Ownership Types for Safe Programming: Preventing Data Races and Deadlocks

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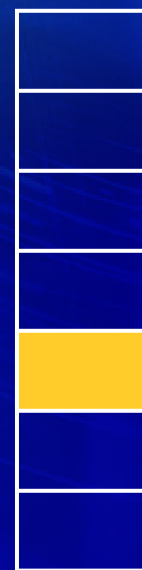
Data Races in Multithreaded Programs

Thread 1:

x = x + 1;



Thread 2:

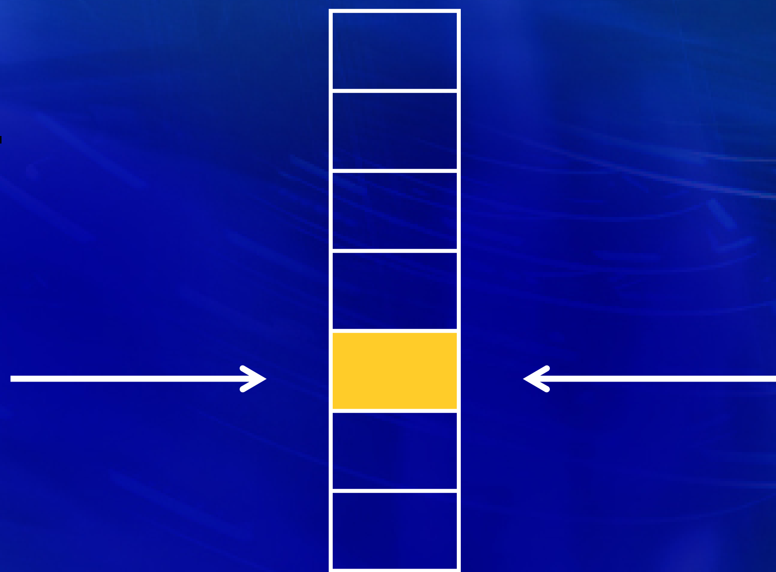
x = x + 2;

- Two threads access same data
- At least one access is a write
- No synchronization to separate accesses

Avoiding Data Races

Thread 1:

x = x + 1;



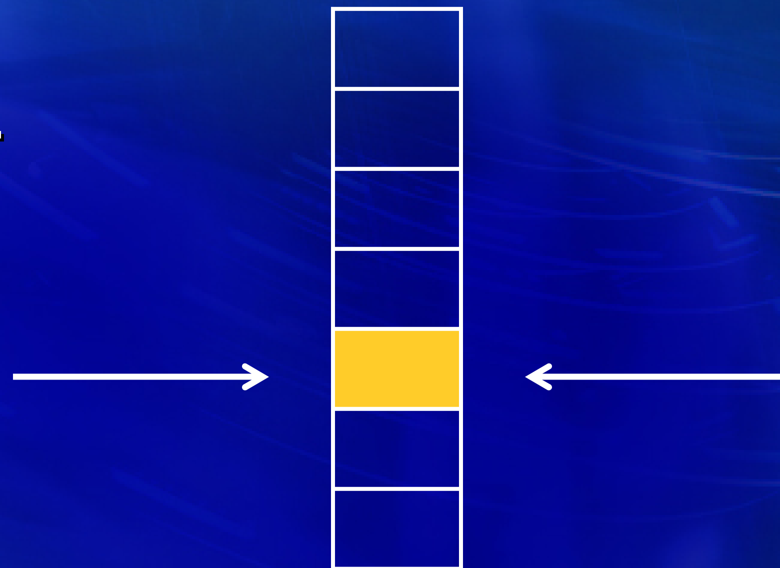
Thread 2:

x = x + 2;

