Design of Parallel and High-Performance Computing

Fall 2016

Lecture: Languages and Locks

Motivational video: *https://www.youtube.com/watch?v=1o4YViBAGU0*

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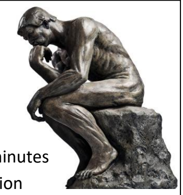
Administrivia

- **Final project presentation: Monday 12/18 during last lecture**
  - Report will be due in January!
    Still, starting to write early is very helpful --- write – rewrite – rewrite (no joke!)
  - Some more ideas what to talk about:
    What tools/programming language/parallelization scheme do you use?
    Which architecture? (we only offer access to Xeon Phi, you may use different)
    How to verify correctness of the parallelization?
    How to argue about performance (bounds, what to compare to?)
    (Somewhat) realistic use-cases and input sets?
    What are the key concepts employed?
    What are the main obstacles?

Review of last lecture

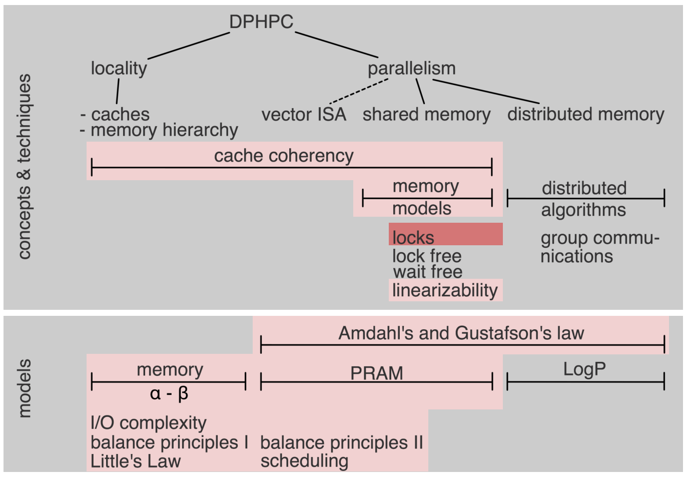
- **Locked Queue**
  - Correctness
  - Lock-free two-thread queue
- **Linearizability**
  - Combine object pre- and postconditions with serializability
  - Additional (semantic) constraints!
- **Histories**
  - Analyze given histories
    Projections, Sequential/Concurrent, Completeness, Equivalence, Well formed, Linearizability (formal)

Peer Quiz



- **Instructions:**
  - Pick some partners (locally) and discuss each question for 2 minutes
  - We then select a random student (team) to answer the question
- **How can histories be used to proof a parallel code correct?**
  - How do histories relate to the source code?
  - Can proofing be automated?
- **What are the practical limits of linearizability?**
  - Can it always be applied?
  - Is there a performance tradeoff? Always? Sometimes? Never?

DPHPC Overview



Goals of this lecture

- **Languages and Memory Models**
  - Java/C++ definition
- **Recap sequential consistency**
  - Races (now in practice)
- **Mutual exclusion**
- **Locks**
  - Two-thread
  - Peterson
  - N-thread
  - Many different locks, strengths and weaknesses
  - Lock options and parameters
- **Problems and outline to next class**

Language Memory Models

- **Which transformations/reorderings can be applied to a program**
- **Affects platform/system**
  - Compiler, (VM), hardware
- **Affects programmer**
  - What are possible semantics/output
  - Which communication between threads is legal?
- **Without memory model**
  - Impossible to even define "legal" or "semantics" when data is accessed concurrently
- **A memory model is a contract**
  - Between platform and programmer

History of Memory Models

- **Java's original memory model was broken [1]**
  - Difficult to understand => widely violated
  - Did not allow reorderings as implemented in standard VMs
  - Final fields could appear to change value without synchronization
  - Volatile writes could be reordered with normal reads and writes

    => counter-intuitive for most developers
- **Java memory model was revised [2]**
  - Java 1.5 (JSR-133)
  - Still some issues (operational semantics definition [3])
- **C/C++ didn't even have a memory model until much later**
  - Not able to make any statement about threaded semantics!
  - Introduced in C++11 and C11
  - Based on experience from Java, more conservative

[1] Pugh: "The Java Memory Model is Fatally Flawed", CCPE 2000
[2] Manson, Pugh, Adve: "The Java memory model", POPL'05
[3] Aspinall, Sevcik: "Java memory model examples: Good, bad and ugly", VAMP'07

Everybody wants to optimize

- **Language constructs for synchronization**
  - Java: volatile, synchronized, …
  - C++: atomic, (**NOT volatile**!), mutex, …
- **Without synchronization (defined language-specific)**
  - Compiler, (VM), architecture
  - Reorder and appear to reorder memory operations
  - Maintain sequential semantics per thread
  - Other threads may observe any order (have seen examples before)

Java and C++ High-level overview

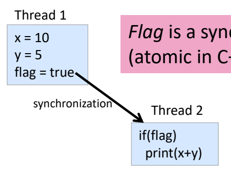
- **Relaxed memory model**
  - No global visibility ordering of operations
  - Allows for standard compiler optimizations
- **But**
  - Program order for each thread (sequential semantics)
  - Partial order on memory operations (with respect to synchronizations)
  - Visibility function defined
- **Correctly synchronized programs**
  - Guarantee sequential consistency
- **Incorrectly synchronized programs**
  - Java: maintain safety and security guarantees

