Effective Software

Lecture 8: Data races, synchronization, atomic operations, non-blocking algorithms

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[3] Russell, K., Detlefs, D.: Eliminating Synchronization-Related Atomic Operations with Biased Locking and Bulk Rebiasing in OOPSLA’06. ACM, USA 2006.

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Outline

- Data races
  - Superscalar execution
  - Memory barrier - Volatile variable
- Synchronization
  - Reentrant locks
- Atomic operations
  - Java support
  - Array-based atomic operations
  - Complex types
- Non-blocking algorithms
  - LIFO
  - ConcurrentHashMap

Data Races – Multi-threaded Environments

```java
public int A = 0;
public int B = 0;
public int C = 0;
public int D = 0;
```

Thread 1	Thread 2
`public void method1() { int r2 = A; B = 1; D = r2; }`	`public void method2() { int r1 = B; A = 2; C = r1; }`

- what can be the results for C and D?

Data Races – Multi-threaded Environments

```java
public int A = 0;
public int B = 0;
public int C = 0;
public int D = 0;
```

Thread 1	Thread 2

`public void method1() {`
`    int r2 = A;`
`    B = 1;`
`    D = r2;`
`}`
	`public void method2() {`
	`    int r1 = B;`
	`    A = 2;`
	`    C = r1;`
	`}`

» what can be the results for C and D?

- C=0, D=0
- C=1, D=0
- C=0, D=2
- anything else?

Data Races – Disassembled Method and Assembly Code

```java
public void method1() {
    int r2 = A;
    B = 1;
    D = r2;
}
```

```
 0: aload_0
 1: getfield      #2 // Field A:I
 4: istore_1
 5: aload_0
 6: iconst_1
 7: putfield      #3 // Field B:I
10: aload_0
11: iload_1
12: putfield      #5 // Field D:I
15: return
```

Heap object structure:

8B - mark word
4B / 8B – Klass ref.
… object data

Klass – internal JVM representation of class Metadata

4B – 32bit, or 64bit <32GB heap
8B – 64bit no compressedOOP

instructions **reordered in C2 compiler**:

RSI is **this**

```
0x000000010639924c: movl   $0x1,0x10(%rsi)     ;*putfield B
                                               ; - datarace.DataRace::method1@7 (line 11)

0x0000000106399253: mov    0xc(%rsi),%r11d
0x0000000106399257: mov    %r11d,0x18(%rsi)    ;*putfield D
                                               ; - datarace.DataRace::method1@12 (line 12)
```

note: all machine code examples are from JVM 8 64-bit <32GB, Intel Haswell CPU in AT&T syntax

- » **the same reordering happens in method2 resulting into fourth output**
  - **C=1, D=2**

Data Races – CPU Execution Pipelining

- simplified non-parallel instruction pipelining in **each core**

IF: Instruction fetch
ID : Instruction decode
EX : Execution
MEM: Memory access
WB : Write back