Avoiding Data Races

Thread 1:

```
lock(l);
x = x + 1;
unlock(l);
```

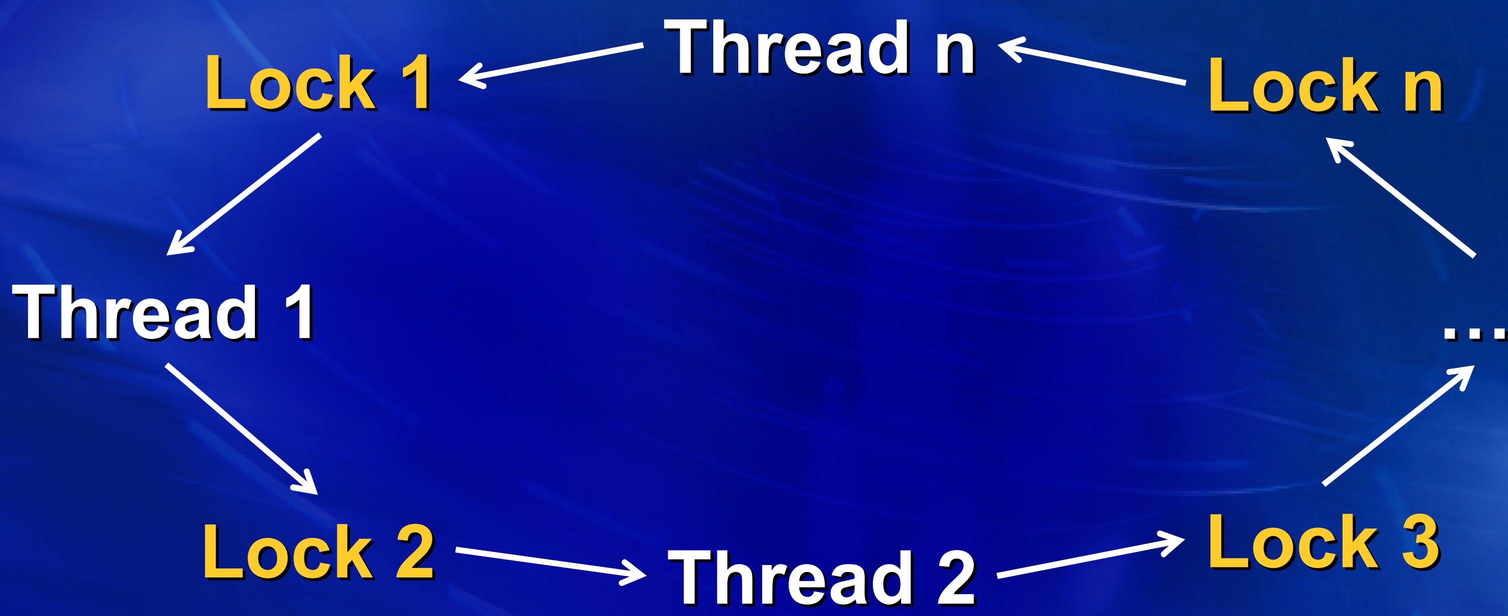


Thread 2:

```
lock(l);
x = x + 2;
unlock(l);
```

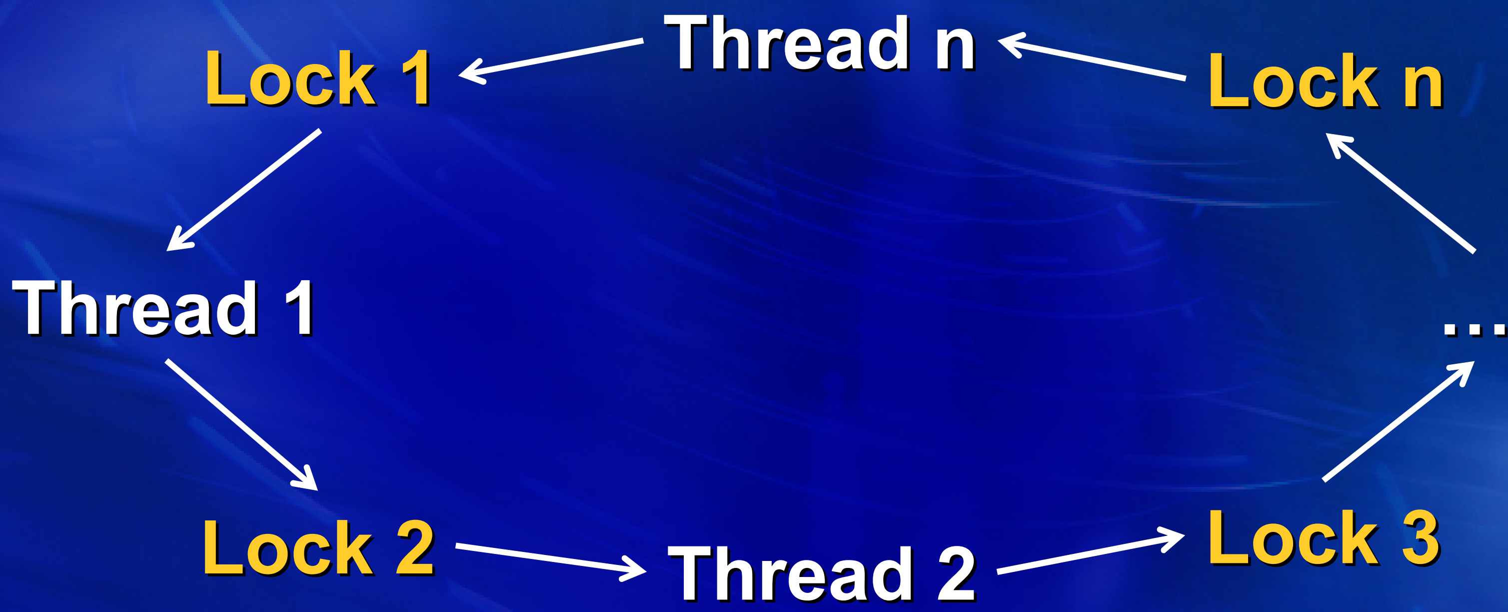
- Associate locks with shared mutable data
- Acquire lock before data access
- Release lock after data access

