Locks vs Variables

- “Which lock corresponds to each data item?”
- Multiple threads accessing some data item concurrently must have acquired the same lock
- Not automatic / not checked
- It is up to the developer to ensure this!

Pitfall: Automatic variables

- Variables in methods are created on every invocation
- The method might still access shared state:
  - Instance variables
  - Class (static) variables

Wrong

```
class SomeClass {
    int s;
    void doSomething() {
        Lock l = new ReentrantLock();
        l.lock();
        s = s+1;
        l.unlock();
    }
}
```

Race: Each thread locks its own lock!

Solution

```
class SomeClass {
    int s;
    Lock l = new ReentrantLock();
    void doSomething() {
        l.lock();
        s = s+1;
        l.unlock();
    }
}
```

Solution: Same scope for shared state and lock

Pitfall: Class/global variables

- Variables marked with “static” in Java are global and (probably) need concurrency control
  - Not if marked “final”
  - Not if the class is used by a single thread

Wrong

```
class SomeClass {
    private static int s;
    void doSomething() {
        s = s+1;
    }
}
```

Race!

Still wrong

```
class SomeClass {
    private Lock l = new ReentrantLock();
    private static int s;
    void doSomething() {
        l.lock();
        s = s+1;
        l.unlock();
    }
}
```

There is one lock for each object, but s is shared!

Solution

```
class SomeClass {
    private static Lock l = new ReentrantLock();
    private static int s;
    void doSomething() {
        l.lock();
        s = s+1;
        l.unlock();
    }
}
```

Pitfall: Encapsulated locks

- Keep variables and the corresponding lock encapsulated within the same object
- (The default using old-style “synchronized” in Java.)

Wrong

```
class SomeClass {
    SomeState s;
    void doSomething() {
        if (s.contains(x))
            s.remove(x)
    }
}
```

Race: No such element exception….

```
class SomeState {
    private Lock l;
    boolean contains(...) {
        l.lock(); … l.unlock();
    }
    void remove(...) {
        l.lock(); … l.unlock();
    }
}
```

Solution

```
class SomeClass {
    private Lock l;
    SomeState s;
    void doSomething() {
        l.lock();
        if (s.contains(x))
            s.remove(x)
        l.unlock();
    }
}
```

Now useless...

```
class SomeState {
    private Lock l;
    boolean contains(...) {
        l.lock(); … l.unlock();
    }
    void remove(...) {
        l.lock(); … l.unlock();
    }
}
```

Better solution

class SomeClass {
    private Lock l;
    SomeState s;
    void doSomething() {
        l.lock();
        if (s.contains(x))
            s.remove(x)
        l.unlock();
    }
}

class SomeState {
    ~~private Lock l;~~
    boolean contains(...) {
        ~~l.lock();~~ ... ~~l.unlock();~~
    }
    void remov .) {
        ~~l.lock()~~ ~~unlock();~~
    }
}

Rely on locking by the callers. This is done by Java Collections (Lists, ...)

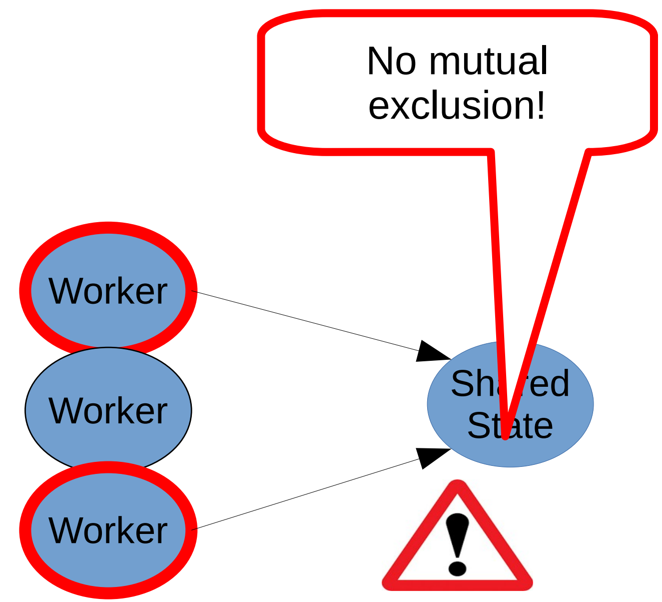
Pitfall: Shared vs thread-local state

- Program state often contains:
  - Local thread state in workers
  - Shared state, used by all threads
- Both are objects, with instance variables