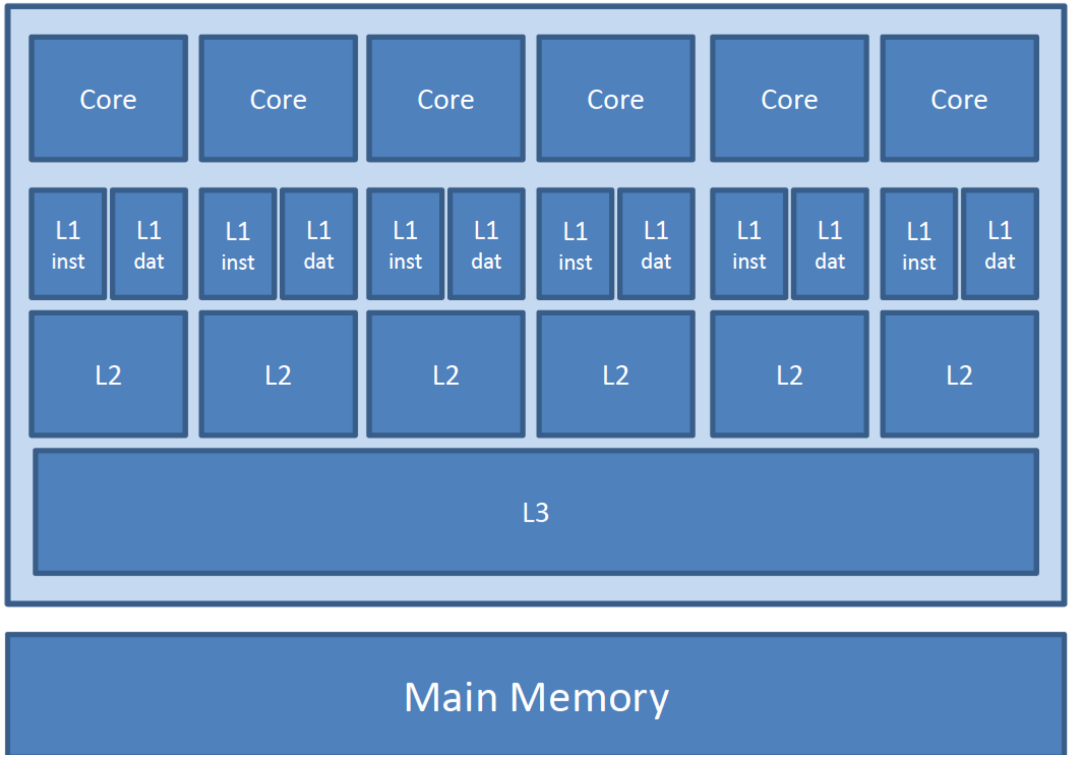
Cycles

Instruction #	1	2	3	4	5	6	7	8	9
Instruction i	IF	ID	EX	MEM	WB				
Instruction i+1		IF	ID	EX	MEM	WB			
Instruction i+2			IF	ID	EX	MEM	WB		
Instruction i+3				IF	ID	EX	MEM	WB	
Instruction i+4					IF	ID	EX	MEM	WB

- each step is parallelized as well, e.g. Haswell does 4 instructions in single cycle (execution depends on type and independency of instructions)

Data Races – CPU Memory Model

» CPU vs. core vs. thread



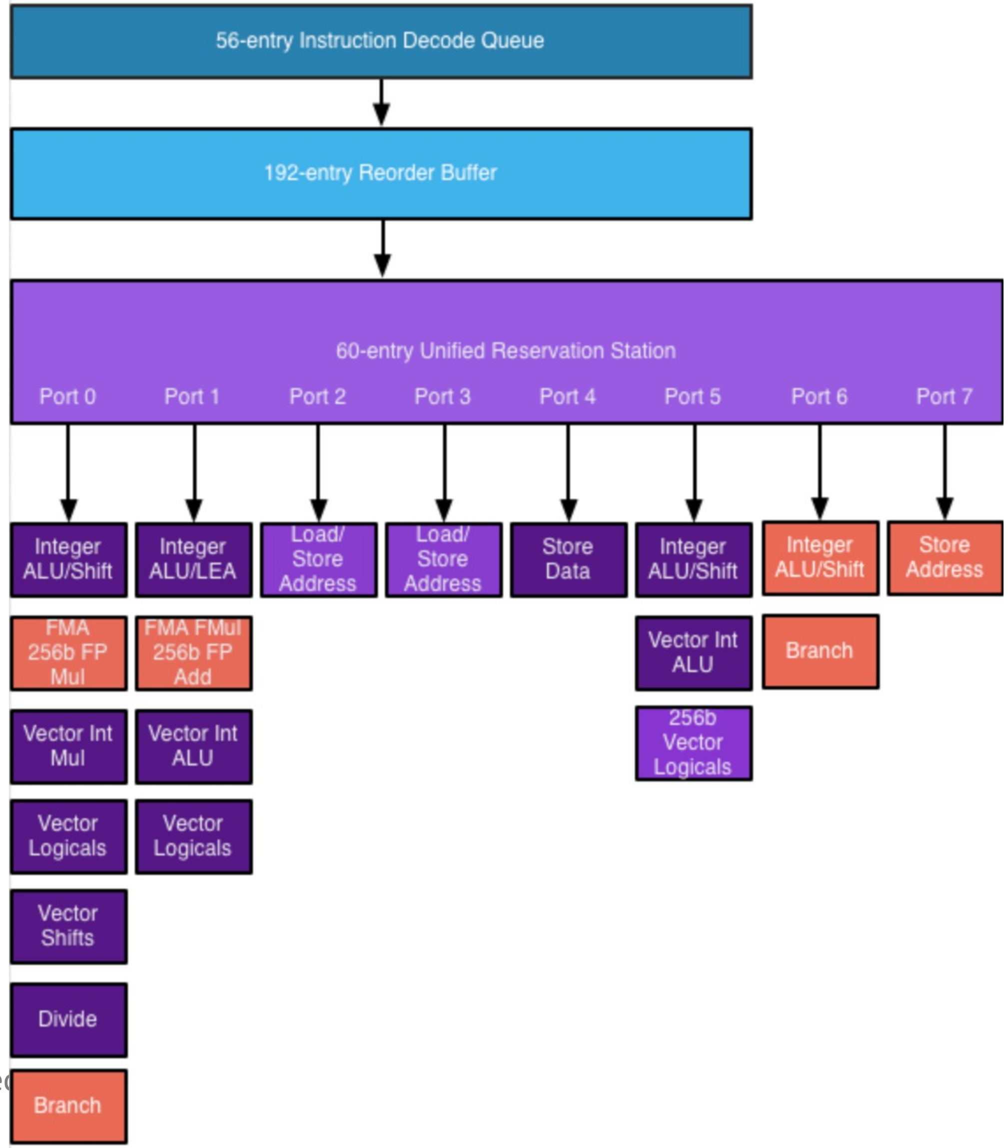
L1 Data Cache			
Size	Line Size	Latency	Associativty
32 KB	64 bytes	4 ns	8-way
L1 Instruction Cache			
Size	Line Size	Latency	Associativty
32 KB	64 bytes	4 ns	4-way
L2 Cache			
Size	Line Size	Latency	Associativty
256 KB	64 bytes	10 ns	8-way
L3 Cache			
Size	Line Size	Latency	Associativty
12 MB	64 bytes	50 ns	16-way
Main Memory			
Size	Line Size	Latency	Associativty
	64 bytes	75 ns	