Deadlocks in Multithreaded Programs

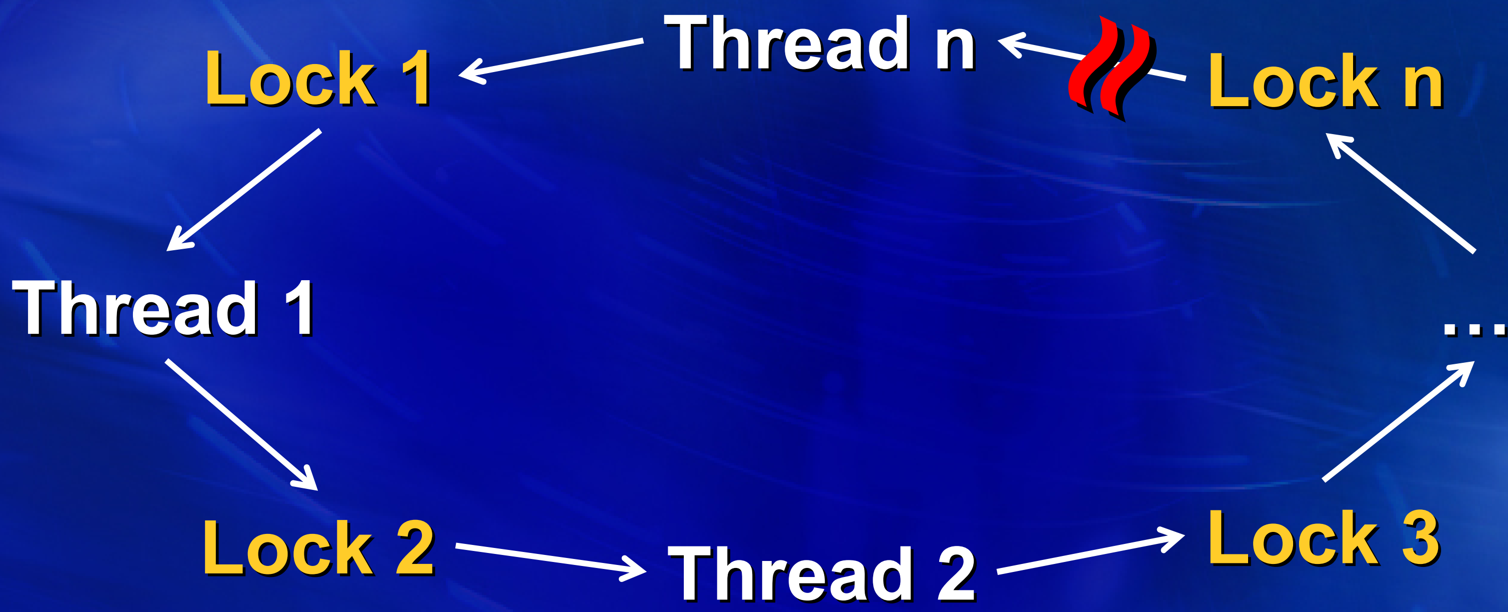


- Cycle of the form
  - Thread 1 holds Lock 1, waits for Lock 2
  - Thread 2 holds Lock 2, waits for Lock 3 …
  - Thread n holds Lock n, waits for Lock 1

Avoiding Deadlocks



Avoiding Deadlocks



- Associate a partial order among locks
- Acquire locks in order

Problem With Current Practice

- Locking discipline is not enforced
- Inadvertent programming errors
  - Can cause data races and deadlocks
- Consequences can be severe
  - Non-deterministic, timing dependent bugs
  - Difficult to detect, reproduce, eliminate

Our Solution

- Static type system
  - Prevents both data races and deadlocks

Our Solution

- Static type system
  - Prevents both data races and deadlocks
- Programmers specify
  - How each object is protected from races
  - Partial order among locks
- Type checker statically verifies
  - Objects are used only as specified
  - Locks are acquired in order

Talk Outline

- Motivation
- Type system
  - Preventing data races
  - Preventing deadlocks
- Experience
- Related work
- Conclusions

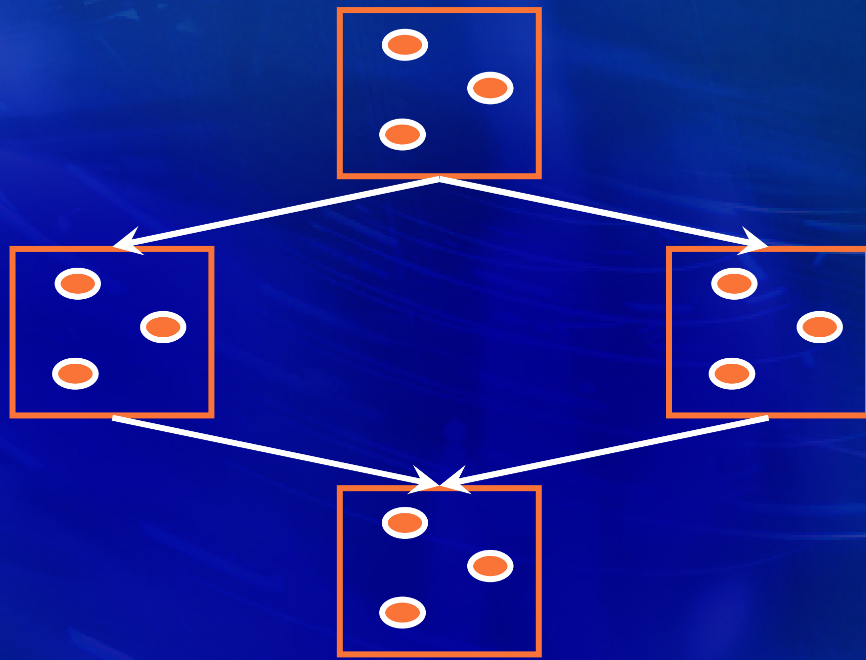
Preventing Data Races

- Programmers specify for every object
  - Lock protecting the object, or
  - That the object needs no locks because
    - Object is immutable
    - Object is thread-local
    - Object has a unique pointer

Preventing Deadlocks

- Programmers specify lock ordering using
  - Static lock levels
  - Recursive data structures
    - Mutable trees
    - Monotonic DAGs
  - Runtime ordering
- Type checker statically verifies
  - Locks are acquired in descending order
  - Specified order is a partial order

Lock Level Based Partial Orders



- Lock levels are partially ordered
- Locks belong to lock levels
- Threads must acquire locks in descending order of lock levels

Lock Level Based Partial Orders

```
class CombinedAccount {



    final Account savingsAccount   = new Account();
    final Account checkingAccount = new Account();

    int balance()  {
        synchronized (savingsAccount) {
            synchronized (checkingAccount) {
                return savingsAccount.balance + checkingAccount.balance;
    }}}
}
```

Lock Level Based Partial Orders

```
class CombinedAccount {

    LockLevel savingsLevel;
    LockLevel checkingLevel < savingsLevel;

    final Account⟨self : savingsLevel⟩   savingsAccount   = new Account();
    final Account⟨self : checkingLevel⟩ checkingAccount = new Account();

    int balance() locks (savingsLevel)  {
        synchronized (savingsAccount) {
            synchronized (checkingAccount) {
                return savingsAccount.balance + checkingAccount.balance;
    }}}
}
```

Lock Level Based Partial Orders

checkingLevel < savingsLevel

```
class CombinedAccount {

    LockLevel savingsLevel;
    LockLevel checkingLevel < savingsLevel;

    final Account⟨self : savingsLevel⟩   savingsAccount   = new Account();
    final Account⟨self : checkingLevel⟩ checkingAccount = new Account();

    int balance() locks (savingsLevel)  {
        synchronized (savingsAccount) {
            synchronized (checkingAccount) {
                return savingsAccount.balance + checkingAccount.balance;
    }}}
}
```

Lock Level Based Partial Orders

savingsAccount belongs to savingsLevel
checkingAccount belongs to checkingLevel

```
class CombinedAccount {

    LockLevel savingsLevel;
    LockLevel checkingLevel < savingsLevel;

    final Account⟨self : savingsLevel⟩  savingsAccount  = new Account();
    final Account⟨self : checkingLevel⟩ checkingAccount = new Account();

    int balance() locks (savingsLevel)  {
        synchronized (savingsAccount) {
            synchronized (checkingAccount) {
                return savingsAccount.balance + checkingAccount.balance;
    }}}
}
```