Wrong

```
class Worker
            extends Thread {
    Lock l = new ...;
    SharedState s;
    void doSomething() {
        l.lock(); s.doit(); l.unlock();
    }
    public void run() {
        doSomething();
    }
}
```

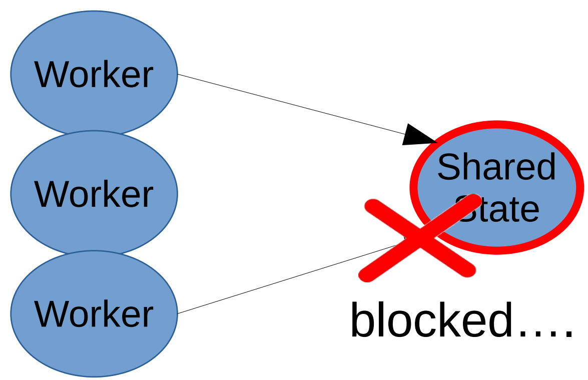
```
class SharedState {
    public void doit() {
        ...
    }
}
```



Solution

```
class Worker
    extends  Thread {
    SharedState s;
    void doit() {
        s.doit();
    }
    public void run() {
        doit();
    }
}
```

```
class SharedState {
    Lock l = new ...;
    public void doit() {
        l.lock(); ... l.unlock();
    }
}
```



Quiz

- Two variables:
  - int i=0, j=0;
- Writer code:
  - i=1; j=1;
- Reader code:
  - rj=j; ri=i; System.out.println(rj+", "+ri);
- Possible results:

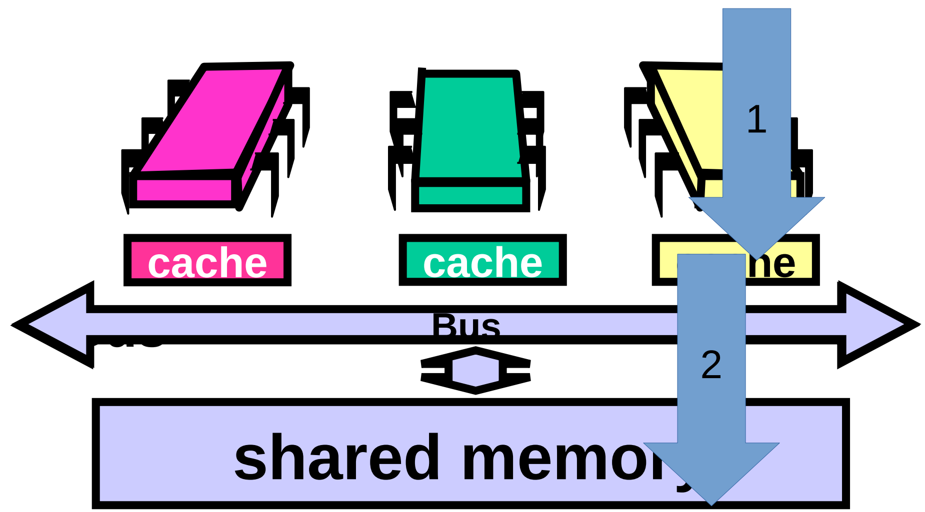
  a) 0, 0 ✓
  b) 1, 1 ✓
  c) 0, 1 ✓
  d) 1, 0 ✓

running concurrently!