    Type safety etc. (require behavior bounded by causality)
  - C++: undefined behavior

    No safety (anything can happen/change)

Communication between threads: Intuition

- **Not guaranteed unless by:**
  - Synchronization
  - Volatile/atomic variables
  - Specialized functions/classes (e.g., java.util.concurrent, …)



```
x = 10
y = 5
flag = true
```

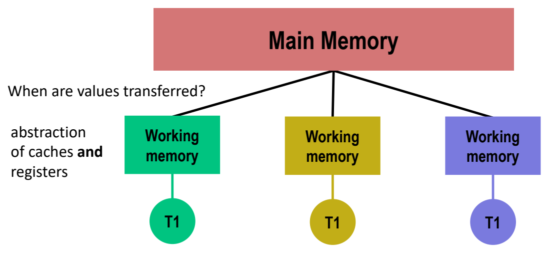
```
if(flag)
  print(x+y)
```

Flag is a synchronization variable (atomic in C++, volatile in Java),

i.e., all memory written by T1 must be visible to T2 after it reads the value true for *flag*!

Recap: Memory Model (Intuition)

- **Abstract relation between threads and memory**
  - Local thread view!


Main Memory
When are values transferred?
abstraction of caches and registers
Working memory
Working memory
Working memory
T1
T1
T1

- **Does not talk about classes, objects, methods, …**
  - Linearizability is a higher-level concept!

Lock synchronization

- **Java**

```
synchronized (lock) {
  // critical region
}
```

  - Synchronized methods as syntactic sugar

- **C++ (RAII)**

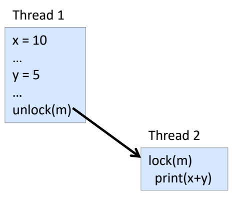
```
{
  unique_lock<mutex> l(lock);
  // critical region
}
```

  - Many flexible variants

- **Semantics:**
  - mutual exclusion
  - at most one thread may hold a lock at a time
  - a thread B trying to acquire a lock held by thread A blocks until thread A releases the lock
  - note: threads may wait forever (no progress guarantee!)

Memory semantics

- **Similar to synchronization variables**



```
x = 10
…
y = 5
…
unlock(m)
```

```
lock(m)
  print(x+y)
```

  - All memory accesses before an unlock …
  - are ordered before and are visible to …
  - any memory access after a matching lock!

Synchronization variables

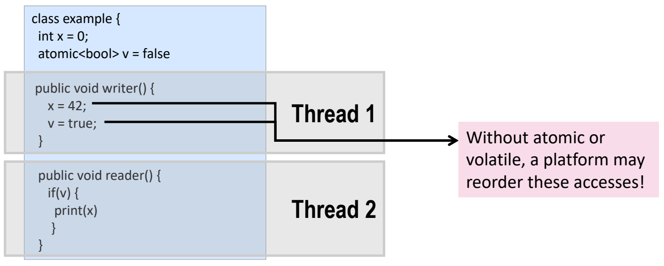
- **Variables can be declared volatile (Java) or atomic (C++)**

- **Reads and writes to synchronization variables**
  - Are totally ordered with respect to all threads
  - Must not be reordered with normal reads and writes

- **Compiler**
  - Must not allocate synchronization variables in registers
  - Must not swap variables with synchronization variables
  - May need to issue memory fences/barriers
  - …

Synchronization variables

- **Write to a synchronization variable**
  - Similar memory semantics as unlock (no process synchronization!)
- **Read from a synchronization variable**
  - Similar memory semantics as lock (no process synchronization!)


Thread 1
Thread 2
Without atomic or volatile, a platform may reorder these accesses!

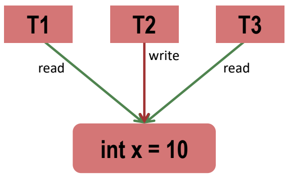
```
class example {
  int x = 0;
  atomic<bool> v = false

  public void writer() {
    x = 42;
    v = true;
  }

  public void reader() {
    if(v) {
      print(x)
    }
  }
```

Intuitive memory model rules

- **Java/C++: Correctly synchronized programs will execute sequentially consistent**
- **Correctly synchronized = data-race free**
  - iff all sequentially consistent executions are free of data races
- **Two accesses to a shared memory location form a data race in the execution of a program if**
  - The two accesses are from different threads
  - At least one access is a write and
  - The accesses are not synchronized



Case Study: Locks - Lecture Goals

- **Among the simplest concurrency constructs**
  - Yet, complex enough to illustrate many optimization principles
- **Goal 1: You understand locks in detail**
  - Requirements / guarantees
  - Correctness / validation
  - Performance / scalability
- **Goal 2: Acquire the ability to design your own locks**
  - Understand techniques and weaknesses/traps
  - Extend to other concurrent algorithms

    Issues are very much the same
- **Goal 3: Feel the complexity of shared memory!**

Preliminary Comments

- **All code examples are in C/C++ style**
  - Neither C nor C++ <11 have a clear memory model
  - C++ is one of the languages of choice in HPC
  - Consider source as exemplary (and pay attention to the memory model)!