Lock Level Based Partial Orders

locks are acquired in descending order

```
class CombinedAccount {

    LockLevel savingsLevel;
    LockLevel checkingLevel < savingsLevel;

    final Account⟨self : savingsLevel⟩   savingsAccount   = new Account();
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    int balance() locks (savingsLevel)  {
        synchronized (savingsAccount) {
            synchronized (checkingAccount) {
                return savingsAccount.balance + checkingAccount.balance;
    }}}
}
```

Lock Level Based Partial Orders

locks held by callers > savingsLevel

```
class CombinedAccount {

    LockLevel savingsLevel;
    LockLevel checkingLevel < savingsLevel;

    final Account⟨self : savingsLevel⟩  savingsAccount  = new Account();
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    int balance() locks (savingsLevel) {
        synchronized (savingsAccount) {
            synchronized (checkingAccount) {
                return savingsAccount.balance + checkingAccount.balance;
    }}}
}
```

Lock Level Based Partial Orders

balance can acquire these locks

```
class CombinedAccount {

    LockLevel savingsLevel;
    LockLevel checkingLevel < savingsLevel;

    final Account⟨self : savingsLevel⟩   savingsAccount   = new Account();
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    int balance() locks (savingsLevel)  {
        synchronized (savingsAccount) {
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                return savingsAccount.balance + checkingAccount.balance;
    }}}
}
```
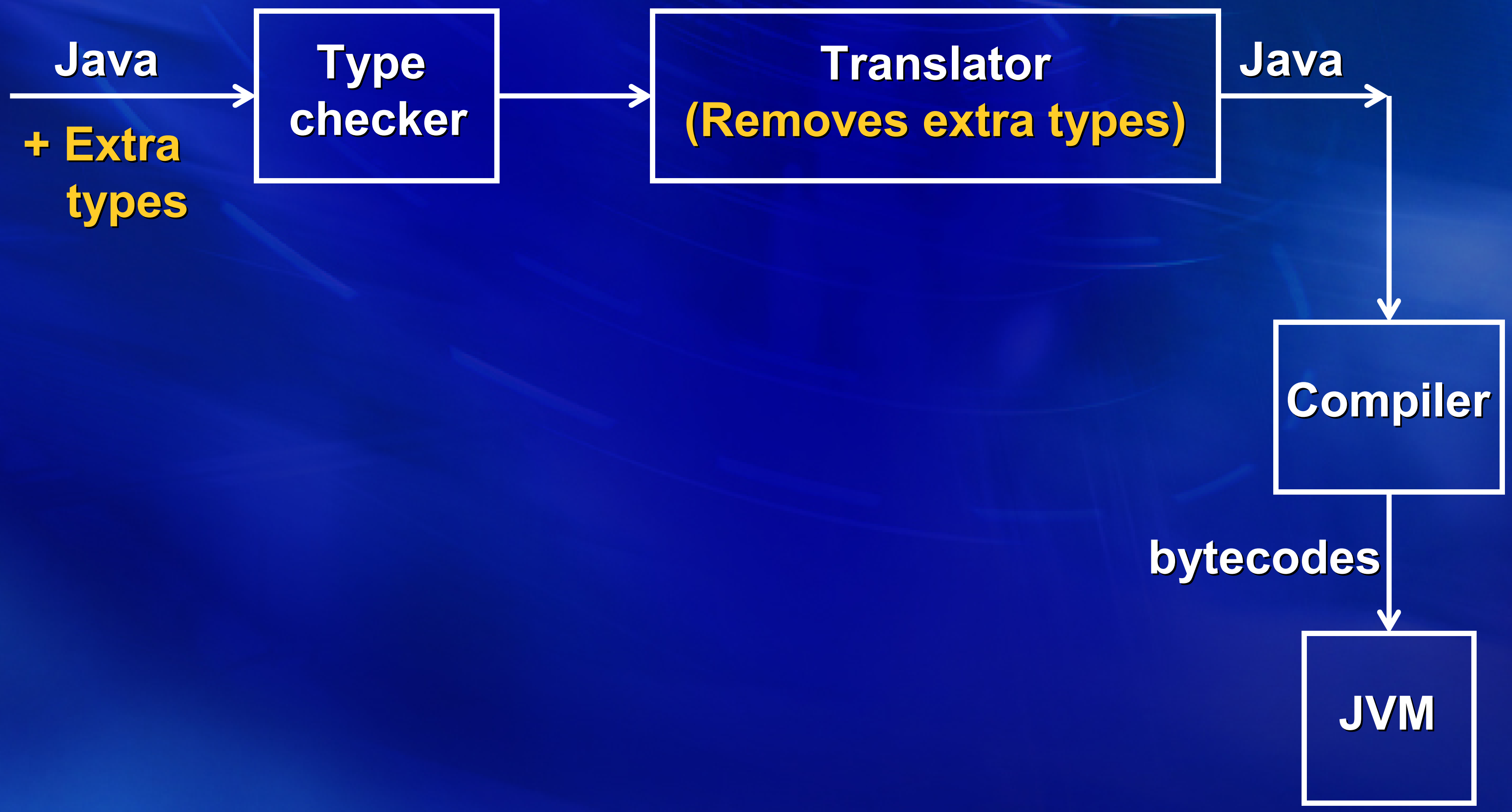

Types Impose No Dynamic Overhead



Lock Level Based Partial Orders

- Bounded number of lock levels
- Unbounded number of locks

- Lock levels support programs where the maximum number of locks simultaneously held by a thread is bounded

