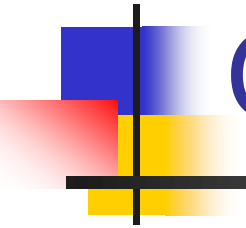

CSE P 501 – Compilers

Threads and Memory Models

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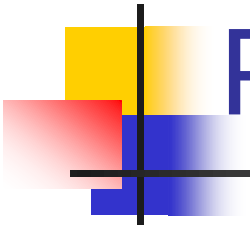
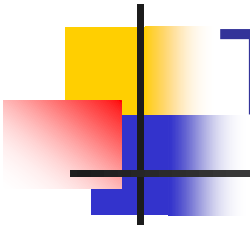
Autumn 2011



References

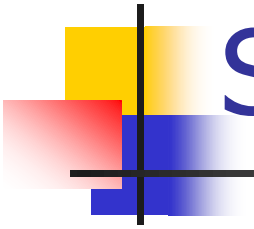
- *Memory Models: A Case for Rethinking Parallel Languages and Hardware*
  Adve and Boehm, CACM Aug. 2010
- *Foundations of the C++ Concurrency Memory Model*
  Boehm and Adve, PLDI 2008
- *The Java Memory Model*
  Manson, Pugh, and Adve, POPL 2005

- Slides by Vijay Menon, CSE 501, Sp09



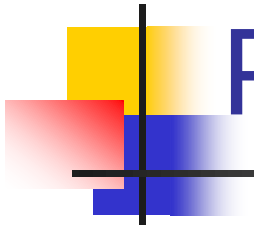
Threads and shared memory

- Multithreaded programs allow multiple threads to run concurrently
  - each thread has its own local variables (stack and registers), but...
  - all threads share a common view of memory (globals / statics)
- Pervasive with multiple cores



Safety of optimization

- A standard constraint / definition:
  - *If, in their actual program context, the result of evaluating e' cannot be distinguished from the result of evaluating e, the compiler can substitute e' for e*
- What does this mean in a multi-threaded setting?



Register promotion

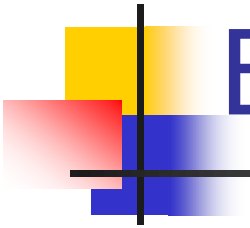
```
// x is global, initially 0

void foo(int* a, int n) {
  for (int i = 0; i < n; ++i)
    x += i;
}
```

Register promotion

```
// x is global, initially 0

void foo(int* a, int n) {
  for (int i = 0; i < n; ++i)
    x += i;
}
```



```
// Optimized

void foo(int* a, int n) {
  int reg = x;
  for (int i = 0; i < n; ++i)
    reg += i;
  x = reg;
}
```



Before optimization

```
// x is global, initially 0

// Thread 1

void foo(int* a, int n) {
  for (int i = 0; i < n; ++i)
    x += i;
}
```

```
// Thread 2

void bar() {
  x = 10;
  ...
}
```

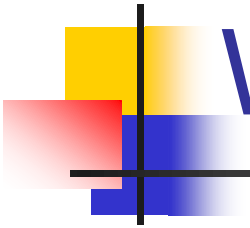
What happens when n == 0?

After optimization

```
// x is global, initially 0

// Thread 1

void foo(int* a, int n) {
  int reg = x;
  for (int i = 0; i < n; ++i)
    reg += i;
  x = reg;
}
```

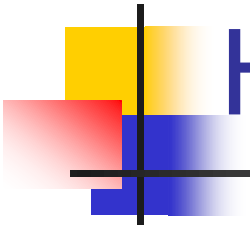
```
// Thread 2

void bar() {
  x = 10;
  ...
}
```

What happens when n == 0?



What happened?

- In executions where n == 0, the compiler optimization creates a value out of thin air.
  - Original code: x == 10 is guaranteed
  - Optimized code: new write of x = 0 (inserted x = reg) creates new result
- Safety is no longer maintained



How did we get here?

- C & C++ originally defined as single-threaded languages
  - Compilers didn't consider threads
  - Threads were provided by externally libraries (e.g. pthreads) that defined their own semantics
- This is a broken model!
  - New specs explicitly deal with threads (Boehm, et al)

Dekker's example

- Initially, x == y == 0

Thread 1		Thread 2	
x = 1;	(a)	y = 1;	(c)
r1 = y;	(b)	r2 = x;	(d)

- What are possible executions?

Dekker's example

- Initially, x == y == 0

Thread 1		Thread 2	
x = 1;	(a)	y = 1;	(c)
r1 = y;	(b)	r2 = x;	(d)

- What are possible executions?
  - Consider interleavings of thread 1 & 2:
    - abcd, acbd, acdb, cdab, cadb, cabd

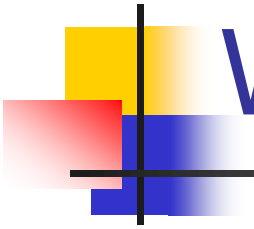
Dekker's example

- Initially, x == y == 0

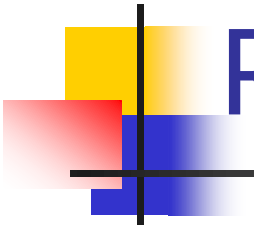
Thread 1	Thread 2
x = 1;	y = 1;
r1 = y;	r2 = x;

- Can r1 == r2 == 0?
  - No interleaving gives this results, but...
  - Most hardware will allow it (store buffers)
  - Many compilers will allow it (instruction scheduling)

What is a correct execution?

