Universe Types for Race Safety

Dave Cunningham
(PhD student of Susan Eisenbach, Sophia Drossopoulou)
Imperial College

London Theory Day
19/04/2007

Race Conditions

Race conditions:

Race Conditions

Race conditions:

- are bugs in shared memory concurrent software.
- are caused by incorrect synchronisation.

Race Conditions

Race conditions:

- are bugs in shared memory concurrent software.
- are caused by incorrect synchronisation.
- can corrupt program state.
- can lead to strange program behaviour.

Race Conditions

Race conditions:

- are bugs in shared memory concurrent software.
- are caused by incorrect synchronisation.
- can corrupt program state.
- can lead to strange program behaviour.
- are hard to reproduce.

Race Conditions

Race conditions:

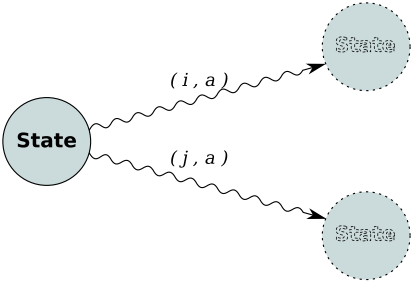
- are bugs in shared memory concurrent software.
- are caused by incorrect synchronisation.
- can corrupt program state.
- can lead to strange program behaviour.
- are hard to reproduce.

Preventing race conditions with a static type system would eliminate these problems.

We give such a type system and prove it works.

Instantaneous Race Condition

Two threads are not allowed to access the same object simultaneously:



NTP: Instantaneous race conditions never occur.

Object Accesses and Locks

If we know that:

- No two threads simultaneously hold the same lock.
  (basic property of a lock implementation)

Object Accesses and Locks

If we know that:

- No two threads simultaneously hold the same lock. (basic property of a lock implementation)
- Threads only access objects for which they hold the lock.

Then instantaneous race conditions can never happen.

Object Accesses and Locks

If we know that:

- No two threads simultaneously hold the same lock.
  (basic property of a lock implementation)
- Threads only access objects for which they hold the lock.

Then instantaneous race conditions can never happen.

Our type system ensures the second property.

General Approach

Enforcing synchronisation is the key:

```
e.f = 10;
```

General Approach

Enforcing synchronisation is the key:

```
sync (???) {
        ...
        e.f = 10;

        ...
}
```

General Approach

Enforcing synchronisation is the key:

```
sync (e’) {
        ...
        e.f = 10;

        ...
}
```

General Approach

Enforcing synchronisation is the key:

```
sync (e') {
        ...
        e.f = 10;
        ...
}
```

Require that e' is **guarded by** the same lock:

$\vdash_{gb} e : l$
$\vdash_{gb} \texttt{e'} : l$

General Approach

Enforcing synchronisation is the key:

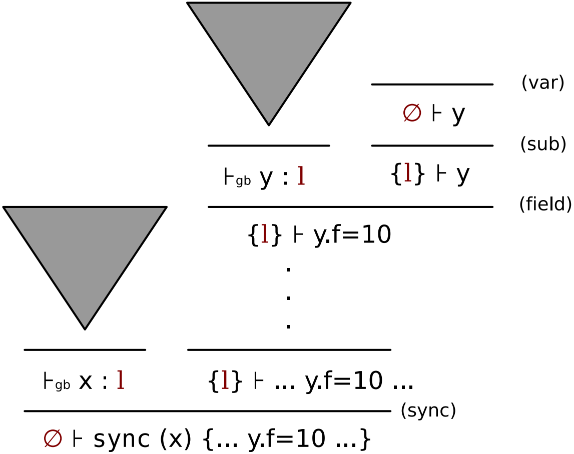
```
sync (e') {
        ...
        e.f = 10;
        ...
}
```

Require that e' is **guarded by** the same lock:

$\vdash_{gb} e : l$
$\vdash_{gb} e' : l$

(Defining a good $\vdash_{gb}$ is 90% of the problem!)