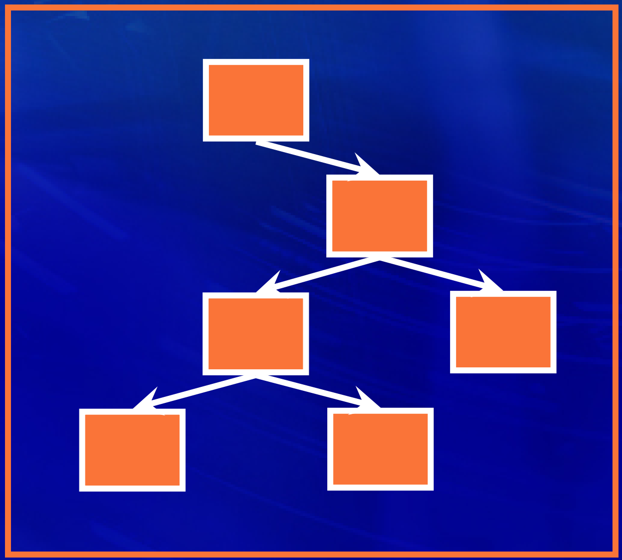
- We use other mechanisms for other cases

Type System

- Preventing data races

- Preventing deadlocks using
  - Static lock levels
  - Recursive data structures
    - Mutable trees
    - Monotonic DAGs
  - Runtime ordering

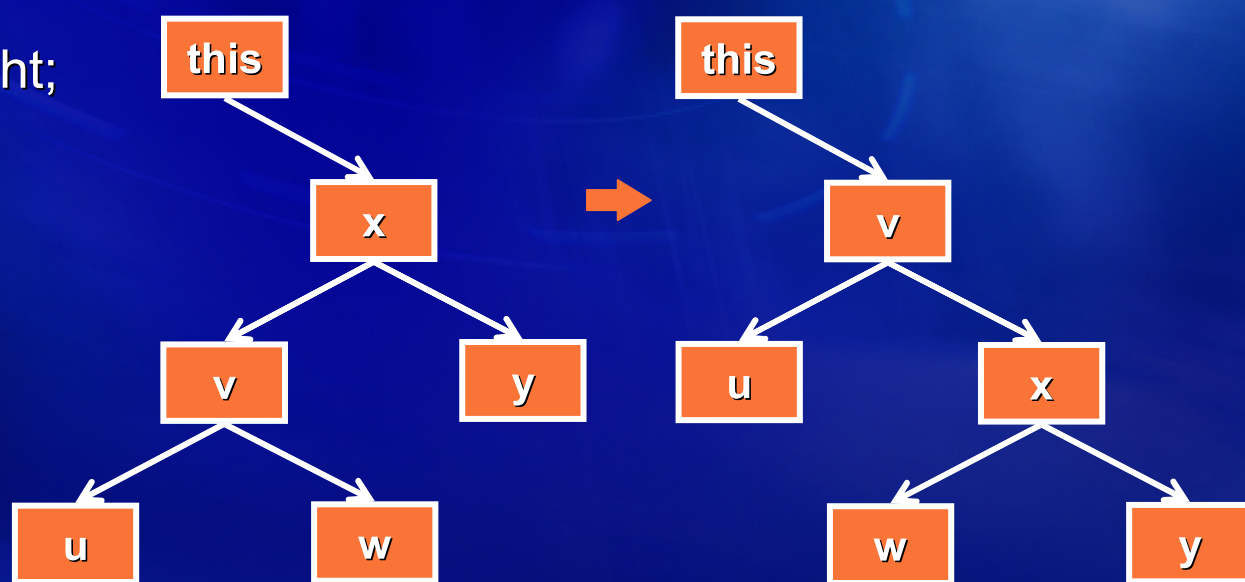
Tree Based Partial Orders



- Locks in a level can be tree-ordered
- Using data structures with tree backbones
  - Doubly linked lists
  - Trees with parent/sibling pointers
  - Threaded trees…

Tree Based Partial Orders

```
class Node {
  Node left;
  Node right;

  synchronized void rotateRight() {
    Node x = this.right;  synchronized (x) {
    Node v = x.left;      synchronized (v) {

      Node w    = v.right;
      v.right   = null;
      x.left    = w;
      this.right = v;
      v.right   = x;
  }}}
}
```



Tree Based Partial Orders

```
class Node⟨self : l⟩ {
    tree Node⟨self : l⟩ left;
    tree Node⟨self : l⟩ right;

    synchronized void rotateRight() locks (this) {
        Node x = this.right;  synchronized (x) {
        Node v = x.left;      synchronized (v) {

          Node w   = v.right;
          v.right     = null;
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    }}}
}
```
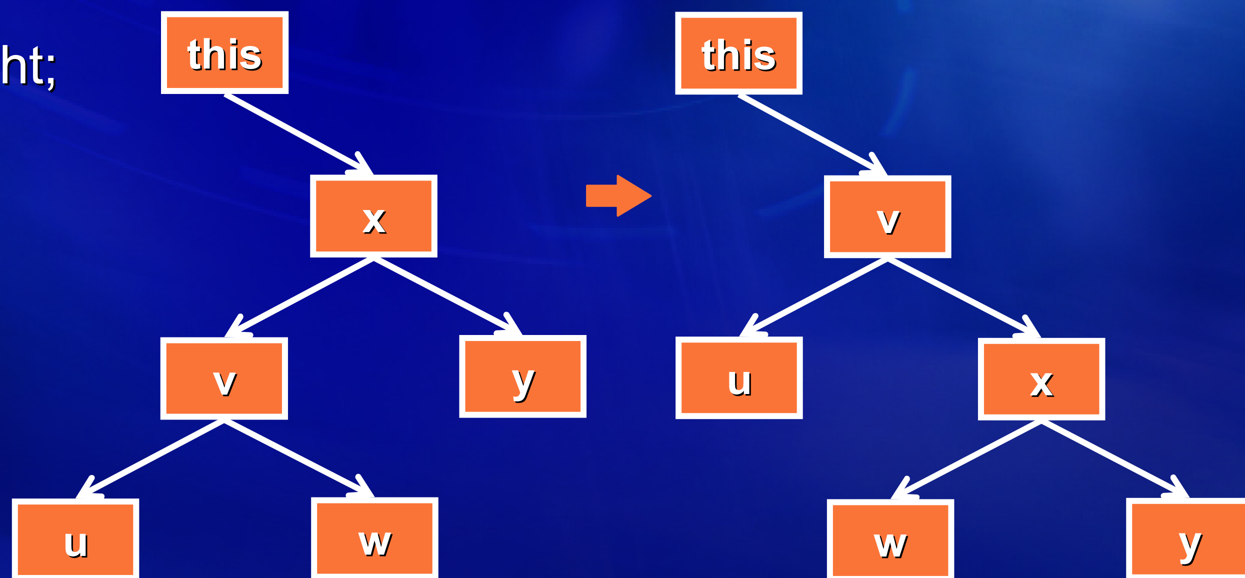