» all writes to main memory are done in **write-back** cache mode

- standard writes requires data to be cached (expensive cache miss)
- non-temporal writes (especially useful for large block writes)
  - content directly queued to memory without caching at all
- prefetch instructions available

Data Races – CPU Execution Pipelining – Superscalar Execution

- » modern CPUs have multiple execution units **in each core** (8 in Intel Haswell)
  - units have various capabilities (4x integer ALU, 2x FPU mul, 2x mem read, …)
  - multiple **μops** with various latency executed **in parallel** during each per cycle
- » independent instructions can be **executed out-of-order** or in parallel
  - not using the same register or address
- » **memory reads are never reordered**
  - parallel independent reads
- » **later independent reads can be reordered and executed before writes**
  - serialized writes only



Volatile Variable – Memory Barrier

<u>making A and B volatile:</u>

```java
public volatile int A = 0;
public volatile int B = 0;
public int C = 0;
public int D = 0;

public void method1() {
    int r2 = A;
    B = 1;
    D = r2;
}
```

<u>results into assembly code:</u>

```
0x000000010710e08c: mov     0xc(%rsi),%r11d
0x000000010710e090: movl    $0x1,0x10(%rsi)
0x000000010710e097: lock addl $0x0,(%rsp)
0x000000010710e09c: mov     %r11d,0x18(%rsi)
```

8B - mark word
4B / 8B – Klass ref.
… object data

- memory operations over store in volatile are **not reordered** in C1/C2 compiler
- no need for **read** barriers – not reordered during execution in CPU
- instruction **lock prefix** **forbids all instruction reordering around** and **synchronize all previous writes to be visible by all other CPUs**
- *lock addl $0x0,(%rsp)* is fastest memory barrier – no operation inside CPU

Volatile Variable

» **never cached thread-locally** – all access directly to main memory

» guarantees **atomic read and write** operations (defines memory barrier)

» can be used for both primitives and references to objects

» don't block thread execution

» BUT:

- volatile writes are much slower due to cache flush (~100x)
- volatile reads **(if there are writes)** are slower (~25x, #CPU/cores)
  - due to invalidated cache
- still faster than synchronization/locks

» <u>not necessary for:</u>

- immutable objects
- variable accessed by only one thread (context switch properly flushes cache already)
- where variable is within complex synchronized operation

Counter Example - Volatile

```java
public class VolatileCounter {
    private volatile int cnt=0;

    public int get() {
        return cnt;
    }

    public void increment() {
        cnt++;
    }
}
```

» will it work as expected in multi-threaded environment?

Counter Example - Volatile

```java
public class VolatileCounter {
    private volatile int cnt=0;

    public int get() {
        return cnt;
    }

    public void increment() {
        cnt++;
    }
}
```

<u>increment assembly code:</u>

RSI is **this**

```
0x000000010911544c: mov    0xc(%rsi),%edi


0x000000010911544f: inc    %edi
0x0000000109115451: mov    %edi,0xc(%rsi)
0x0000000109115454: lock addl $0x0,(%rsp)
```

8B - mark word
4B / 8B – Klass ref.
… object data

» will it work as expected in multi-threaded environment?
NO

» **volatile**

- **not suitable for read-update-write operations**
- **useful for one-thread write** (e.g. termination flag)
  - must be used if flag is set by different thread otherwise C2 compiler could create **infinite loop** without testing

Volatile Arrays

```
public class VolatileIntArray {
    private volatile int[] array;

    public VolatileIntArray(int capacity) {
        array = new int[capacity];
    }

    public int get(int index) {
        return array[index];
    }

    public void put(int index, int value) {
        array[index] = value;
    }
}
```

» Is put operation to array member volatile?