Example



Type System (for illustrative purposes only!)

$$\frac{}{\emptyset \vdash \texttt{this}}\text{(Var)}$$

Type System (for illustrative purposes only!)

$$\frac{}{\emptyset \vdash \texttt{this}}\text{(Var)} \qquad \frac{\mathbb{L} \vdash e \quad \vdash_{gb} e : l \quad l \in \mathbb{L}}{\mathbb{L} \vdash e.f}\text{(Field)}$$

Type System (for illustrative purposes only!)

$$\frac{}{\emptyset \vdash \texttt{this}}\text{(Var)} \qquad \frac{\mathbb{L} \vdash e \quad \vdash_{gb} e : l \quad l \in \mathbb{L}}{\mathbb{L} \vdash e.f}\text{(Field)} \qquad \frac{\mathbb{L} \vdash e' \quad \vdash_{gb} e' : l \quad \mathbb{L} \cup \{l\} \vdash e}{\mathbb{L} \vdash \texttt{sync}\ e'\ e}\text{(Sync)}$$

Type System (for illustrative purposes only!)

$$\frac{}{\emptyset \vdash \texttt{this}}\text{(Var)} \qquad \frac{\mathbb{L} \vdash e \quad \vdash_{gb} e : l \quad l \in \mathbb{L}}{\mathbb{L} \vdash e.f}\text{(Field)} \qquad \frac{\mathbb{L} \vdash e' \quad \vdash_{gb} e' : l \quad \mathbb{L} \cup \{l\} \vdash e}{\mathbb{L} \vdash \texttt{sync}\ e'\ e}\text{(Sync)}$$

$$\frac{\mathbb{L}' \vdash e \quad \mathbb{L}' \subseteq \mathbb{L}}{\mathbb{L} \vdash e}\text{(Sub)}$$

Type System (for illustrative purposes only!)

$$\frac{}{\emptyset \vdash \texttt{this}}\text{(Var)}$$

$$\frac{\mathbb{L} \vdash e \quad \vdash_{gb} e : l \quad l \in \mathbb{L}}{\mathbb{L} \vdash e.f}\text{(Field)}$$

$$\frac{\mathbb{L} \vdash e' \quad \vdash_{gb} e' : l \quad \mathbb{L} \cup \{l\} \vdash e}{\mathbb{L} \vdash \texttt{sync}\ e'\ e}\text{(Sync)}$$

$$\frac{\mathbb{L}' \vdash e \quad \mathbb{L}' \subseteq \mathbb{L}}{\mathbb{L} \vdash e}\text{(Sub)}$$

Now we need only define $\vdash_{gb}$

A first attempt at defining $\vdash_{gb}$

Paths are sequences of field accesses starting from a variable e.g.

A first attempt at defining $\vdash_{gb}$

Paths are sequences of field accesses starting from a variable e.g.

- `x.f.g`

A first attempt at defining $\vdash_{gb}$

Paths are sequences of field accesses starting from a variable e.g.

- `x.f.g`
- `this.first.next.next`

A first attempt at defining $\vdash_{gb}$

Paths are sequences of field accesses starting from a variable e.g.

- `x.f.g`
- `this.first.next.next`

We use them to statically characterise objects.

A first attempt at defining $\vdash_{gb}$

Paths are sequences of field accesses starting from a variable e.g.

- `x.f.g`
- `this.first.next.next`

We use them to statically characterise objects.

Suppose the progammer wrote: `sync` (p) { ... p`.f=20` }

A first attempt at defining $\vdash_{gb}$

Paths are sequences of field accesses starting from a variable e.g.

- `x.f.g`
- `this.first.next.next`

We use them to statically characterise objects.

Suppose the progammer wrote: `sync` (p) { ... p`.f=20` }
We can allow this if we let $\vdash_{gb}\ p : p$

A first attempt at defining $\vdash_{gb}$

Paths are sequences of field accesses starting from a variable e.g.

- `x.f.g`
- `this.first.next.next`

We use them to statically characterise objects.

Suppose the progammer wrote: `sync` (p) { ... p`.f=20` }
We can allow this if we let $\vdash_{gb} p : p$

(i.e. the set of all locks = the set of all paths)

Derivation tree with paths

$$\dfrac{\dfrac{}{\vdash_{gb} x.f : x.f}\,(\text{path}) \qquad \dfrac{\dfrac{}{\vdash_{gb} x.f : x.f}\,(\text{path}) \qquad \dfrac{\dfrac{}{\vdash_{gb} x : x}\,(\text{path}) \qquad \dfrac{\dfrac{}{\emptyset \vdash x}\,(\text{var})}{\{x, x.f\} \vdash x}\,(\text{sub})}{\{x, x.f\} \vdash x.f}\,(\text{field})}{\{x, x.f\} \vdash x.f.g{=}10}\,(\text{field})}{\{x\} \vdash \text{sync } (x.f)\ \{x.f.g{=}20\}}\,(\text{sync})$$

A problem

$\emptyset \vdash$ `sync (x) { x=y ; x.f=20 }`

A problem

$\emptyset \vdash$ `sync (x) { x=y ; x.f=20 }`

$\uparrow$

A problem

$\emptyset \vdash$ `sync (x) { x=y ; x.f=20 }`

↑ accesses the object y

A problem

$\emptyset \vdash$ `sync (x) { x=y ; x.f=20 }`

↑ accesses the object y

similarly...