Why!?!?

Memory order

- Steps to write a variable:
  1. Write to cache
  2. Flush cache to memory

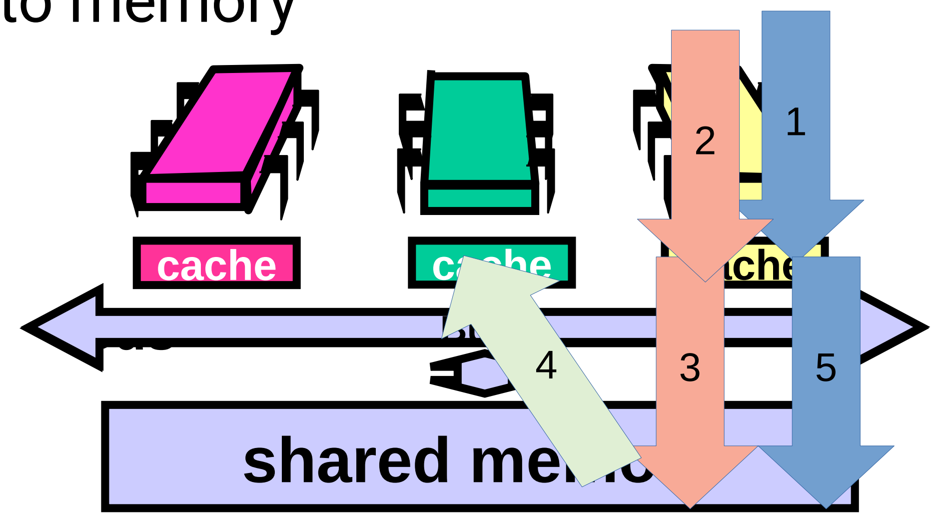


(Image from http://booksite.elsevier.com/9780123705914/?ISBN=9780123705914 . CC By-SA-3.0.)

Memory order

- Possible outcome with two variables:
  1. Write i to cache
  2. Write j to cache
  3. Flush j from cache to memory
  5. Flush i from cache to memory

4. Paradox observed if i,j read here!!



(Image from http://booksite.elsevier.com/9780123705914/?ISBN=9780123705914 . CC By-SA-3.0.)

Pitfall: Read races

```
class X {
    private Y y;
    void changeY() {
        l.lock();
        tmp.i = 1;
        y = tmp;
        l.unlock();
    }
    int getY() {return y.i;}
}
```

- Can we omit synchronization in getters?

Pitfall: Read races

```
class X {
    private Y y;
    void changeY() {
        l.lock();
        tmp.i = 1;
        y = tmp;
        l.unlock();
    }
    int get[illegible] {[illegible]turn y.i;}
}
```

- Can we omit synchronization in getters?
  - **NO!**
- Can read inconsistent Y fields!
- In this case:
  - reader might not see y.i == 1!!!!

Pitfall: Collections and getters

- Getter methods may return references to shared collections (or other mutable objects)
  - Iterators include references to the original object!

Wrong

```
class SomeClass {
    private Lock l = new ReentrantLock();
    private List l;
    List getElements() {
        try { l.lock();
            return l;
        } finally { l.unlock(); }
    }
}
```

```
SomeClass s = ...;
    List l = l.getElements();
    l.add(...);
```

Race!

Wrong

```
class SomeClass {
    private Lock l = new ReentrantLock();
    private List l;
    Iterator getElements() {
        try { l.lock();
            return l.iterator();
        } finally { l.unlock(); }
    }
}
```

```
SomeClass s = ...;
    Iterator i = l.getElements();
    while(i.hasNext())
        ...
```

Race!