    In fact, many/most of the examples are incorrect in anything but sequential consistency!

    In fact, you'll most likely not need those algorithms, but the principles will be useful!
- **x86 is really only used because it is common**
  - This does not mean that we consider the ISA or memory model elegant!
  - We assume atomic memory (or registers)!

    Usually given on x86 (easy to enforce)
- **Number of threads/processes is p, tid is the thread id**

Recap Concurrent Updates

```
const int n=1000;
volatile int a=0;
for (int i=0; i<n; ++i)
   a++;
```

gcc -O3

```
     movl  $1000, %eax     // i=n=1000
.L2:
     movl  (%rdx), %ecx     // ecx = *a
     addl  $1, %ecx         // ecx++
     subl  $1, %eax         // i—
     movl  %ecx, (%rdx)     // *a = ecx
     jne   .L2              // loop if i>0
```

- **Multi-threaded execution!**
  - Value of a for p=1?
  - Value of a for p>1?

    Why? Isn't it a single instruction?

```
const int n=1000;
std::atomic<int> a;
a=0;
for (int i=0; i<n; ++i)
   a++;
```

g++ -O3

```
     movl  $1000, %eax     // i=n=1000
     movl  $0, -24(%rsp)   // a = 0
     mfence                // a is visible!
.L2:
     lock addl $1 , -24(%rsp)  // (*a)++
     subl  $1, %eax         // i—
     jne   .L2              // loop if i>0
```

One instruction less! Performance!?

- **run with larger n (10^8)**
- **Compiler: gcc version 4.9.2 (enabled experimental c++11 support, -O3)**
- **Single-threaded execution only!**

```
const int n= 10^8;
volatile int a=0;
for (int i=0; i<n; ++i)
   a++;
```

0.23s

```
const int n= 10^8;
std::atomic<int> a;
a=0;
for (int i=0; i<n; ++i)
   a++;
```

Guess! 0.78s

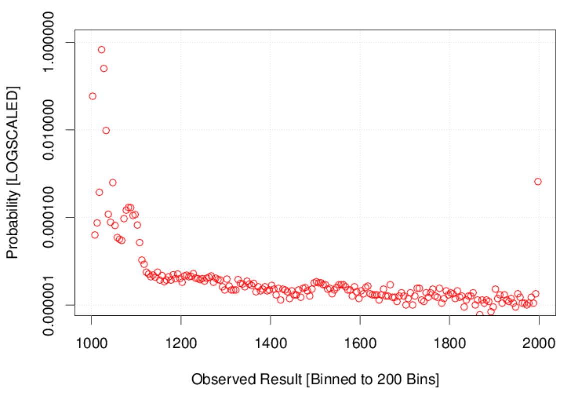
Schweizer, Besta, Hoefler: "Evaluating the Cost of Atomic Operations on Modern Architectures", PACT'15

Some Statistics

- **Nondeterministic execution**
  - Result depends on timing (probably not desired)
- **What do you think are the most significant results?**
  - Running two threads on Core i5 dual core
  - a=1000? 2000? 1500? 1223? 1999?

```
const int n=1000;
volatile int a=0;
for (int i=0; i<n; ++i)
   a++;
```

Some Statistics

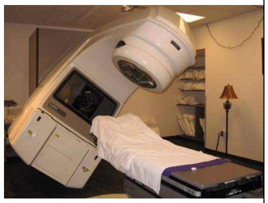


Conflicting Accesses

- **(recap) two memory accesses conflict if they can happen at *the same time* (in happens-before) and one of them is a write (store)**
- **Such a code is said to have a "race condition"**
  - Also data-race
  - Trivia around races:

    The Therac-25 killed three people due to a race

    A data-race lead to a large blackout in 2003, leaving 55 million people without power causing $1bn damage
- **Can be avoided by critical regions**
  - Mutually exclusive access to a set of operations



Mutual Exclusion

- **Control access to a critical region**
  - Memory accesses of all processes happen in program order (a partial order, many interleavings)

    An execution history defines a total order of memory accesses
  - Some subsets of memory accesses (issued by the same process) need to happen atomically (thread a's memory accesses may not be interleaved with other thread's accesses)

    To achieve linearizability!

    We need to restrict the valid executions
- **→ Requires synchronization of some sort**
  - Many possible techniques (e.g., TM, CAS, T&S, …)
  - We first discuss locks which have wait semantics

```
    movl   $1000, %eax    // i=1000
.L2:
    movl   (%rdx), %ecx   // ecx = *a
    addl   $1, %ecx       // ecx++
    subl   $1, %eax       // i—
    movl   %ecx, (%rdx)   // *a = ecx
    jne    .L2            // loop if i>0
```