$\{x\} \vdash$ `sync (x.f) { x.f=y ; x.f.g=20 }`

A problem

$\emptyset \vdash$ `sync (x) { x=y ; x.f=20 }`

↑ accesses the object `y`

similarly...

$\{x\} \vdash$ `sync (x.f) { x.f=y ; x.f.g=20 }`

↑ accesses the object `y`

A problem

$\emptyset \vdash$ `sync (x) { x=y ; x.f=20 }`

↑ accesses the object `y`

similarly...

$\{x\} \vdash$ `sync (x.f) { x.f=y ; x.f.g=20 }`

↑ accesses the object `y`

In neither case were we required to lock `y`.

A problem

$\emptyset \vdash$ `sync (x) { x=y ; x.f=20 }`

↑ accesses the object `y`

similarly...

$\{x\} \vdash$ `sync (x.f) { x.f=y ; x.f.g=20 }`

↑ accesses the object `y`

In neither case were we required to lock `y`.

So, we restrict assignments to vars/fields within a sync block, so that locks cannot be affected.

A problem

$\emptyset \vdash$ `sync (x) { x=y ; x.f=20 }`

↑ accesses the object `y`

similarly...

$\{x\} \vdash$ `sync (x.f) { x.f=y ; x.f.g=20 }`

↑ accesses the object `y`

In neither case were we required to lock `y`.

So, we restrict assignments to vars/fields within a sync block, so that locks cannot be affected.

How does this affect expressiveness?

Iteration

```
class Node { Node next; int cargo }

Node i = ...;
sync(i) {
        while (i!=null) {
                i.cargo = 20;
                i = i.next;
        }
}
```

Iteration

```
class Node { Node next; int cargo }

Node i = ...;
sync(i) {
        while (i!=null) {
                i.cargo = 20;
                i = i.next;
        }
}
```

Here, assigning to `i` conflicts with the locking of `i`

A conceptual problem

A bit of a recap:

- Currently locks and objects are 1:1. $(\vdash_{gb} p : p)$

A conceptual problem

A bit of a recap:

- Currently locks and objects are 1:1. $(\vdash_{gb} p : p)$
- When iterating over a list, n nodes may be accessed.

A conceptual problem

A bit of a recap:

- Currently locks and objects are 1:1. $(\vdash_{gb} p : p)$
- When iterating over a list, n nodes may be accessed.
- Should we be taking n locks?

A conceptual problem

A bit of a recap:

- Currently locks and objects are 1:1. $(\vdash_{gb} p : p)$
- When iterating over a list, n nodes may be accessed.
- Should we be taking n locks?
- No, we should associate one lock for all the nodes.

A conceptual problem

A bit of a recap:

- Currently locks and objects are 1:1. $(\vdash_{gb} p : p)$
- When iterating over a list, n nodes may be accessed.
- Should we be taking n locks?
- No, we should associate one lock for all the nodes.
- Need to be careful with assignment.

A conceptual problem

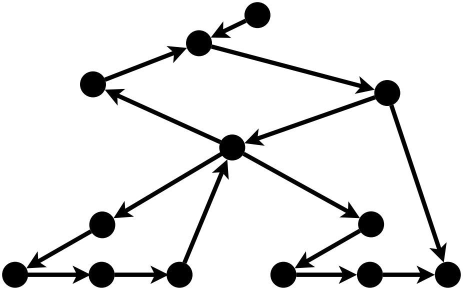
A bit of a recap:

- Currently locks and objects are 1:1. $(\vdash_{gb} p : p)$
- When iterating over a list, n nodes may be accessed.
- Should we be taking n locks?
- No, we should associate one lock for all the nodes.
- Need to be careful with assignment.

Can we extend $\vdash_{gb}$ to do this?

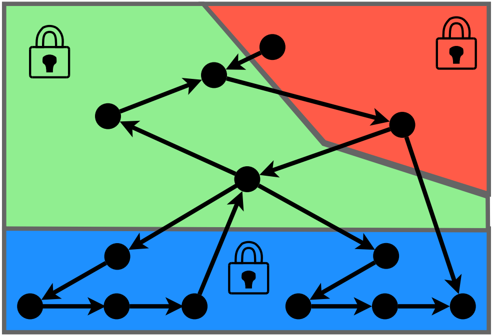
Carving the Heap

Artist's impression of a heap:



Carving the Heap

Artist's impression of a heap:



Regions

Other work has used a programmer-supplied set, e.g. {RED, BLUE}

The source code looks like:

```
RED Object r = new RED Object();
BLUE Object b = new BLUE Object();
```