Volatile Arrays

```java
public class VolatileIntArray {
    private volatile int[] array;

    public VolatileIntArray(int capacity) {
        array = new int[capacity];
    }

    public int get(int index) {
        return array[index];
    }

    public void put(int index, int value) {
        array[index] = value;
    }
}
```

8B - mark word
4B / 8B – Klass ref.
… object data

8B - mark word
4B / 8B – Klass ref.
4B – array length
sequence of values

» Is put operation to array member volatile?
NO – see assembly code, there is no cache synchronization with lock

```
# this:      rsi:rsi    = 'datarace/VolatileIntArray'
# parm0:     rdx        = int
# parm1:     rcx        = int

0x000000011170bbcc: mov    0xc(%rsi),%esi
0x000000011170bbcf: shl    $0x3,%rsi            ;*getfield array
                                                ; - datarace.VolatileIntArray::put@1 (line 15)

0x000000011170bbd3: movslq %edx,%rdi
0x000000011170bbd6: cmp    0xc(%rsi),%edx       ; implicit exception: dispatches to 0x000000011170bbef
0x000000011170bbd9: jae    0x000000011170bbf9
0x000000011170bbdf: mov    %ecx,0x10(%rsi,%rdi,4)  ;*iastore
                                                ; - datarace.VolatileIntArray::put@6 (line 15)
```

ArrayOutOfBoundsException

Volatile Arrays - Solution

```java
private volatile int[] array;

public void put(int index, int value) {
    array[index] = value;
    array = array;
}
```

8B - mark word
4B / 8B – Klass ref.
… object data

- just array reference is volatile
- added unnecessary **array** reference update adds assembly code

```
0x000000010db21a67: mov     %r8d,0xc(%rsi)
0x000000010db21a80: lock addl $0x0,(%rsp)      ;*putfield array
                                               ; - datarace.VolatileIntArray::put@12 (line 16)
```

- instruction **lock prefix** forbids all instruction reordering around and synchronize previous writes to be visible by all others CPUs
- **not suitable for read-update-write operations**

Counter Example – Synchronized and ReentrantLock

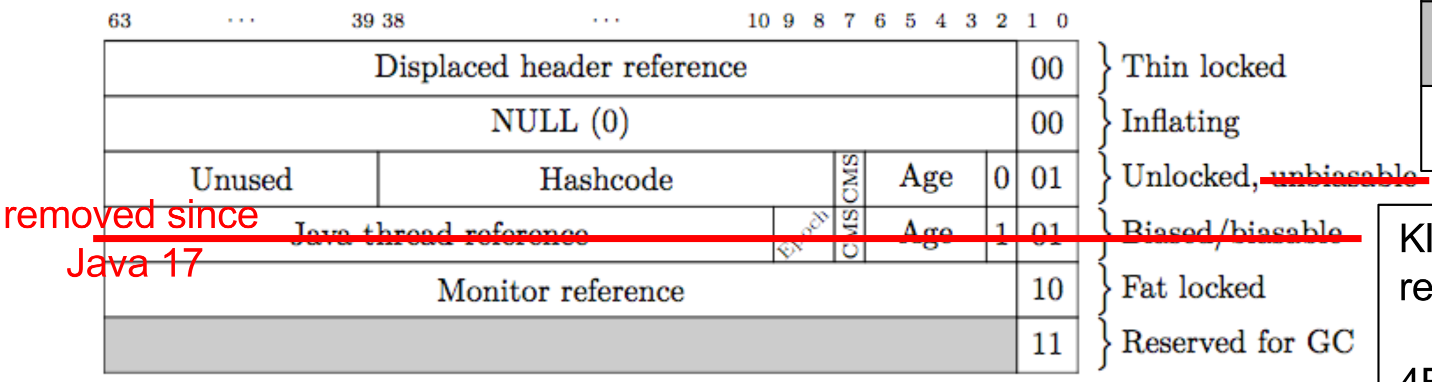
```java
public class SynchronizedCounter {
    private int cnt=0;

    public int get() {
        return cnt;
    }

    public synchronized void increment() {
        cnt++;
    }
}
```

```java
public class ReentrantCounter {
    private int cnt=0;
    private ReentrantLock lock = new ReentrantLock();

    public int get() {
        return cnt;
    }

    public void increment() {
        lock.lock();
        try {
            cnt++;
        } finally {
            lock.unlock();
        }
    }
}
```

!

- no issue with read-update-write operations
- synchronized
  - method vs. block
  - object instance vs. class instance (static methods)

Mark word (64-bit JVM):



