Types For Atomicity

Race Conditions

```
class Ref {
  int i;
  void inc() {
    int t;
    t = i;
    i = t+1;
  }
}

Ref x = new Ref(0);
parallel {
    x.inc();    // two calls happen
    x.inc();    // in parallel
}
assert x.i == 2;
```

A race condition occurs if

- two threads access a shared variable at the same time
- at least one of those accesses is a write

Lock-Based Synchronization

```
class Ref {
  int i;              // guarded by this
  void inc() {
    int t;
    synchronized (this) {
      t = i;
      i = t+1;
    }
  }
}

Ref x = new Ref(0);
parallel {
    x.inc();    // two calls happen
    x.inc();    // in parallel
}
assert x.i == 2;
```

- Field guarded by a lock
- Lock acquired before accessing field
- Ensures race freedom

Limitations of Race-Freedom

```
class Ref {
  int i;              // guarded by this
  void inc() {
    int t;
    synchronized (this) {
      t = i;
      i = t+1;
    }
  }
}

Ref x = new Ref(0);
parallel {
    x.inc();    // two calls happen
    x.inc();    // in parallel
}
assert x.i == 2;
```

Ref.inc()

- race-free
- behaves correctly in a multithreaded context

Limitations of Race-Freedom

```
class Ref {
  int i;
  void inc() {
    int t;
    synchronized (this) {
      t = i;
    }
    synchronized (this) {
      i = t+1;
    }
  }
  ...
}
```

Ref.inc()

- race-free
- behaves incorrectly in a multithreaded context

Race freedom does not prevent errors due to unexpected interactions between threads

Limitations of Race-Freedom

```
class Ref {
  int i;
  void inc() {
    int t;
    synchronized (this) {
      t = i;
      i = t+1;
    }
  }

  synchronized
  void read() { return i; }
  ...
}
```

Limitations of Race-Freedom

```
class Ref {
  int i;
  void inc() {
    int t;
    synchronized (this) {
      t = i;
      i = t+1;
    }
  }

  void read() { return i; }
  ...
}
```

Ref.read()

- has a race condition
- behaves correctly in a multithreaded context

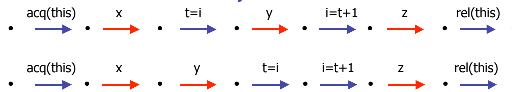
Race freedom is not necessary to prevent errors due to unexpected interactions between threads

Race-Freedom

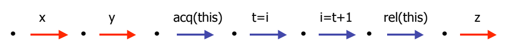
- Race-freedom is neither *necessary* nor *sufficient* to ensure the absence of errors due to unexpected interactions between threads

Atomicity

- The method inc() is atomic if concurrent threads do not interfere with its behavior
- Guarantees that for every execution