Fixing it with locks

```
const int n=1000;
volatile int a=0;
omp_lock_t lck;
for (int i=0; i<n; ++i) {
  omp_set_lock(&lck);
  a++;
  omp_unset_lock(&lck);
}
```

gcc -O3

```
    movl  $1000, %ebx    // i=1000
.L2:
    movq  0(%rbp), %rdi  // (SystemV CC)
    call  omp_set_lock   // get lock
    movq  0(%rbp), %rdi  // (SystemV CC)
    movl  (%rax), %edx   // edx = *a
    addl  $1, %edx       // edx++
    movl  %edx, (%rax)   // *a = edx
    call  omp_unset_lock // release lock
    subl  $1, %ebx       // i—
    jne   .L2            // repeat if i>0
```

- **What must the functions lock and unlock guarantee?**
  - **#1: prevent two threads from simultaneously entering CR**

    i.e., accesses to CR must be mutually exclusive!
  - **#2: ensure consistent memory**

    i.e., stores must be globally visible before new lock is granted!
- **Any performance guesses (remember, 0.23s → 0.78s for atomics)**
  - **2.26s**

Lock Overview

- **Lock/unlock or acquire/release**
  - Lock/acquire: before entering CR
  - Unlock/release: after leaving CR
- **Semantics:**
  - Lock/unlock pairs have to match
  - Between lock/unlock, a thread holds the lock

Desired Lock Properties

- **Mutual exclusion**
  - Only one thread is on the critical region
- **Consistency**
  - Memory operations are visible when critical region is left
- **Progress**
  - If any thread a is not in the critical region, it cannot prevent another thread b from entering
- **Starvation-freedom (implies deadlock-freedom)**
  - If a thread is requesting access to a critical region, then it will eventually be granted access
- **Fairness**
  - A thread a requested access to a critical region before thread b. Did is also granted access to this region before b?
- **Performance**
  - Scaling to large numbers of contending threads

?

Simplified Notation (cf. Histories)

- **Time defined by precedence (a total order on events)**
  - Events are instantaneous (linearizable)
  - Threads produce sequences of events a_0,a_1,a_2,…
  - Program statements may be repeated, denote i-th instance of a as a^i
  - Event a occurs before event b: a → b
  - An interval (a,b) is the duration between events a → b
  - Interval I_1=(a,b) precedes interval I_2=(c,d) iff b → c
- **Critical regions**
  - A critical region CR is an interval (a,b), where a is the first operation in the CR and b the last
- **Mutual exclusion**
  - Critical regions CR_A and CR_B are mutually exclusive if:

    Either $CR_A \rightarrow CR_B$ or $CR_B \rightarrow CR_A$ for all valid executions!
- **Assume atomic registers (for now)**

Simple Two-Thread Locks

- **A first simple spinlock**

```
volatile int flag=0;

void lock() {
  while(flag);
  flag = 1;
}

void unlock() {
  flag = 0;
}
```

Busy-wait to acquire lock (spinning)

Is this lock correct?

Why does this not guarantee mutual exclusion?

Proof Intuition

- **Construct a sequentially consistent history that permits both processes to enter the CR**

Simple Two-Thread Locks

- **Another two-thread spin-lock: LockOne**

```
volatile int flag[2];

void lock() {
  int j = 1 - tid;
  flag[tid] = true;
  while (flag[j]) {} // wait
}

void unlock() {
  flag[tid] = false;
}
```

When and why does this guarantee mutual exclusion?

Correctness Proof

- **In sequential consistency!**
- **Intuitions:**
  - Situation: both threads are ready to enter
  - Show that situation that allows both to enter leads to a schedule violating sequential consistency

    Using transitivity of program and synchronization orders

Simple Two-Thread Locks

- **Another two-thread spin-lock: LockOne**

```
volatile int flag[2];

void lock() {
  int j = 1 - tid;
  flag[tid] = true;
  while (flag[j]) {} // wait
}

void unlock() {
  flag[tid] = false;
}
```

When and why does this guarantee mutual exclusion?

Does it work in practice?

Simple Two-Thread Locks

- **A third attempt at two-thread locking: LockTwo**

```
volatile int victim;

void lock() {
  victim = tid; // grant access
  while (victim == tid) {} // wait
}

void unlock() {}
```

Does this guarantee mutual exclusion?

Correctness Proof

- **Intuition:**
  - Victim is only written once per lock()
  - A can only enter after B wrote
  - B cannot enter in any sequentially consistent schedule

Simple Two-Thread Locks

- **A third attempt at two-thread locking: LockTwo**

```
volatile int victim;

void lock() {
  victim = tid; // grant access
  while (victim == tid) {} // wait
}

void unlock() {}
```

Does this guarantee mutual exclusion?

Does it work in practice?

Simple Two-Thread Locks

- **The last two locks provide mutual exclusion**
  - LockOne succeeds iff lock attempts do not overlap
  - LockTwo succeeds iff lock attempts do overlap
- **Combine both into one locking strategy!**
  - Peterson's lock (1981)

Peterson's Two-Thread Lock (1981)

- **Combines the first lock (request access) with the second lock (grant access)**

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1;      // I'm interested
  victim = tid;      // other goes first
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  flag[tid] = 0;  // I'm not interested
}
```

Proof Correctness

- **Intuition:**
  - Victim is written once
  - Pick thread that wrote victim last
  - Show thread must have read flag==0
  - Show that no sequentially consistent schedule permits that

Starvation Freedom

- **(recap) definition: Every thread that calls lock() eventually gets the lock.**
  - Implies deadlock-freedom!
- **Is Peterson's lock starvation-free?**

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1;      // I'm interested
  victim = tid;      // other goes first
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  flag[tid] = 0;  // I'm not interested
}
```

Proof Starvation Freedom

- **Intuition:**
  - Threads can only wait/starve in while()
    Until flag==0 or victim==other
  - Other thread enters lock() → sets victim to other
    Will definitely "unstuck" first thread
  - So other thread can only be stuck in lock()
    Will wait for victim==other, victim cannot block both threads → one must leave!