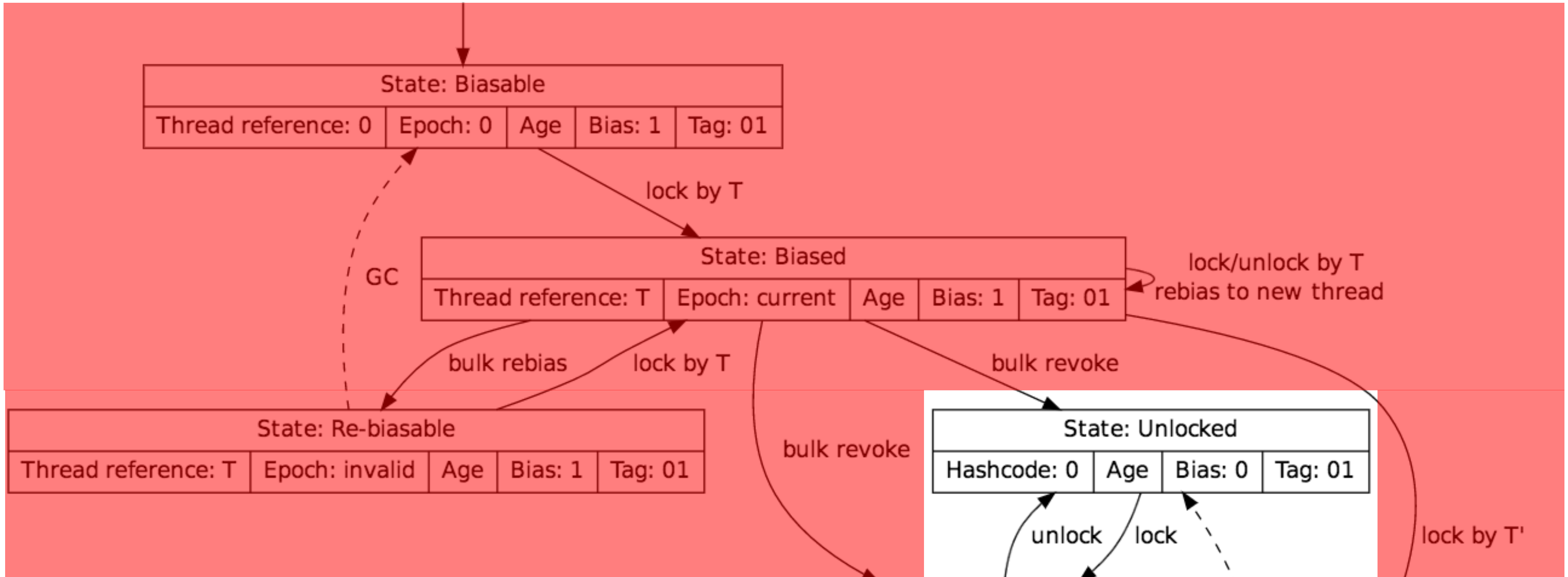
8B - mark word
4B / 8B – Klass ref.
… object data

Klass – internal JVM representation of class Metadata

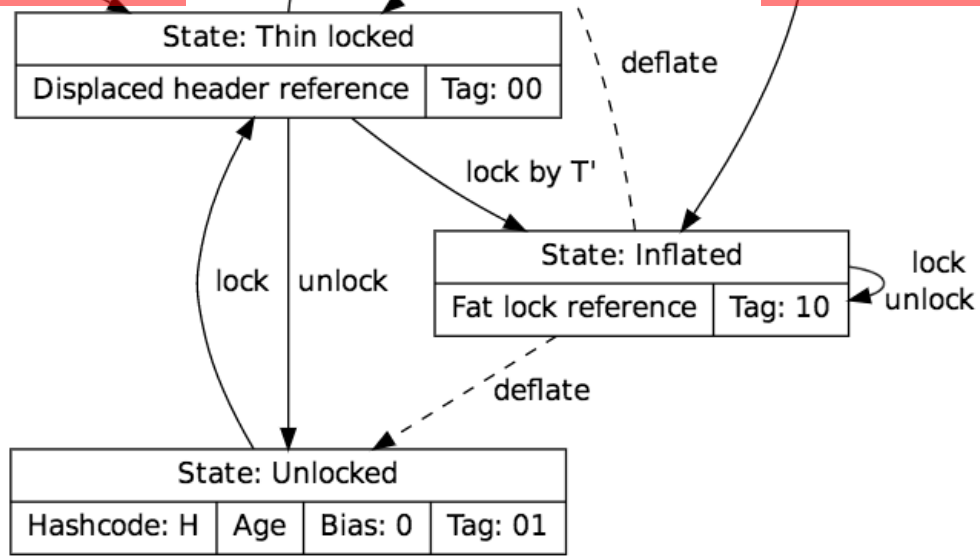
4B – 32bit, or 64bit <32GB heap
8B – 64bit no compressedOOP

- » *prototype mark word* in Klass
- » **lock records** in stack (on pre-compiled locations for compiled code)
  - 8B - displacement of original object mark word – recursive lock has 0
  - 4B / 8B - compressedOOP/OPP to locked object
- » **thin lock** is using CAS instruction on lock/unlock to modify mark word
  - use spin-locking (10 cycles with volatile read + NOPs) before fat locking
- » **fat lock** is using monitor object on heap (inflating creates, deflating destroys)
  - contended lock or call of **wait/notify**
  - monitor: original mark word, OS lock, conditions, set of threads; support parking