nodes must be locked in tree order



Tree Based Partial Orders

nodes are locked in tree order

```
class Node⟨self : l⟩ {
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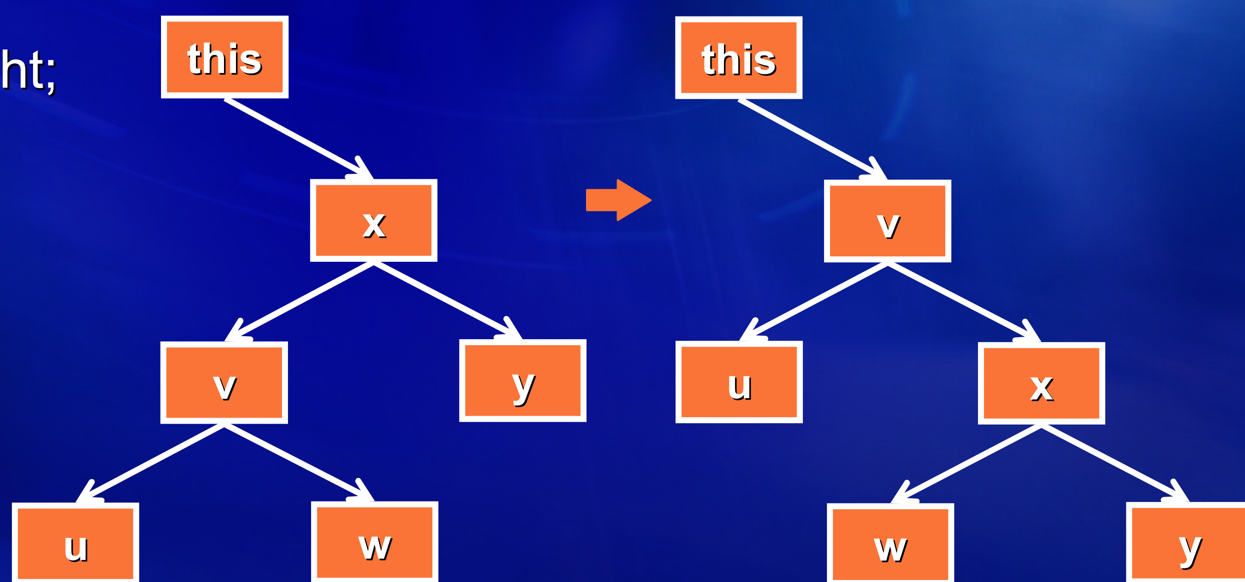

Checking Tree Mutations

- A tree edge may be deleted
- A tree edge from x to y may be added iff
  - y is a Root
  - x is not in Tree(y)
- For onstage nodes x & y, analysis tracks
  - If y is a Root
  - If x is not in Tree(y)
  - If x has a tree edge to y
- Lightweight shape analysis

Checking Tree Mutations

```
class Node⟨self : l⟩ {
  tree Node⟨self : l⟩ left;
  tree Node⟨self : l⟩ right;

  synchronized void rotateRight() locks (this) {
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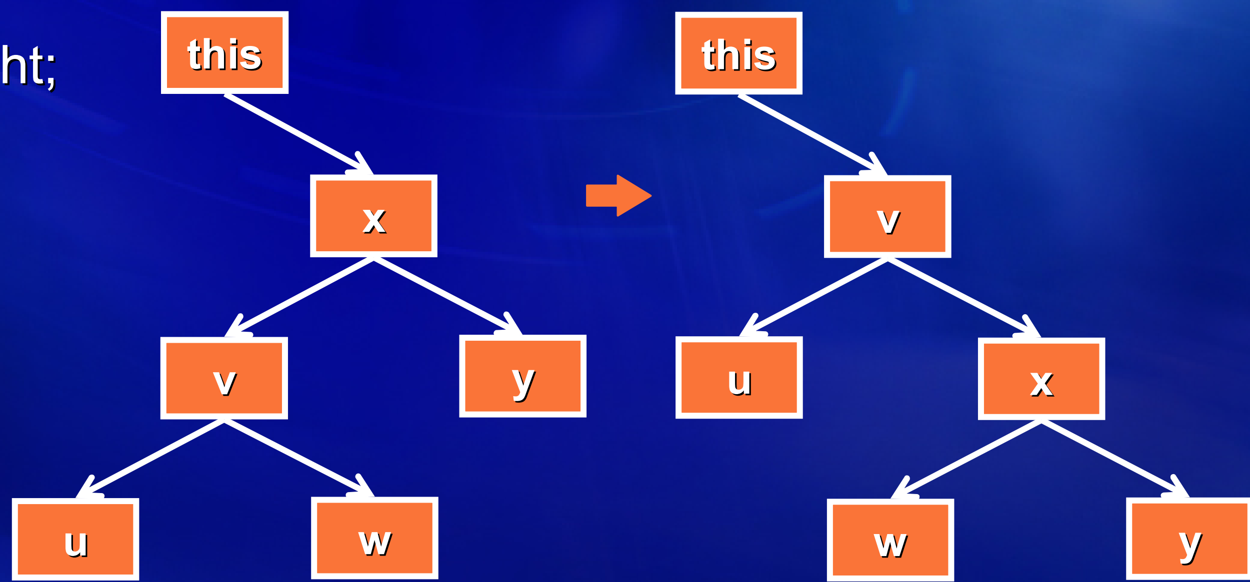
  }}}
}
```



Checking Tree Mutations

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         Node w    = v.right;
         v.right   = null;
         x.left    = w;
         this.right = v;
         v.right   = x;
   }}}
}
```
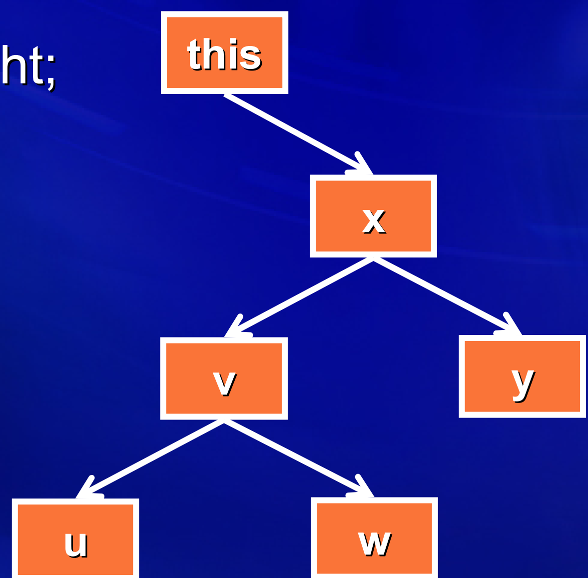

```
x  = this.right
v  = x.left
w = v.right
```