Peterson in Practice … on x86

- **Implement and run our little counter on x86**
- **100000 iterations**
  - $1.6 \cdot 10^{-6}$% errors
  - What is the problem?

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1;      // I'm interested
  victim = tid;      // other goes first
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  flag[tid] = 0;  // I'm not interested
}
```

Peterson in Practice … on x86

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  - What is the problem?

    No sequential consistency for W(v) and R(flag[j])

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1;      // I'm interested
  victim = tid;      // other goes first
  asm ("mfence");
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  flag[tid] = 0;  // I'm not interested
}
```

Peterson in Practice … on x86

- **Implement and run our little counter on x86**
- **100000 iterations**
  - $1.6 \cdot 10^{-6}$% errors
  - What is the problem?

    No sequential consistency for W(v) and R(flag[j])
  - Still $1.3 \cdot 10^{-6}$%

    Why?

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1;      // I'm interested
  victim = tid;      // other goes first
  asm ("mfence");
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  flag[tid] = 0;  // I'm not interested
}
```

Peterson in Practice … on x86

- **Implement and run our little counter on x86**
- **100000 iterations**
  - $1.6 \cdot 10^{-6}$% errors
  - What is the problem?

    No sequential consistency for W(v) and R(flag[j])
  - Still $1.3 \cdot 10^{-6}$%

    Why?

    Reads may slip into CR!

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1;      // I'm interested
  victim = tid;      // other goes first
  asm ("mfence");
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  asm ("mfence");
  flag[tid] = 0;  // I'm not interested
}
```

Correct Peterson Lock on x86

- **Unoptimized (naïve sprinkling of mfences)**
- **Performance:**
  - No mfence

    375ns
  - mfence in lock

    379ns
  - mfence in unlock

    404ns
  - Two mfence

    427ns (+14%)

```
volatile int flag[2];
volatile int victim;

void lock() {
  int j = 1 - tid;
  flag[tid] = 1;      // I'm interested
  victim = tid;      // other goes first
  asm ("mfence");
  while (flag[j] && victim == tid) {}; // wait
}

void unlock() {
  asm ("mfence");
  flag[tid] = 0;  // I'm not interested
}
```

Locking for N threads

- **Simple generalization of Peterson's lock, assume n levels l = 0…n-1**
  - Is it correct?

```
volatile int level[n] = {0,0,…,0}; // indicates highest level a thread tries to enter
volatile int victim[n]; // the victim thread, excluded from next level
void lock() {
  for (int i = 1; i < n; i++) { //attempt level i
    level[tid] = i;
    victim[i] = tid;
    // spin while conflicts exist
    while ((∃k != tid) (level[k] >= i && victim[i] == tid )) {};
  }
}

void unlock() {
  level[tid] = 0;
}
```

Filter Lock - Correctness

- **Lemma: For 0<j<n-1, there are at most n-j threads at level j!**
- **Intuition:**
  - Recursive proof (induction on j)
  - By contradiction, assume n-j+1 threads at level j-1 and j
  - Assume last thread to write victim
  - Any other thread writes level before victim
  - Last thread will stop at spin due to other thread's write
- **j=n-1 is critical region**

Locking for N threads

- **Simple generalization of Peterson's lock, assume n levels l = 0…n-1**
  - Is it starvation-free?

```
volatile int level[n] = {0,0,…,0}; // indicates highest level a thread tries to enter
volatile int victim[n]; // the victim thread, excluded from next level
void lock() {
  for (int i = 1; i < n; i++) { //attempt level i
    level[tid] = i;
    victim[i] = tid;
    // spin while conflicts exist
    while ((∃k != tid) (level[k] >= i && victim[i] == tid )) {};
  }
}

void unlock() {
  level[tid] = 0;
}
```

Filter Lock Starvation Freedom

- **Intuition:**
  - Inductive argument over j (levels)
  - Base-case: level n-1 has one thread (not stuck)
  - Level j: assume thread is stuck

    Eventually, higher levels will drain (induction)

    Last entering thread is victim, it will wait

    Thus, only one thread can be stuck at each level

    Victim can only have one value → older threads will advance!