JVM - Synchronize Implementation



removed since Java 17



- assembly code optimized for biasing and thin locking
- biased locking startup options:
  -XX:-UseBiasedLocking
  -XX:BiasedLockingStartupDelay=0
  (initial **4 seconds**)

Reentrant Locks

» locking with extended operations in comparison to **synchronized**
  - lock(), unlock()
  - lockInterruptibly() throws InterruptedException
  - boolean tryLock()
  - boolean tryLock(long timeout, TimeUnit unit) throws InterruptedException

» **fairness**
  - blocked threads are **ordered** for fair locking
  - **new** ReentrantLock(boolean fair), by default unfair
  - **synchronized** is unfair
  - unfair ReentrantLocks are slightly faster than synchronized
    - but another instance in HEAP
  - fair locks are slower (~100x)

Counter Example – AtomicInteger

```java
public class AtomicCounter {
    private AtomicInteger cnt = new AtomicInteger( initialValue: 0);

    public int get() {
        return cnt.get();
    }

    public void increment() {
        cnt.incrementAndGet();
    }
}
```

<u>AtomicInteger implementation</u>

```java
private static final long valueOffset;

static {
    try {
        valueOffset = unsafe.objectFieldOffset
            (AtomicInteger.class.getDeclaredField( name: "value"));
    } catch (Exception ex) { throw new Error(ex); }
}

private volatile int value;

public final int getAndAddInt(Object var1, long var2, int var4) {
    int var5;
    do {
        var5 = this.getIntVolatile(var1, var2);
    } while(!this.compareAndSwapInt(var1, var2, var5,  var5: var5 + var4));

    return var5;
}

public final int getAndIncrement() {
    return unsafe.getAndAddInt( o: this, valueOffset,  i: 1);
}
```

non-blocking pattern

Counter Example – AtomicInteger – Assembly Code

C2 compiler assembly code for AtomicCounter::increment

RSI is **this**

```
0x000000010b108d4c: mov    0xc(%rsi),%r11d     ;*getfield cnt
                                               ; - datarace.AtomicCounter::increment@1 (line 13)

0x000000010b108d50: test   %r11d,%r11d
0x000000010b108d53: je     0x000000010b108d68
0x000000010b108d55: lock addl $0x1,0xc(%r12,%r11,8)  ;*invokevirtual getAndAddInt
                                               ; - java.util.concurrent.atomic.AtomicInteger::incrementAndGet@8 (line 186)
                                               ; - datarace.AtomicCounter::increment@4 (line 13)
```

null pointer check with **exception**

- while cycle optimized and replaced with **single instruction**
- instruction **lock prefix** forbids all reordering around and synchronize previous writes to be visible by all other CPUs
- instruction **lock prefix** ensures that core has exclusive ownership of the appropriate cache line for the duration of the operation
  - cache coherency using **MESIF** (Haswell) with fallback to mem bus lock
- **AtomicInteger-based counter is fastest of all for multi-threaded**

Atomic Operations

- 32-bit CPUs support 64-bit CAS operations
  - **cmpxchg** src_operand, dst_operand – implicit instruction lock prefix
- 64-bit CPUs support 128-bit CAS operations
  - **cmpxchg16b** – works with RDX:RAX and RCX:RBX register pairs

- JAVA uses only 64-bit CAS operations in java.util.concurrent.atomic
  - AtomicBoolean
  - AtomicInteger
  - AtomicLong
  - AtomicReference
  - AtomicIntegerArray
  - AtomicLongArray
  - AtomicReferenceArray

Atomic Field Updaters

- **suitable for large number of objects** of the given type – it saves memory
  - don't require single instance to have an extra object embedded
- refer volatile variable directly without getter and setters

```
public class ObjectWithAtomic {
    private final AtomicInteger value =
        new AtomicInteger(0);
    // ...

    public void method1() {
        // ...
        if (value.compareAndSet(1, 2)) {
            // ...
        }
    }
}
```

```
public class ObjectWithAtomic {
    private static AtomicIntegerFieldUpdater<ObjectWithAtomic>
        valueUpdater = AtomicIntegerFieldUpdater.newUpdater(ObjectWithAtomic.class, "value");
    private volatile int value = 0;
    // ...

    public void method1() {
        // ...
        if (valueUpdater.compareAndSet(this, 1, 2)) {
            // ...
        }
    }
}
```

Atomic Field Updaters

- but beware of **less efficient** operations for atomic field updaters
- AtomicIntegerFieldUpdater implementation

```
private void fullCheck(T obj) {
    if (!tclass.isInstance(obj))
        throw new ClassCastException();
    if (cclass != null)
        ensureProtectedAccess(obj);
}

public boolean compareAndSet(T obj, int expect, int update) {
    if (obj == null || obj.getClass() != tclass || cclass != null) fullCheck(obj);
    return unsafe.compareAndSwapInt(obj, offset, expect, update);
}
```

