Methods Take Time

```
Method call

invocation 12:00

response 12:01
```

```
q.enq(...)

void
```
Concurrent Methods Take *Overlapping* Time
Reminder: Linearizable means: each method takes effect instantaneously, sometime in its observed time window.
Today

- From our model of strict happens-before to... how programming languages really work
- Plus condition variables, monitors and semaphores
- Reading: H&S 3.8, 8.1-8.5
- Several new hints/updates this week
Alternative: Sequential Consistency

- No need to preserve real-time order
  - Cannot re-order operations done by the same thread
  - Can re-order non-overlapping operations done by different threads
- Often used to describe multiprocessor memory architectures
- Formulation:
  - There is some total order of operations so that:
  - Each CPUs operations appear in order
  - All CPUs see results according to that order (read most recent writes)
Example

\[ \text{time} \]
Example

q.enq(x)

time
Example

- `q.enq(x)`
- `q.deq(y)`
- `time`
Example

- \( q.\text{enq}(x) \)
- \( q.\text{deq}(y) \)
- \( q.\text{enq}(y) \)

Time progression:
Example

\[ \begin{align*}
q.\text{enq}(x) \\
q.\text{enq}(y) \\
q.\text{deq}(y) \\
q.\text{enq}(y)
\end{align*} \]
Example

q.enq(x)
q.enq(y)
q.deq(y)
q.enq(y)
q.enq(x)

Not linearizable!
Example

- Reminder, sequentially consistent if there is some total order of operations so that:
  - Each CPUs operations appear in order
  - All CPUs see results according to that order (read most recent writes)
# Sequential Consistency vs Linearizability

<table>
<thead>
<tr>
<th>Linearizable</th>
<th>t=0</th>
<th>t=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU0</td>
<td>W(X) 1</td>
<td>R(Y) 1</td>
</tr>
<tr>
<td>CPU1</td>
<td>W(Y) 1</td>
<td>R(X) 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sequential Consistency</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU0</td>
<td>W(X) 1 R(Y) 1</td>
</tr>
<tr>
<td>CPU1</td>
<td>W(Y) 1 R(X) 0</td>
</tr>
</tbody>
</table>
Theorem
Sequential Consistency is not a local property
(and thus we lose composability...)

FIFO Queue Example

Diagram:

- p.enq(x)
- q.enq(x)
- p.deq(y)

Arrow indicating time movement.
FIFO Queue Example

- `p.enq(x)`
- `q.enq(x)`
- `p.deq(y)`
- `q.enq(y)`
- `p.enq(y)`
- `q.deq(x)`

*Time*
FIFO Queue Example

History H

time

\[
p\text{.enq}(x) \quad q\text{.enq}(x) \quad p\text{.deq}(y) \\
q\text{.enq}(y) \quad p\text{.enq}(y) \quad q\text{.deq}(x)
\]
H|p Sequentially Consistent

- p.enq(x)
- q.enq(x)
- p.deq(y)
- q.enq(y)
- p.enq(y)
- q.deq(x)

**Time**
H|q Sequentially Consistent

p.enq(x) → q.enq(x) → p.deq(y) → q.enq(y) → p.enq(y) → q.deq(x)

time
Ordering imposed by p
Ordering imposed by q

- p.enq(x)
- q.enq(x)
- p.deq(y)
- q.enq(y)
- p.enq(y)
- q.deq(x)

Time
Ordering imposed by both

p.enq(x)  q.enq(x)  p.deq(y)
q.enq(y)  p.enq(y)  q.deq(x)

time
Sequentially Consistent Overall?

The only way to make this work is if these operations are reordered: but we can not reorder operations within a thread!

P: must enq y before x to make deq right

Q: must enq x before y to make deq right!
Sequential Consistency vs Linearizability

- Linearizability can be composed:
  - If p’s execution and q’s execution are both linearizable, then the combination must also be linearizable
- Sequential consistency can not be composed:
  - If p’s execution and q’s execution are both sequential, then the combination MAY also be sequential (but not guaranteed!)
- Why use sequential consistency?
  - Does not require global clock
Sequential Consistency

• Even though it’s easier to support than linearizability…
• Most hardware architectures don’t support sequential consistency
• Because they think it’s too strong
• Here’s another story …
The Flag Example

```
x.write(1)
y.write(1)
y.read(0)
x.read(0)
```

time
The Flag Example

- Each thread’s view is sequentially consistent
  - It went first
The Flag Example

- Entire history isn’t sequentially consistent
  - Can’t both go first
The Flag Example

• Is this behavior really so wrong?
  – We can argue either way …
Opinion 1: It’s Wrong

• This pattern
  – Write mine, read yours
• Is exactly the flag principle
  – Beloved of Alice and Bob
  – Heart of mutual exclusion
    • We used this to implement our lock…
• It’s non-negotiable!
Opinion 2: But It Feels So Right …

