **or** A = 1 and R4 = 0; R2 & R4 != 0

5a Example: order 1

/* Pre condition: A= flag1 = flag2 = 0 */

Thread 1	Thread 2
flag1 = 1	flag2 = 1
A = 1 **(1)**	A = 2 **(3)**
barrier	barrier
Register1 = A	Register3 = A
Register2 = flag2 **(2)**	Register4 = flag1

A = 2 and R2 = 0 **or** A = 1 and R4 = 0; R2 & R4 != 0

5a Example: order 2

/* Pre condition: A= flag1 = flag2 = 0 */

Thread 1	Thread 2
flag1 = 1	flag2 = 1
A = 1 **(3)**	A = 2 **(1)**
barrier	barrier
Register1 = A	Register3 = A
Register2 = flag2	Register4 = flag1 **(2)**

A = 2 and R2 = 0 **or** A = 1 and R4 = 0; R2 & R4 != 0

Summary

- Identifying where to put memory barriers is hard
  - Takes a lot of practice and careful thought
  - Looks easy until you try it alone
- But, CPUs would be super-slow on sequential consistency
- Understand: Why relaxed consistency? What is TSO? Roughly when do developers need barriers?
- Advice: Take grad architecture; read this paper yearly