- existing field updaters
  - AtomicIntegerFieldUpdater
  - AtomicLongFieldUpdater
  - AtomicReferenceFieldUpdater
- no array field updaters

Atomic Complex Types

» **AtomicMarkableReference**

- **object reference** along with a **mark bit**

» **AtomicStampedReference**

- **object reference** along with an **integer “stamp”**

» notes:

- useful for ABA problem
  – A -> B and B -> A, how can I know that A has been changed since the last observation?
- doesn’t use double-wide CAS (CAS2, CASX) -> much slower than simple atomic types due to **object allocation**

Atomic Complex Types – Larger Than 64-bits

» **AtomicMarkableReference**

- **object reference** along with a **mark bit**

» **AtomicStampedReference**

- **object reference** along with an **integer “stamp”**

```
public class AtomicStampedReference<V> {

    private static class Pair<T> {
        final T reference;
        final int stamp;
        private Pair(T reference, int stamp) {
            this.reference = reference;
            this.stamp = stamp;
        }
        static <T> Pair<T> of(T reference, int stamp) {
            return new Pair<T>(reference, stamp);
        }
    }

    private volatile Pair<V> pair;

    public boolean compareAndSet(V   expectedReference,
                                 V   newReference,
                                 int expectedStamp,
                                 int newStamp) {
        Pair<V> current = pair;
        return
            expectedReference == current.reference &&
            expectedStamp == current.stamp &&
            ((newReference == current.reference &&
              newStamp == current.stamp) ||
             casPair(current, Pair.of(newReference, newStamp)));
    }
```

Non-blocking Algorithms

- **lock-free**, block-less but not usually **wait-free** (because of unbounded loops)
  - based on CAS / CMPXCHG and LOCK prefixed instructions
- shared resources secured by locks have drawbacks
  - high-priority thread can be blocked (e.g. interrupt handler)
  - parallelism reduced by coarse-grained locking (unfair locks)
  - fine-grained locking and fair locks increases overhead
  - can lead to **deadlocks**, **priority inversion** (low-priority thread holds a shared resource which is required by high-priority thread)

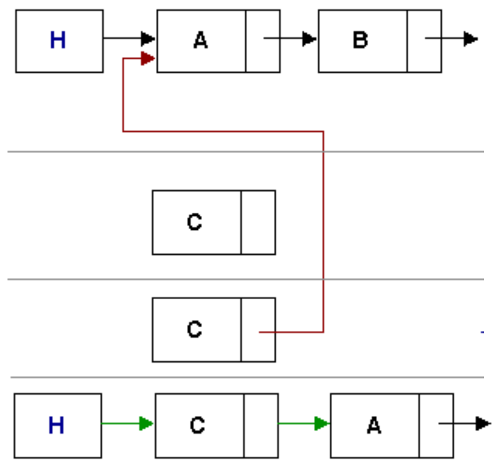
- **non-blocking algorithms properties**:
  - outperform blocking algorithms because most of CAS / CMPXCHG succeeds on the first try
  - removes cost for synchronization, thread suspension, context switching

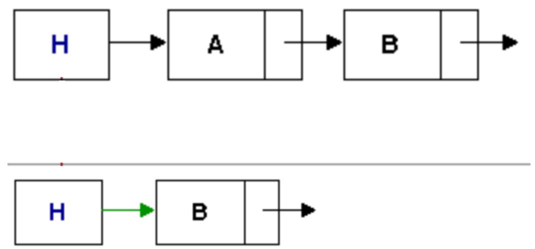
- note: **real-time systems require wait-free algorithms** (finite number of steps) and lock-free is not sufficient

Non-blocking stack (LIFO)

» Treiber's algorithm (1986)

```
static class Node<E> {
    final E item;
    Node<E> next;

    public Node(E item) { this.item = item; }
}

AtomicReference<Node<E>> head = new AtomicReference<Node<E>>();

public void push(E item) {
    Node<E> newHead = new Node<E>(item);
    Node<E> oldHead;
    do {
        oldHead = head.get();
        newHead.next = oldHead;
    } while (!head.compareAndSet(oldHead, newHead));
}

public E pop() {
    Node<E> oldHead;
    Node<E> newHead;
    do {
        oldHead = head.get();
        if (oldHead == null)
            return null;
        newHead = oldHead.next;
    } while (!head.compareAndSet(oldHead,newHead));
    return oldHead.item;
}
```





push after pop can cause ABA problem if address is reused !