Filter Lock

- **What are the disadvantages of this lock?**

```
volatile int level[n] = {0,0,…,0}; // indicates highest level a thread tries to enter
volatile int victim[n]; // the victim thread, excluded from next level
void lock() {
  for (int i = 1; i < n; i++) { // attempt level i
    level[tid] = i;
    victim[i] = tid;
    // spin while conflicts exist
    while ((∃k != tid) (level[k] >= i && victim[i] == tid )) {};
  }
}

void unlock() {
  level[tid] = 0;
}
```

Lock Fairness

- **Starvation freedom provides no guarantee on how long a thread waits or if it is "passed"!**
- **To reason about fairness, we define two sections of each lock algorithm:**
  - Doorway D (bounded # of steps)
  - Waiting W (unbounded # of steps)

```
void lock() {
  int j = 1 - tid;
  flag[tid] = true; // I'm interested
  victim = tid;      // other goes first
  while (flag[j] && victim == tid) {};
}
```

- **FIFO locks:**
  - If T_A finishes its doorway before T_B the $CR_A \rightarrow CR_B$
  - Implies fairness

Lamport's Bakery Algorithm (1974)

- **Is a FIFO lock (and thus fair)**
- **Each thread takes a number in the doorway and threads enter in the order of their number!**

```
volatile int flag[n] = {0,0,…,0};
volatile int label[n] = {0,0,….,0};

void lock() {
  flag[tid] = 1; // request
  label[tid] = max(label[0], ...,label[n-1]) + 1; // take ticket
  while ((∃k != tid)(flag[k] && (label[k],k) <* (label[tid],tid))) {};
}
public void unlock() {
  flag[tid] = 0;
}
```

Lamport's Bakery Algorithm (1974)

- **Advantages:**
  - Elegant and correct solution
  - Starvation free, even FIFO fairness
- **Not used in practice!**
  - Why?
  - Needs to read/write N memory locations for synchronizing N threads
  - Can we do better?

    Using only atomic registers/memory

A Lower Bound to Memory Complexity

- **Theorem 5.1 in [1]: *"If S is a [atomic] read/write system with at least two processes and S solves mutual exclusion with global progress [deadlock-freedom], then S must have at least as many variables as processes"***
- **So we're doomed! Optimal locks are available and they're fundamentally non-scalable. Or not?**

[1] J. E. Burns and N. A. Lynch. Bounds on shared memory for mutual exclusion. Information and Computation, 107(2):171–184, December 1993

Hardware Support?

- **Hardware atomic operations:**
  - Test&Set

    Write const to memory while returning the old value
  - Atomic swap

    Atomically exchange memory and register
  - Fetch&Op

    Get value and apply operation to memory location
  - Compare&Swap

    Compare two values and swap memory with register if equal
  - Load-linked/Store-Conditional LL/SC

    Loads value from memory, allows operations, commits only if no other updates committed $\rightarrow$ mini-TM
  - Intel TSX (transactional synchronization extensions)

    Hardware-TM (roll your own atomic operations)

Relative Power of Synchronization

- **Design-Problem I: Multi-core Processor**
  - Which atomic operations are useful?
- **Design-Problem II: Complex Application**
  - What atomic should I use?
- **Concept of "consensus number" C if a primitive can be used to solve the "consensus problem" in a finite number of steps (even if threads stop)**
  - atomic registers have C=1 (thus locks have C=1!)
  - TAS, Swap, Fetch&Op have C=2
  - CAS, LL/SC, TM have C=∞

Test-and-Set Locks

- **Test-and-Set semantics**
  - Memoize old value
  - Set fixed value TASval (true)
  - Return old value
- **After execution:**
  - Post-condition is a fixed (constant) value!

```
bool test_and_set (bool *flag) {
  bool old = *flag;
  *flag = true;
  return old;
} // all atomic!
```

Test-and-Set Locks

- **Assume TASval indicates "locked"**
- **Write something else to indicate "unlocked"**
- **TAS until return value is != TASval (1 in this example)**
- **When will the lock be granted?**
- **Does this work well in practice?**

```
volatile int lck = 0;

void lock() {
  while (TestAndSet(&lck) == 1);
}

void unlock() {
  lck = 0;
}
```

Contention

- **On x86, the XCHG instruction is used to implement TAS**
  - x86 lock is implicit in xchg!
- **Cacheline is read and written**
  - Ends up in exclusive state, invalidates other copies
  - Cacheline is "thrown" around uselessly
  - High load on memory subsystem

    x86 lock is essentially a full memory barrier ☹

```
movl   $1, %eax
xchg   %eax, (%ebx)
```

Test-and-Test-and-Set (TATAS) Locks

- **Spinning in TAS is not a good idea**
- **Spin on cache line in shared state**
  - All threads at the same time, no cache coherency/memory traffic
- **Danger!**
  - Efficient but use with great care!
  - Generalizations are very dangerous

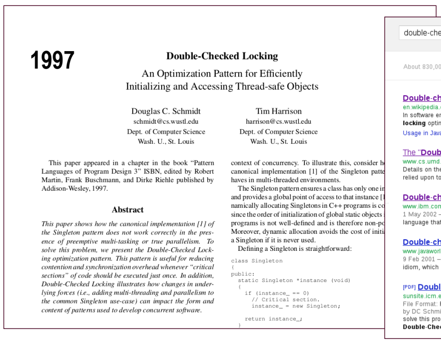
```
volatile int lck = 0;

void lock() {
  do {
    while (lck == 1);
  } while (TestAndSet(&lck) == 1);
}

void unlock() {
  lck = 0;
}
```

Warning: Even Experts get it wrong!