- there is a *serial* execution with same behavior



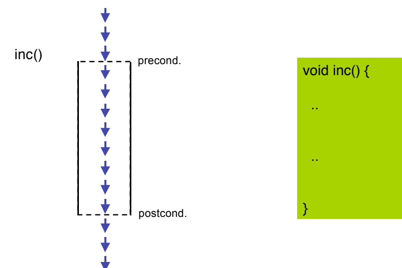
Motivations for Atomicity

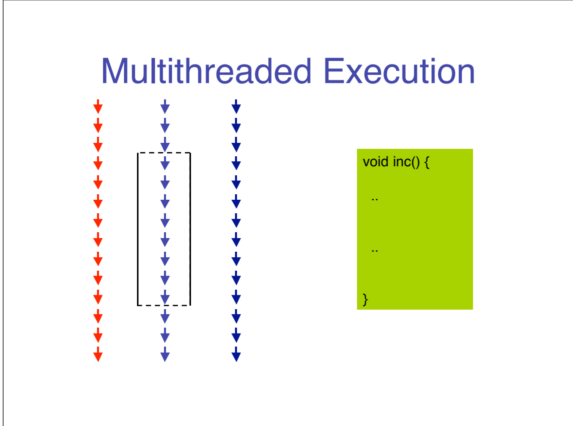
1. Stronger property than race freedom

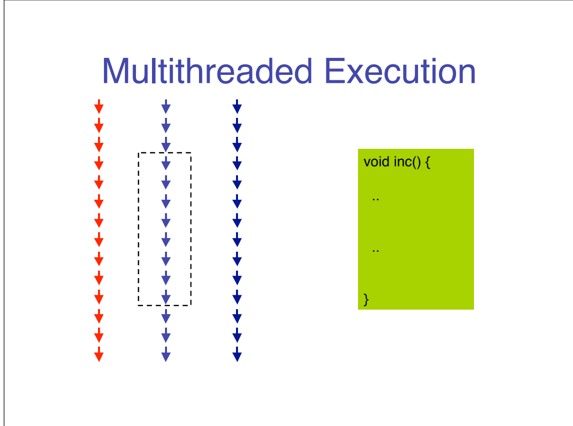
Motivations for Atomicity

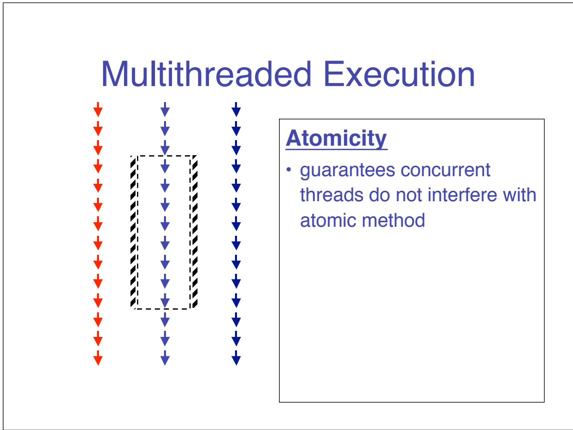
1. Stronger property than race freedom
2. Enables sequential reasoning

Sequential Program Execution



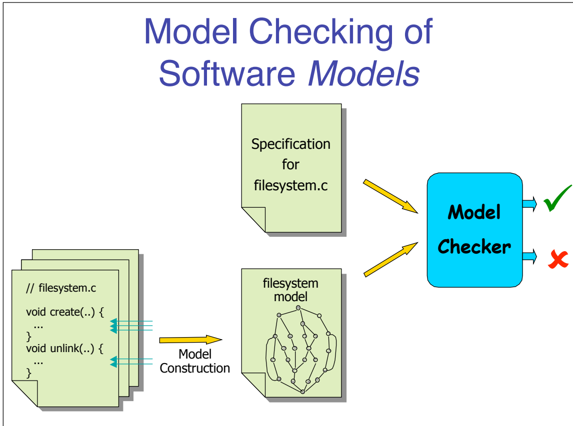


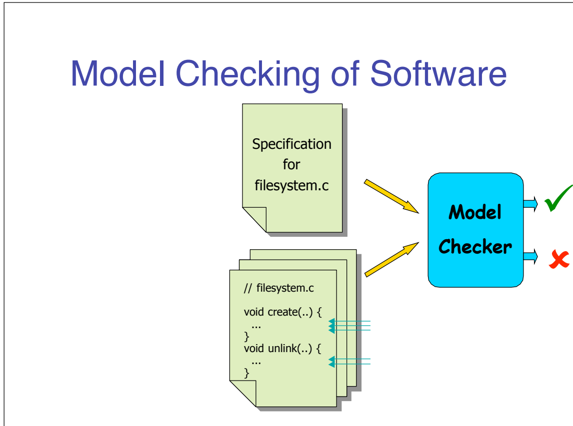




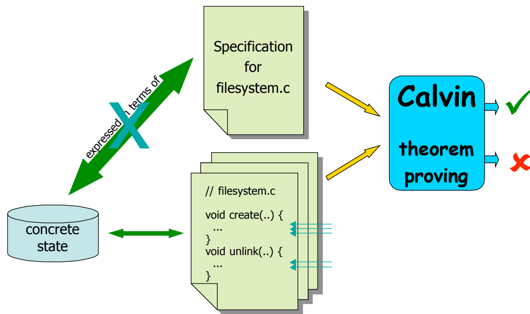
Motivations for Atomicity

1. Stronger property than race freedom
2. Enables sequential reasoning
3. Simple, powerful correctness property





Experience with Calvin Software Checker



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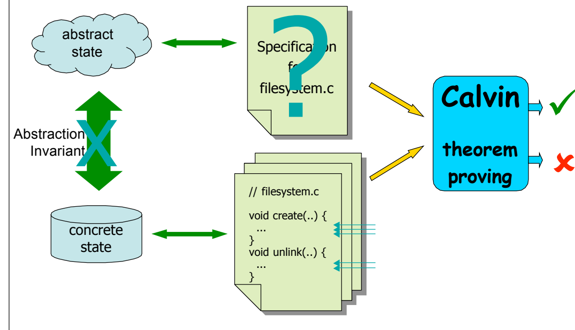