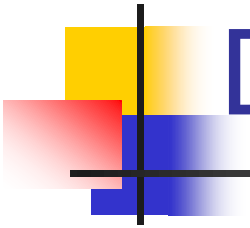


- Simplest notion: *sequential consistency* (Lamport '79)
  "... the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program."
- This is essentially the interleaving model
- Too expensive (?)
  - Nobody implements this in practice



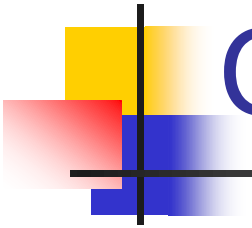
Refined notion

- Guarantee sequential consistency only for *correctly synchronized* programs (Adve)
  - Give the programmer rules to follow
  - Give simple semantics when rules are obeyed
- Correctly synchronized
  - Must be intuitive to programmer
  - Must not be restrictive for implementer



Data races

- Two operations *conflict* if they both access a memory location and one is a write
- A execution contains a *data race* if two adjacent operations from two different threads conflict
  - x = 1; y = 1; r1 = y; r2 = x;
- A program is *race free* if no sequentially consistent execution (i.e., interleaving) has a data race



Correct synchronization

- We call a program *correctly synchronized* if it is data race free
- Basic contract:
  - If programmers write race free programs, implementers will provide sequentially consistent semantics
  - This is the fundamental underpinning for Java, C, and C++ memory models

How do we avoid races?

- Mutual exclusion:
  - Thread acquires lock before accessing a shared variable:

```
Thread 1                    Thread 2
  lock (mutex);               lock (mutex);
  tmp1 = x;                   tmp3 = x;
  tmp2 = tmp1 + 1;            tmp4 = tmp3 + 1;
  x = tmp2                    x = tmp4
  unlock (mutex);             unlock (mutex);
```

  - Locks disallow problematic interleavings

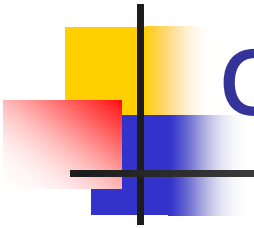
How do we avoid races?

- Volatile variables (atomic in new C++):
  - Certain variables are declared with stronger ordering semantics (initially, x and flag are 0):

```
Thread 1                    Thread 2
  x = 1;                      if (flag == 1)
  flag = 1;                     t = x;
```

  - If flag is declared volatile, then write to x cannot be sunk in T1 and read from x cannot be hoisted in T2 by definition
    - Compiler must respect ordering

What does this mean for compilers?



- In the absence of synchronization, compilers may *almost* operate as if programs were single-threaded
- Compilers must respect ordering due to synchronization (and generate necessary hardware instructions)
- Caveat: compiler must not introduce races into correctly synchronized code (e.g. register promotion)

What happens on a race?

- In C++, undefined semantics

Thread 1 (x == y == 0) Thread 2

```
x = 1;   (a)        y = 1;   (c)
r1 = y;  (b)        r2 = x;  (d)
```

- Valid results:

What happens on a race?

- In C++, undefined semantics

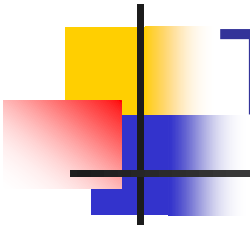
```
Thread 1     (x == y == 0)     Thread 2
 x = 1;    (a)                   y = 1;    (c)
 r1 = y;   (b)                   r2 = x;   (d)
```

- Valid results:
  - r1 = 0 and r2 = 0
  - r1 = 0 and r2 = 2
  - “format c:\”
- No such thing as a benign race in C++!

Hard to bound effects

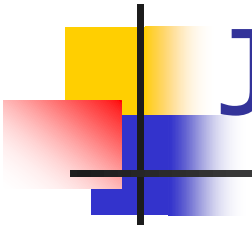
```
unsigned x;

if (x < 3) {
  // x modified by another
  // thread
  switch (x) {
    case 0: ...
    case 1: ...
    case 2: ...
  }
}
```

- Compiler should be able to generate table
  - Assumes x in range after check
  - Async change to x causes arbitrary behavior



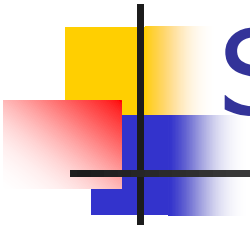
Type-safety issues

- In Java, data races cannot violate type safety
  - Java promises a measure of security
  - Synchroization errors may be used on purposed by untrusted code to open / exploit holes
  - Java memory model must provide some guarantees in the presence of races



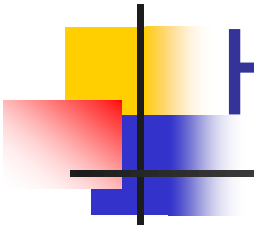
Java ordering

- Java's memory model defines a partial order over all actions in a program
  - For each thread, actions must happen in program order
  - Globally, synchronization actions must be totally ordered
  - These two must be consistent



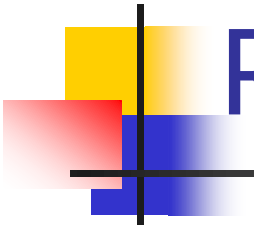
Synchronization edges

- A *synchronization edge* is defined from each release to each matching acquire that follows in synchronization order
  - A volatile write has an edge to all later volatile reads to the same variable
  - An unlock has an edge to all later lock operations to the same monitor



Happens-before

- Java defines a *happens-before* relationship as the transitive closure over program order and synchronization edges
- A read r is not allowed to see a write w to the same variable v if
  - r happens before w or
  - there exists another write w' to v such that w happens before w' happens before r
  - otherwise, r may see w



Races in Java

- Incorrectly synchronization programs in Java must still obey happens-before
- Additional subtle restrictions:
  - final fields
  - causal safety
- Much more in Manson's thesis, related papers, and Java 5.0 specification
  - And still not the end of the story…