- **Example: Double-Checked Locking**



1997

Double-Checked Locking

An Optimization Pattern for Efficiently
Initializing and Accessing Thread-safe Objects

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This paper appeared in a chapter in the book "Pattern Languages of Program Design 3" ISBN, edited by Robert Martin, Frank Buschmann, and Dirke Riehle published by Addison-Wesley, 1997.

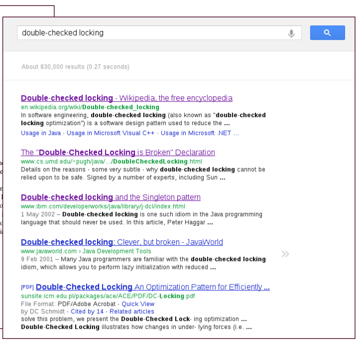
Abstract

This paper shows how the canonical implementation [1] of the Singleton pattern does not work correctly in the presence of preemptive multi-tasking or true parallelism. To solve this problem, we present the Double-Checked Locking optimization pattern. This pattern is useful for reducing contention and synchronization overhead whenever "critical sections" of code should be executed just once. In addition, Double-Checked Locking illustrates how changes in underlying forces (i.e., adding multi-threading and parallelism to the common Singleton use-case) can impact the form and content of patterns used to develop concurrent software.

context of concurrency. To illustrate this, consider h
canonical implementation [1] of the Singleton patte
haves in multi-threaded environments.
The Singleton pattern ensures a class has only one in
and provides a global point of access to that instance [
namically allocating Singletons in C++ programs is co
since the order of initialization of global static objects
programs is not well-defined and is therefore non-po
Moreover, dynamic allocation avoids the cost of initi
a Singleton if it is never used.
Defining a Singleton is straightforward:

```
class Singleton
{
public:
  static Singleton *instance (void)
  {
    if (instance_ == 0)
      // Critical section.
      instance_ = new Singleton;

    return instance_;
  }
```



double-checked locking

About 830,000 results (0.27 seconds)

Double-checked locking - Wikipedia, the free encyclopedia
en.wikipedia.org/wiki/**Double-checked_locking**
In software engineering, **double-checked locking** (also known as "**double-checked locking** optimization") is a software design pattern used to reduce the **...**
Usage in Java · Usage in Microsoft Visual C++ · Usage in Microsoft .NET ...

The "**Double-Checked Locking** is Broken" Declaration
www.cs.umd.edu/~pugh/java/.../**DoubleCheckedLocking**.html
Details on the reasons · some very subtle · why **double-checked locking** cannot be relied upon to be safe. Signed by a number of experts, including Sun **...**

Double-checked locking and the Singleton pattern
www.ibm.com/developerworks/java/library/j-dcl/index.html
1 May 2002 – **Double-checked locking** is one such idiom in the Java programming language that should never be used. In this article, Peter Haggar **...**

Double-checked locking: Clever, but broken - JavaWorld
www.javaworld.com › Java Development Tools
9 Feb 2001 – Many Java programmers are familiar with the **double-checked locking** idiom, which allows you to perform lazy initialization with reduced **...**

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by DC Schmidt · Cited by 14 · Related articles
solve this problem, we present the **Double-Checked Lock**- ing optimization **...**
Double-Checked Locking illustrates how changes in under- lying forces (i.e. **...**

Problem: Memory ordering leads to race-conditions!

Contention?

- **Do TATAS locks still have contention?**
- **When lock is released, k threads fight for cache line ownership**
  - One gets the lock, all get the CL exclusively (serially!)
  - What would be a good solution? (think "collision avoidance")

```
volatile int lck = 0;

void lock() {
  do {
    while (lck == 1);
  } while (TestAndSet(&lck) == 1);
}

void unlock() {
  lck = 0;
}
```

TAS Lock with Exponential Backoff

- **Exponential backoff eliminates contention statistically**
  - Locks granted in unpredictable order
  - Starvation possible but unlikely

    How can we make it even less likely?

```
volatile int lck = 0;

void lock() {
  while (TestAndSet(&lck) == 1) {
    wait(time);
    time *= 2; // double waiting time
  }
}

void unlock() {
  lck = 0;
}
```

Similar to: T. Anderson: "The performance of spin lock alternatives for shared-memory multiprocessors", TPDS, Vol. 1 Issue 1, Jan 1990

TAS Lock with Exponential Backoff

- **Exponential backoff eliminates contention statistically**
  - Locks granted in unpredictable order
  - Starvation possible but unlikely

    Maximum waiting time makes it less likely

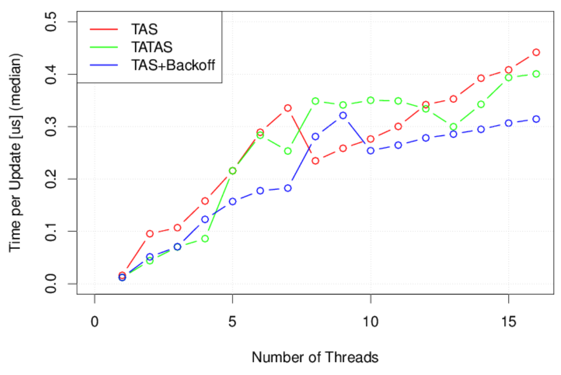
```
volatile int lck = 0;
const int maxtime=1000;

void lock() {
  while (TestAndSet(&lck) == 1) {
    wait(time);
    time = min(time * 2, maxtime);
  }
}

void unlock() {
  lck = 0;
}
```

Similar to: T. Anderson: "The performance of spin lock alternatives for shared-memory multiprocessors", TPDS, Vol. 1 Issue 1, Jan 1990

Comparison of TAS Locks



Improvements?