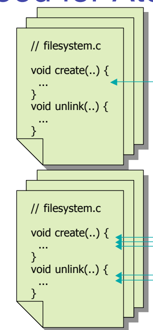
Experience with Calvin Software Checker

```
 /*@ global_invariant (\forall int i; inodeLocks[i] == null ==>
                        0 <= inodeBlocknos[i] && inodeBlocknos[i] < Daisy.MAXBLOCK) */
//@ requires 0 <= inodenum && inodenum < Daisy.MAXINODE;
//@ requires i != null
//@ requires DaisyLock.inodeLocks[inodenum] == \tid
//@ modifies i.blockno, i.size, i.used, i.inodenum
//@ ensures i.blockno  == inodeBlocknos[inodenum]
//@ ensures i.size     == inodeSizes[inodenum]
//@ ensures i.used     == inodeUsed[inodenum]
//@ ensures i.inodenum == inodenum
//@ ensures 0 <= i.blockno && i.blockno < Daisy.MAXBLOCK

static void readi(long inodenum, Inode i) {
        i.blockno = Petal.readLong(STARTINODEAREA + (inodenum * Daisy.INODESIZE));
        i.size    = Petal.readLong(STARTINODEAREA +  (inodenum * Daisy.INODESIZE) + 8);
        i.used    = Petal.read(STARTINODEAREA + (inodenum * Daisy.INODESIZE) + 16) == 1;
        i.inodenum = inodenum;
        // read the right bytes, put in inode
}
```

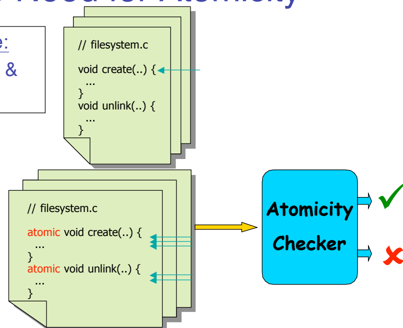
The Need for Atomicity

Sequential case:
code inspection &
testing mostly ok



The Need for Atomicity

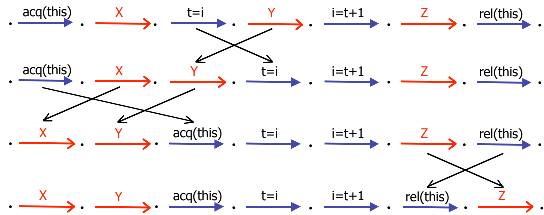
Sequential case:
code inspection &
testing ok



Atomicity

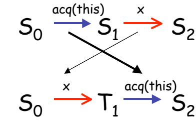
- Canonical property
  - (cmp. serializability, linearizability, ...)
- Enables sequential reasoning
  - simplifies validation of multithreaded code
- Matches practice in existing code
  - most methods (80%+) are atomic
  - many interfaces described as “thread-safe”
- Can verify atomicity statically or dynamically
  - atomicity violations often indicate errors
  - leverages Lipton’s theory of reduction

Reduction [Lipton 75]



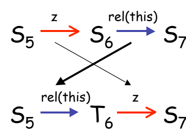
Movers

- right-mover
  - lock acquire



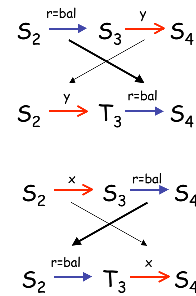
Movers

- right-mover
  - lock acquire
- left-mover
  - lock release



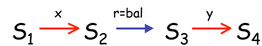
Movers

- right-mover
  - lock acquire
- left-mover
  - lock acquire
- both-mover
  - race-free field access



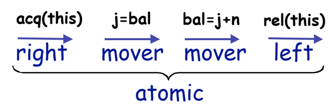
Movers

- right-mover
  - lock acquire
- left-mover
  - lock acquire
- both-mover
  - race-free field access
- non-mover (atomic)
  - access to "racy" fields