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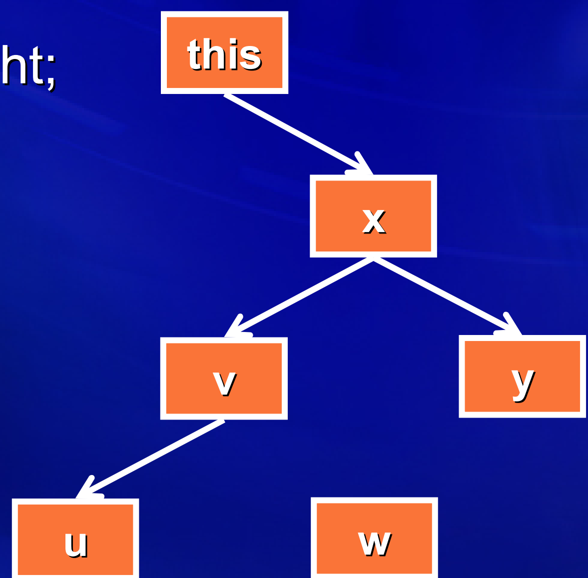
      x.left       = w;
      this.right = v;
      v.right     = x;
  }}}
}
```

x = this.right
v = x.left

w is Root

v not in Tree(w)
x not in Tree(w)
this not in Tree(w)



Checking Tree Mutations

```
class Node⟨self : I⟩ {
    tree Node⟨self : I⟩ left;
    tree Node⟨self : I⟩ right;

    synchronized void rotateRight() locks (this) {
        Node x = this.right;  synchronized (x) {
        Node v = x.left;      synchronized (v) {

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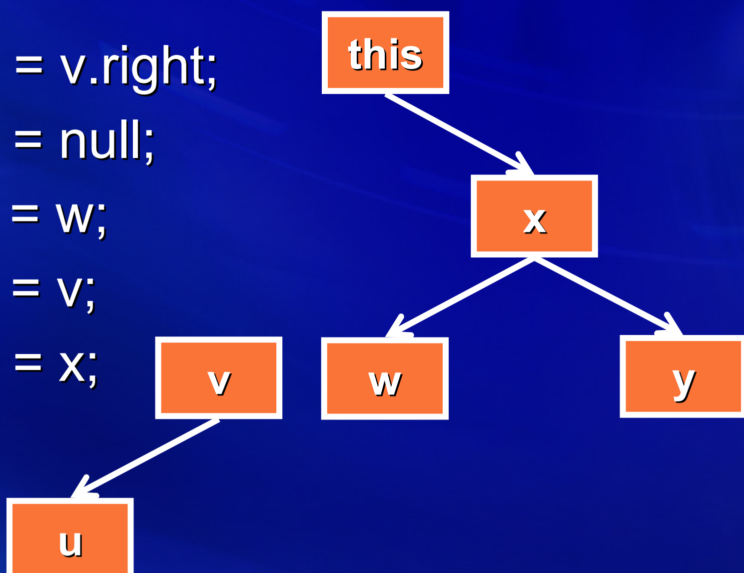

x = this.right
w = x.left

v is Root

x not in Tree(v)
w not in Tree(v)
this not in Tree(v)

Checking Tree Mutations

```
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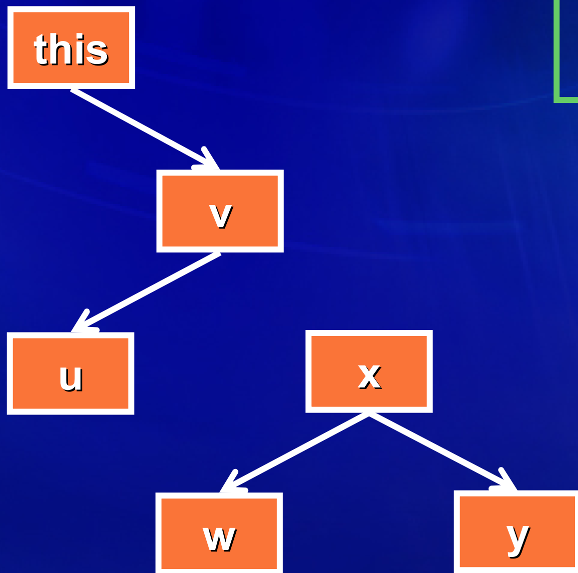
v = this.right
w = x.left

x is Root

this not in Tree(x)
v not in Tree(x)



Checking Tree Mutations

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      v.right     = x;
  }}}
}
```
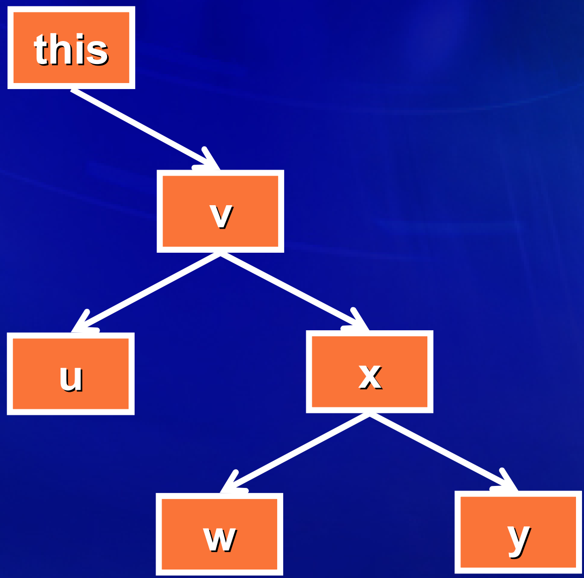

```
v  = this.right
w = x.left
x  = v.right
```