• Many hardware architects think that sequential consistency is too strong
• Too expensive to implement in modern hardware
• OK if flag principle
  – violated by default
  – Honored by explicit request
Memory Operations are Slow

CPU 1
- thread0()
- CPU 1 Cache
- 7ns
- Main Memory
- 100ns

CPU 2
- thread1()
- CPU 2 Cache
A processor can execute hundreds, or even thousands of instructions
Why delay on every memory write?
Instead, write back in parallel with rest of the program.
Revisionist History

- Flag violation history is actually OK
  - processors delay writing to memory
  - Until after reads have been issued.
- Otherwise unacceptable delay between read and write instructions.
- Who knew you wanted to synchronize?
Who knew you wanted to synchronize?

- Writing to memory = mailing a letter
- Vast majority of reads & writes
  - Not for synchronization
  - No need to idle waiting for post office
- If you want to synchronize
  - Announce it explicitly
  - Pay for it only when you need it
- Foreshadowing: Writing to network = mailing a letter to the moon
Explicit Synchronization

• Memory barrier instruction
  – Flush unwritten caches
  – Bring caches up to date
• Compilers often do this for you
  – Entering and leaving critical sections
• Expensive
Volatile

- In Java, can ask compiler to keep a variable up-to-date with volatile keyword
- Also inhibits reordering, removing from loops, & other “optimizations”
Volatile Keyword

CPU 1

thread0() → CPU 1 Cache

7ns

CPU 2

thread1() → CPU 2 Cache

100ns

Main Memory
Linearizability, Sequential Consistency, Java, and Us

• What guarantees can we get, and how?
  • Different threads’ access to the same variable is sequential -> volatile
  • Different threads’ access to different variables is linear -> a lock around every read/write to those variables
Revisionist History

class Bouncer {
    public static final int DOWN = 0;
    public static final int RIGHT = 1;
    public static final int STOP = 2;
    private boolean goRight = false;
    private ThreadLocal<Integer> myIndex;
    private int last = -1;

    int visit() {
        int i = myIndex.get();
        last = i;
        if (goRight)
            return RIGHT;
        goRight = true;
        if (last == i)
            return STOP;
        else
            return DOWN;
    }
}
Revisionist History

class Bouncer {
    public static final int DOWN = 0;
    public static final int RIGHT = 1;
    public static final int STOP = 2;
    private volatile boolean goRight = false;
    private ThreadLocal<Integer> myIndex;
    private volatile int last = -1;

    int visit() {
        int i = myIndex.get();
        last = i;
        if (goRight)
            return RIGHT;
        goRight = true;
        if (last == i)
            return STOP;
        else
            return DOWN;
    }
}

Without volatile, it would actually be possible for ALL threads to see STOP
Synchronization beyond locks and flags
Return to the FIFO queue

• What if we want our lock based queue to be *bounded*

• Recall: what we did was use a lock around the enqueue and dequeue methods
  
  ```java
  mutex.lock()
  try{
    queue.enq(x);
  } finally{
    mutex.unlock();
  }
  ```

• What happens if the queue is full?
  • Throw an exception?
  • Can’t we make it wait until the queue has space?
Conditions

• When a thread is waiting for something to happen, it might want to release the lock and be notified when that thing has happened
• Ex: while queue is full, release the lock to let someone else empty it
• This is what a condition does
• Key methods: \texttt{await, signal}

```java
Condition condition = lock.newCondition();
lock.lock();
try{
    while(!\texttt{property})
        condition.await();
} catch(InterruptedException e){
    //Application-dependent response, property may still be false
}
//at this point, property must be true and we have the lock again
condition.signal(); //wake up one thread await'ing
condition.signalAll(); //wake up all threads await'ing
```
An awakened thread must:

- try to reclaim the lock;
- when this has happened, retest the property it is waiting for;
- if the property doesn’t hold, release the lock by calling await().

Wrong: `if "boolean expression" condition.await()`
Correct: `while "boolean expression" condition.await()`
Bounded Queue with Conditions

```java
class BoundedQueue {
    private final Condition notFull = lock.newCondition();
    private final Condition notEmpty = lock.newCondition();
    private final int capacity = 10;

    public void enq(Object x) throws InterruptedException {
        lock.lock();
        try {
            while (count == items.length) notFull.await();
            items[tail] = x;
            if (++tail == items.length) tail = 0;
            ++count;
            notEmpty.signal();
        } finally {
            lock.unlock();
        }
    }

    public Object deq() {
        lock.lock();
        try {
            while (count == 0) notEmpty.await();
            Object y = items[head];
            if (++head == items.length) head = 0;
            --count;
            notFull.signal();
            return y;
        } finally {
            lock.unlock();
        }
    }
}
```
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