Still wrong

```
class SomeClass {
    private Lock l = new ReentrantLock();
    private List l;
    List getElements() {
        try { l.lock();
            return l.clone();
        } finally { l.unlock(); }
    }
}
```

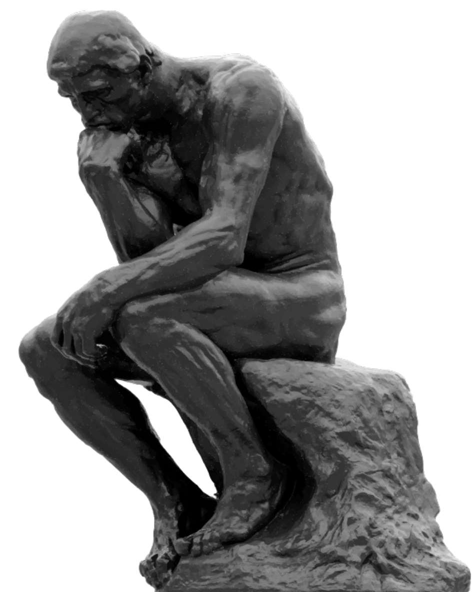
```
SomeClass s = ...;
    List l = l.getElements();
    l.add(...);
```

Not adding to the list...

...reconsider encapsulated lock!

Summary

- There is no simple rule to match locks with variables
- Some thinking needed… :-)



Scaling up

- Example:
  - In a distributed database table with millions of records
  - Executing “select sum(x) from … where …” queries
  - Updating records
- Do we use a single lock?
  - Cannot run more than one query at the same time
- Do we use a lock for each line?
  - Way too many individual locks!

Readers-Writers locks

- Strict mutual exclusion with locks is too conservative:
  - More than one reader would not be a problem
  - A writer must exclude all others (readers and writers)
- Different methods for readers and writers:

```
interface ReadWriteLock {
    Lock readLock();
    Lock writeLock();
}
```

- More costly than a simple lock

Image from: https://www.deccanherald.com/content/354607/dangerous-rail-crossings.html

Readers-Writers locks

- R/W locks also known as shared locks in database management systems:
  - Readers lock <=> Shared mode
  - Writers lock <=> eXclusive mode
- Behavior described by a compatibility matrix:

Mode	R/S	W/X
R/S	Yes	No
W/X	No	No

Readers-Writers example

```
int v;
Lock l = new ReentrantLock();
void doSomething() {
    l.lock();
    v++;
    l.unlock();
}
int getV() {
    try { l.lock();
    return v;
    } finally { l.unlock(); }
}
```

```
int v;
ReadWriteLock l = new ReentrantReadWriteLock();
void doSomething() {
    l.writeLock().lock();
    v++;
    l.writeLock().unlock();
}
int getV() {
    try { l.readLock().lock();
    return v;
    } finally { l.readLock().unlock(); }
}
```

… not worth it for such simple operations!

Revisiting collections with 2PL+RW lock

- void shoot(String sn, String tn) {

```
    l.readLock().lock();
    Player s = players.get(sn);
    Player t = players.get(tn);
      Stream.of(sn,tn).sorted()
     .forEach(n→players.get(n).l.lock());
    l.readLock().unlock();
    t.life--;
    t.l.unlock();
    s.score++;
    s.l.unlock();
}
```

Allow multiple threads to acquire locks concurrently

Sorting is needed again

Readers-Writers fairness

- Priority to readers
  - Allow more readers in, even if a writer is waiting
  - The writer may starve…
- Priority to writers
  - Do not allow more readers in, if a writer is waiting
  - Less concurrency among readers

Lock managers

- Individual locks inefficient for huge collections of objects
  - A lock object uses memory even when not in use
- A lock manager provides locks on demand:

```
interface LockManager {
    void lock(Object name);
    void unlock(Object name);
}
```

lookup lock l for “name” in map
if it doesn’t exist:
    create it and add to map
l.lock()!

lookup lock for “name”
l.unlock()
if nobody else is using it:
    remove it from map