- **Are TAS locks perfect?**
  - What are the two biggest issues?
  - Cache coherency traffic (contending on same location with expensive atomics)

    -- or --
  - Critical section underutilization (waiting for backoff times will delay entry to CR)
- **What would be a fix for that?**
  - How is this solved at airports and shops (often at least)?
- **Queue locks -- Threads enqueue**
  - Learn from predecessor if it's their turn
  - Each threads spins at a different location
  - FIFO fairness

Array Queue Lock

- **Array to implement queue**
  - Tail-pointer shows next free queue position
  - Each thread spins on own location

    CL padding!
  - index[] array can be put in TLS
- **So are we done now?**
  - What's wrong?
  - Synchronizing M objects requires Θ(NM) storage
  - What do we do now?

```
volatile int array[n] = {1,0,…,0};
volatile int index[n] = {0,0,…,0};
volatile int tail = 0;

void lock() {
  index[tid] = GetAndInc(tail) % n;
  while (!array[index[tid]]); // wait to receive lock
}

void unlock() {
  array[index[tid]] = 0; // I release my lock
  array[(index[tid] + 1) % n] = 1; // next one
}
```

CLH Lock (1993)

- **List-based (same queue principle)**
- **Discovered twice by Craig, Landin, Hagersten 1993/94**
- **2N+3M words**
  - N threads, M locks
- **Requires thread-local qnode pointer**
  - Can be hidden!

```
typedef struct qnode {
  struct qnode *prev;
  int succ_blocked;
} qnode;

qnode *lck = new qnode; // node owned by lock

void lock(qnode *lck, qnode *qn) {
  qn->succ_blocked = 1;
  qn->prev = FetchAndSet(lck, qn);
  while (qn->prev->succ_blocked);
}

void unlock(qnode **qn) {
  qnode *pred = (*qn)->prev;
  (*qn)->succ_blocked = 0;
  *qn = pred;
}
```

CLH Lock (1993)

- **Qnode objects represent thread state!**
  - succ_blocked == 1 if waiting or acquired lock
  - succ_blocked == 0 if released lock
- **List is implicit!**
  - One node per thread
  - Spin location changes

    NUMA issues (cacheless)
- **Can we do better?**

```
typedef struct qnode {
  struct qnode *prev;
  int succ_blocked;
} qnode;

qnode *lck = new qnode; // node owned by lock

void lock(qnode *lck, qnode *qn) {
  qn->succ_blocked = 1;
  qn->prev = FetchAndSet(lck, qn);
  while (qn->prev->succ_blocked);
}

void unlock(qnode **qn) {
  qnode *pred = (*qn)->prev;
  (*qn)->succ_blocked = 0;
  *qn = pred;
}
```

MCS Lock (1991)

- **Make queue explicit**
  - Acquire lock by appending to queue
  - Spin on own node until locked is reset
- **Similar advantages as CLH but**
  - Only 2N + M words
  - Spinning position is fixed!

    Benefits cache-less NUMA
- **What are the issues?**
  - Releasing lock spins
  - More atomics!

```
typedef struct qnode {
  struct qnode *next;
  int succ_blocked;
} qnode;

qnode *lck = NULL;

void lock(qnode *lck, qnode *qn) {
  qn->next = NULL;
  qnode *pred = FetchAndSet(lck, qn);
  if(pred != NULL) {
    qn->locked = 1;
    pred->next = qn;
    while(qn->locked);
} }

void unlock(qnode * lck, qnode *qn) {
  if(qn->next == NULL) { // if we're the last waiter
    if(CAS(lck, qn, NULL)) return;
    while(qn->next == NULL); // wait for pred arrival
  }
  qn->next->locked = 0; // free next waiter
  qn->next = NULL;
}
```

Lessons Learned!

- **Key Lesson:**
  - Reducing memory (coherency) traffic is most important!
  - Not always straight-forward (need to reason about CL states)
- **MCS: 2006 Dijkstra Prize in distributed computing**
  - "*an outstanding paper on the principles of distributed computing, whose significance and impact on the theory and/or practice of distributed computing has been evident for at least a decade*"
  - "*probably the most influential practical mutual exclusion algorithm ever*"
  - "*vastly superior to all previous mutual exclusion algorithms*"
  - fast, fair, scalable → widely used, always compared against!

Time to Declare Victory?

- **Down to memory complexity of 2N+M**
  - Probably close to optimal
- **Only local spinning**
  - Several variants with low expected contention
- **But: we assumed sequential consistency ☹**
  - Reality causes trouble sometimes
  - Sprinkling memory fences may harm performance
  - Open research on minimally-synching algorithms!

    Come and talk to me if you're interested