Code Classification

right:	lock acquire
left:	lock release
(both) mover:	race-free variable access
atomic:	conflicting variable access

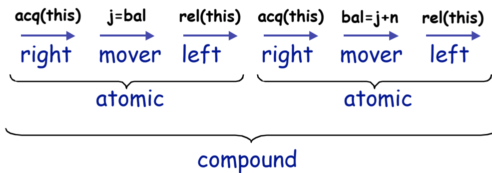


atomic

- composition rules:
  - right; mover = right
  - right; left = atomic
  - right; atomic = atomic
  - atomic; atomic = cmpd

Composing Atomicities

```
void deposit(int n) {
   int j;
   synchronized(this) { j = bal; }
   synchronized(this) { bal = j + n; }
}
```



Conditional Atomicity

```
atomic void deposit(int n) {
  synchronized(this) {      right  }
    int j = bal;            mover  } atomic
    bal = j + n;            mover  }
  }                         left   }
}

Xatomic void depositTwice(int n) {
  synchronized(this) {
    deposit(n);             atomic
    deposit(n);             atomic
  }
}
```

Conditional Atomicity

```
                                          if this already held
atomic void deposit(int n) {
  synchronized(this) {      right  }           mover }
    int j = bal;            mover  } atomic    mover } mover
    bal = j + n;            mover  }           mover }
  }                         left   }           mover }
}

atomic void depositTwice(int n) {
  synchronized(this) {
    deposit(n);             atomic
    deposit(n);             atomic
  }
}
```

Conditional Atomicity

```
(this ? mover : atomic) void deposit(int n) {
  synchronized(this) {
    int j = bal;
    bal = j + n;
  }
}

atomic void depositTwice(int n) {
  synchronized(this) {
    deposit(n);             (this ? mover : atomic)
    deposit(n);             (this ? mover : atomic)
  }
}
```

Conditional Atomicity Details

- In conditional atomicity ($x?b_1:b_2$), x must be a lock expression (i.e., constant)
- Composition rules
  $a ; (x?b_1:b_2) = x ? (a;b_1) : (a;b_2)$

java.lang.StringBuffer

```
/**
 ... used by the compiler to implement the binary string
   concatenation operator ...

 String buffers are safe for use by multiple threads. The methods
   are synchronized so that all the operations on any particular
   instance behave as if they occur in some serial order that is
   consistent with the order of the method calls made by each of the
   individual threads involved.
*/
```

FALSE

public atomic class StringBuffer { ... }

java.lang.StringBuffer is *not* Atomic!

```
public atomic StringBuffer {
  private int count guarded_by this;
A public synchronized int length() { return count; }
A public synchronized void getChars(...) { ... }

  public synchronized void append(StringBuffer sb){
   A int len = sb.length();
C    ...
     ...
   A sb.getChars(...,len,...);
     ...
  }
}
```

sb.length() acquires the lock on sb, gets the length, and releases lock

other threads can change sb

use of stale len may yield StringIndexOutOfBoundsException inside getChars(...)

- append(...) is *not* atomic

java.lang.Vector

```
interface Collection {
  atomic int length();
  atomic void toArray(Object a[]);
}

class Vector {
  int count;
  Object data[];

X atomic Vector(Collection c) {
    count = c.length();          atomic
    data = new Object[count];    mover     } compound
    ...
    c.toArray(data);             atomic
  }
}
```

Bohr

- Type inference for atomicity
  - finds smallest atomicity for each method

Validation

Program	Size (KLOC)	Time (s)	Time (s/KLOC)
elevator	0.5	0.6	1.1
tsp	0.7	1.4	2.0
sor	0.7	0.8	1.2
raytracer	2.0	1.7	0.9
moldyn	1.4	4.9	3.5
montecarlo	3.7	1.5	0.4
mtrt	11.3	7.8	0.7
jbb	30.5	11.2	0.4

(excludes Rcc/Sat time)

Inferred Atomicities

Thread-Safe Classes

Conclusions And Future Directions

- Atomicity a fundamental concept
  - improves over race freedom
  - matches programmer intuition and practice
  - simplifies reasoning about correctness
  - enables concise and trustable documentation