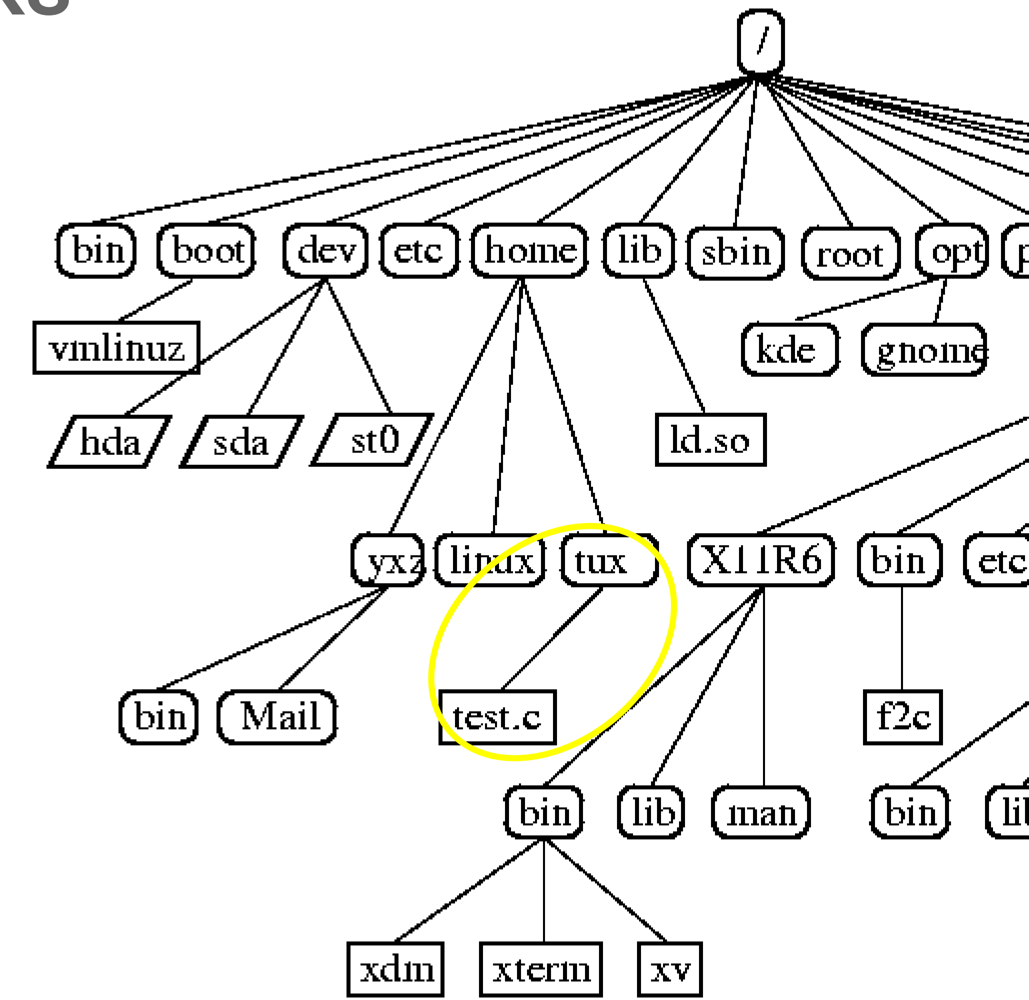
Lock managers

- Usually provides shared/exclusive semantics:

```
enum Mode { SHARED, EXCLUSIVE };
interface LockManager {
    void lock(Object name, Mode mode);
    void unlock(Object name);
}
```