Thread-safe collections and maps

» blocking collections and maps

- static<T> Collection<T> Collections.synchronizedCollection(Collection<T> c)
- static<T> List<T> Collections.synchronizedList(List<T> list)
- static<K,V> Map<K,V> Collections.synchronizedMap(Map<K,V> m)
- static<T> Set<T> Collections.synchronizedSet(Set<T> s)
- also for SortedSet and SortedMap

» non-blocking collections and maps

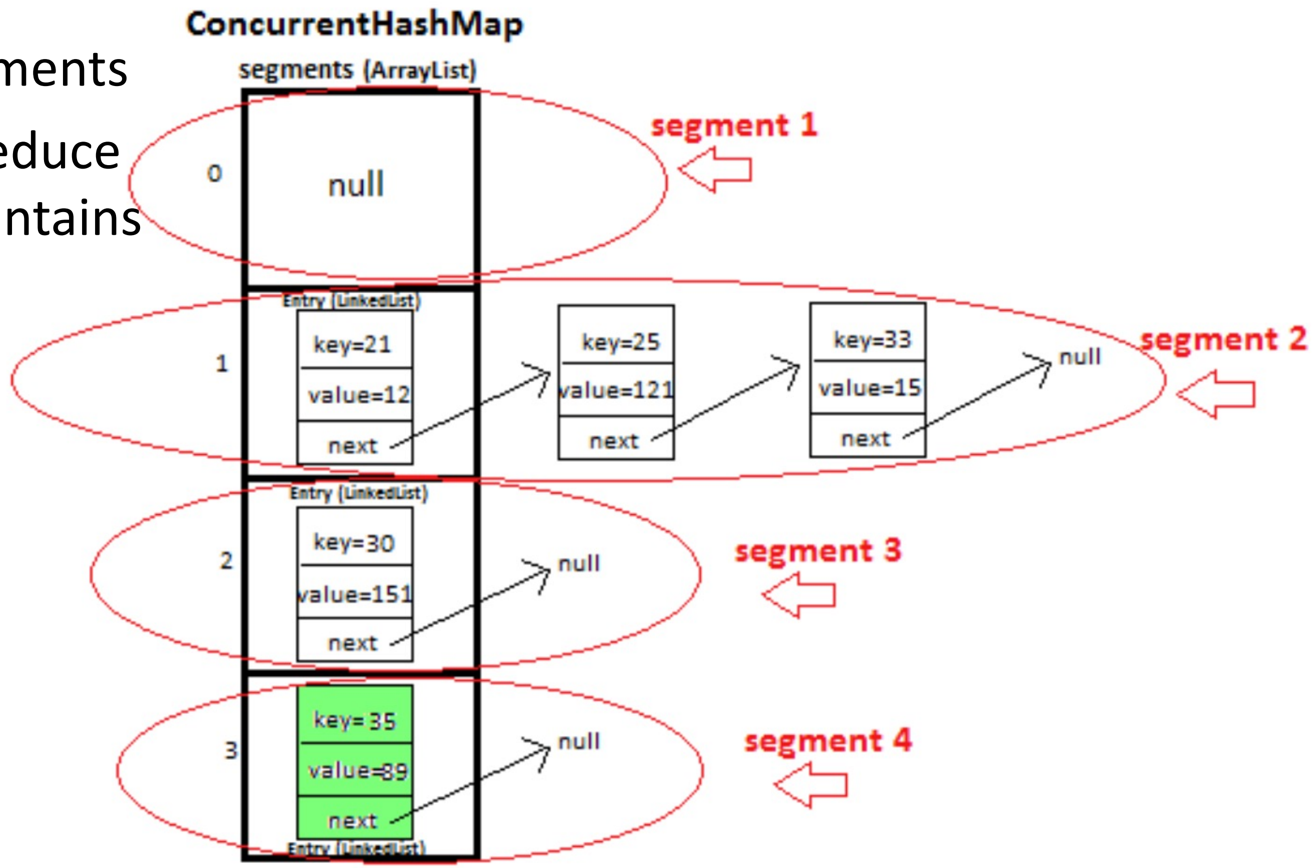
- ConcurrentLinkedQueue (interface Collection, Queue):
  - E peek(), E poll(), add(E)
- ConcurrentHashMap (interface Map):
  - putIfAbsent(K key, V value), remove(Object key, Object value)
  - replace(K key, V oldValue, V newValue)
- ConcurrentSkipListMap (interface SortedMap), ConcurrentSkipListSet (interface SortedSet)

» non-blocking collections and maps are slower for single-threaded access

- due to usage of CAS instructions in comparison to biased locking

ConcurrentHashMap

- **concurrent reads** – get, iterator
- **minimize update contention**
  - initial concurrency level 16 (can be changed) - # updating threads
    - initial insertion into empty segment uses CAS operation
    - later modifications are based on segment-based locks
- segment contention
  - use lists for <8 elements
  - balanced tree to reduce search times – maintains next for iteration



ConcurrentHashMap

- **table resizing** (occupancy exceed load factor 0.75)
  - power of two expansions
    - same index or power of two index
  - reusing internal Node if next is not changed – majority of cases
  - any thread can help resizing instead of block
  - **Forward nodes** are used to notify users about moved