Type System

- Preventing data races
- Preventing deadlocks using
  - Static lock levels
  - Recursive data structures
    - Mutable trees
    - Monotonic DAGs
  - Runtime ordering

DAG Based Partial Orders

```
class Node⟨self : l⟩ {
    dag Node⟨self : l⟩ left;
    dag Node⟨self : l⟩ right;
    …
}
```

- **Locks in a level can be DAG-ordered**

- **DAGs cannot be arbitrarily modified**
- **DAGs can be built bottom-up by**
  - **Allocating a new node**
  - **Initializing its DAG fields**

Type System

- Preventing data races
- Preventing deadlocks using
  - Static lock levels
  - Recursive data structures
    - Mutable trees
    - Monotonic DAGs
  - Runtime ordering

Runtime Ordering of Locks

```
class Account {
    int balance = 0;
    void deposit(int x)    { balance += x; }
    void withdraw(int x) { balance  -= x; }

}

void transfer(Account a1, Account a2, int x) {
    synchronized (a1, a2) in  { a1.withdraw(x); a2.deposit(x); }
}
```

Runtime Ordering of Locks

```
class Account implements Dynamic {
    int balance = 0;
    void deposit(int x)    requires (this)  { balance += x; }
    void withdraw(int x) requires (this)  { balance  -= x; }

}

void transfer(Account⟨self : v⟩ a1, Account⟨self : v⟩ a2, int x) locks(v) {
    synchronized (a1, a2) in  { a1.withdraw(x); a2.deposit(x); }
}
```

Runtime Ordering of Locks

Account objects are dynamically ordered

```
class Account implements Dynamic {
    int balance = 0;
    void deposit(int x)   requires (this)  { balance += x; }
    void withdraw(int x) requires (this)  { balance  -= x; }

}

void transfer(Account⟨self : v⟩ a1, Account⟨self : v⟩ a2, int x) locks(v) {
    synchronized (a1, a2) in  { a1.withdraw(x); a2.deposit(x); }
}
```

Runtime Ordering of Locks

locks are acquired in runtime order

```
class Account implements Dynamic {
    int balance = 0;
    void deposit(int x)   requires (this)  { balance += x; }
    void withdraw(int x) requires (this)  { balance  -= x; }

}

void transfer(Account⟨self : v⟩ a1, Account⟨self : v⟩ a2, int x) locks(v) {
    synchronized (a1, a2) in  { a1.withdraw(x); a2.deposit(x); }
}
```

Reducing Programming Overhead

- Type inference and default types significantly reduce programming overhead
- Single threaded programs need no annotations
- Our approach supports separate compilation

Experience

Multithreaded Server Programs

Program	Lines of code	Lines changed
elevator	523	15
http server	563	26
chat server	308	22
stock quote server	242	12
game server	87	11
phone (database) server	302	10

Java Libraries

Program	Lines of code	Lines changed
java.util.Hashtable	1011	53
java.util.HashMap	852	46
java.util.Vector	992	35
java.util.ArrayList	533	18

Java Libraries

Program	Lines of code	Lines changed
java.io.PrintStream	568	14
java.io.FilterOutputStream	148	5
java.io.OutputStream	134	3
java.io.BufferedWriter	253	9
java.io.OutputStreamWriter	266	11
java.io.Writer	177	6

Related Work

Related Work

- Static tools
  - Korty (USENIX ’89)
  - Sterling (USENIX ’93)
  - Detlefs, Leino, Nelson, Saxe (SRC ’98)
  - Engler, Chen, Hallem, Chou, Chelf (SOSP ’01)
- Dynamic tools
  - Steele (POPL ’90)
  - Dinning, Schonberg (PPoPP ’90)
  - Savage,Burrows,Nelson,Sobalvarro,Anderson (SOSP ’97)
  - Praun, Gross (OOPSLA ’01)
  - Choi,Lee,Loginov,O’Callahan,Sarkar,Sridharan (PLDI ’02)

Related Work

- Type systems
  - Flanagan, Freund (PLDI '00)
  - Bacon, Strom, Tarafdar (OOPSLA '00)

Related Work

- Ownership types
  - Clarke, Potter, Noble (OOPSLA ’98), (ECOOP ’01)
  - Clarke, Drossopoulou (OOPSLA ’02)
  - Aldrich, Kostadinov, Chambers (OOPSLA ’02)

  - Boyapati, Rinard (OOPSLA ’01)
  - Boyapati, Lee, Rinard (OOPSLA ’02)
  - Boyapati, Liskov, Shrira (MIT ’02)
  - Boyapati, Salcianu, Beebee, Rinard (MIT ’02)

Ownership Types

- We have used ownership types for
  - Object encapsulation
  - Constraining heap aliasing
  - Modular effects clauses with subtyping
  - Preventing data races and deadlocks
  - Safe lazy upgrades in OODBs
  - Safe region-based memory management
- Ownership types can serve as a foundation for future OO languages

Conclusions

- Data races and deadlocks make multithreaded programming difficult
- We presented a static type system that prevents data races and deadlocks
- Our type system is expressive
- Programs can be efficient and reliable

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