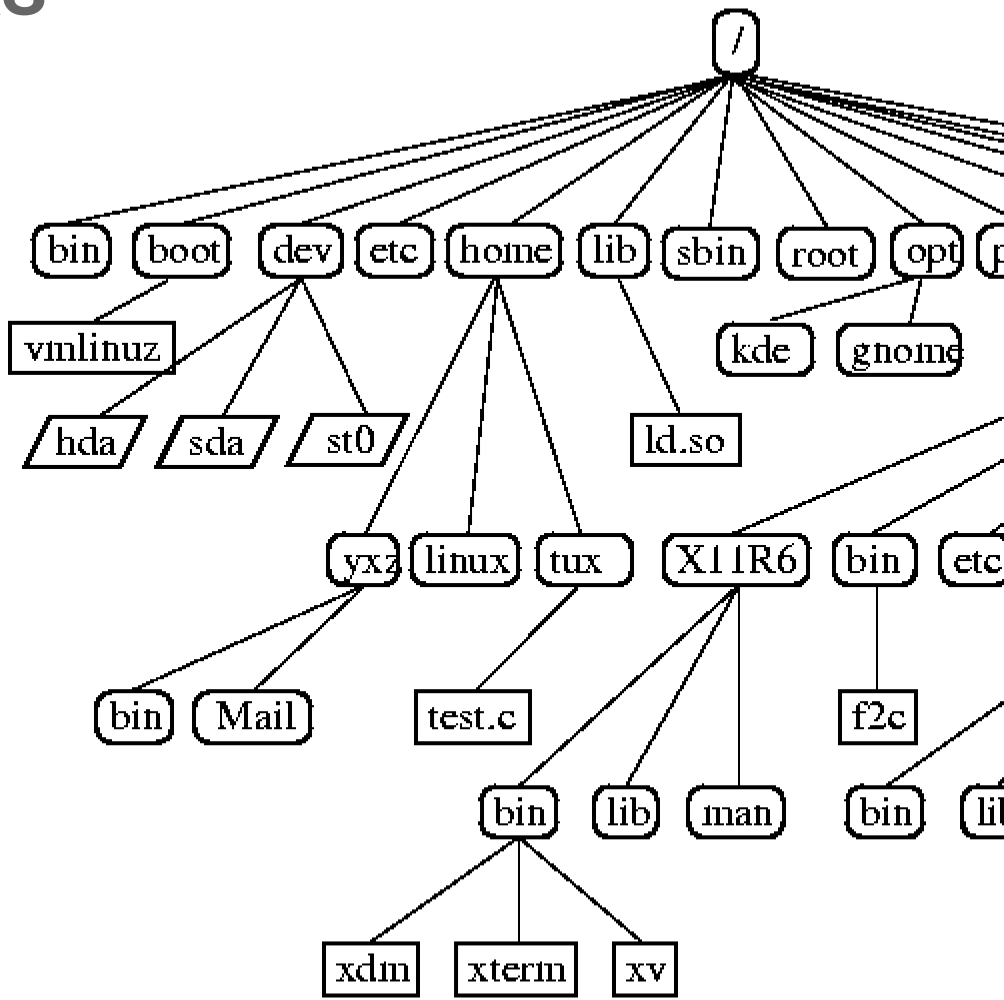
Multiple granularity locks

- Motivation:
  - Locking /home/tux/*
  - Assume large number of files
- Inefficient even with a lock manager
- Idea: Take advantage of hierarchical namespace and lock folders



Multiple granularity locks

- Protocol:
  - “<u>intention</u>” locks on containers
  - “actual” locks on the target
- Intention locks conflict with actual locks, not with other intention locks
- Combine with (S)hared and e(X)clusive semantics



Compatibility matrix

- An MGL is defined by a compatibility matrix:

requesting...

acquired

Mode	IS	IX	S	X
IS	Yes	Yes	Yes	No
IX	Yes	Yes	No	No
S	Yes	No	Yes	No
X	No	No	No	No

Multiple granularity locks

- Shared lock /home/tux
- Shared lock on /home/tux/test.c
- Exclusive lock on /boot
  - Shared lock on /boot/vmlinuz
    - IS on /boot/ conflicts with X
  - Exclusive lock on /home
    - X on /home conflicts with IS