Regions

Other work has used a programmer-supplied set, e.g. {RED, BLUE}

The source code looks like:

```
RED Object r = new RED Object();
BLUE Object b = new BLUE Object();

r = b; //not allowed
```

Regions

Other work has used a programmer-supplied set, e.g. {RED, BLUE}

The source code looks like:

```
RED Object r = new RED Object();
BLUE Object b = new BLUE Object();

r = b; //not allowed

void m(RED Object x, RED Object y) {
      x = y
}
```

Regions

Other work has used a programmer-supplied set, e.g. {RED, BLUE}

The source code looks like:

```
RED Object r = new RED Object();
BLUE Object b = new BLUE Object();

r = b; //not allowed

void m(RED Object x, RED Object y) {
      x = y
}

m(r,b); //not allowed
```

Regions as Locks

Suppose we already have a region type system:

$$\Gamma \vdash e : R$$

Regions as Locks

Suppose we already have a region type system:

$$\frac{\Gamma \vdash e : R}{\Gamma \vdash_{gb} e : R}$$

Regions as Locks

Suppose we already have a region type system:

$$\frac{\Gamma \vdash e : R}{\Gamma \vdash_{gb} e : R}$$

Note we now need a Γ in the other type system too: $\mathbb{L}, \Gamma \vdash e$

Regions as Locks

Suppose we already have a region type system:

$$\frac{\Gamma \vdash e : R}{\Gamma \vdash_{gb} e : R}$$

Note we now need a Γ in the other type system too: $\mathbb{L}, \Gamma \vdash e$

```
RED Object r1, r2 = ...
BLUE Object b = ...
sync(r1) {
      b.f = 10; // not allowed
      r2.f = 10; // OK
}
```

Iteration Example

```
class Node { RED Node next; int cargo }
```

Iteration Example

```
class Node { RED Node next; int cargo }

RED Node i = ...;

sync (i) {
        while (i!=null) {
                i.cargo = 20;
                i = i.next;
        }
}
```

Summary

Carving up the heap helps us verify safe locking:

Summary

Carving up the heap helps us verify safe locking:

- `x.f = y ; x.f.g = 10`
  Here we must lock l where $\ldots \vdash_{gb} y : \mathrm{l}$

Summary

Carving up the heap helps us verify safe locking:

- `x.f = y ; x.f.g = 10`
  Here we must lock l where $\ldots \vdash_{gb} y : \mathrm{l}$
- The region type rule for assignment ensures $\ldots \vdash_{gb} x.f : \mathrm{l}$

Summary

Carving up the heap helps us verify safe locking:

- `x.f = y ; x.f.g = 10`
  Here we must lock l where $\ldots \vdash_{gb} y : \mathrm{l}$
- The region type rule for assignment ensures $\ldots \vdash_{gb} x.f : \mathrm{l}$
- Instead of restricting all assignments to field f, we only restrict assignments where the lock changes.

Summary

Carving up the heap helps us verify safe locking:

- `x.f = y ; x.f.g = 10`
  Here we must lock l where $\ldots \vdash_{gb} y : \mathrm{l}$
- The region type rule for assignment ensures $\ldots \vdash_{gb} x.f : \mathrm{l}$
- Instead of restricting all assignments to field f, we only restrict assignments where the lock changes.
- So soundness is preserved.

Summary 2

Advantages of carving with regions:

Summary 2

Advantages of carving with regions:

- Simple
- Inference is possible (points-to analysis)

Summary 2

Advantages of carving with regions:

- Simple
- Inference is possible (points-to analysis)

Disadvantages of regions:

- Unscalable (number of locks does not scale with program)

Summary 2

Advantages of carving with regions:

- Simple
- Inference is possible (points-to analysis)

Disadvantages of regions:

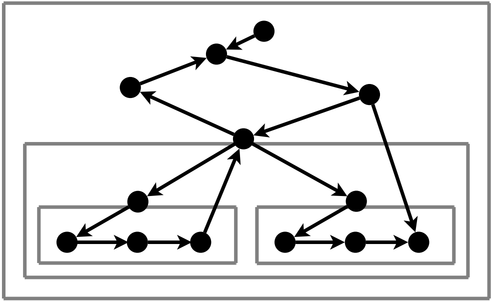
- Unscalable (number of locks does not scale with program)

Regions used by:

- **Guava** – D. Bacon, R. Strom, A. Tarafdar (OOPSLA'00)
- **Sync... with data** – M. Vaziri, F. Tip, J. Dolby (POPL'06)
- **Locksmith** – P. Pratikakis, J. Foster, M. Hicks (PLDI'06)

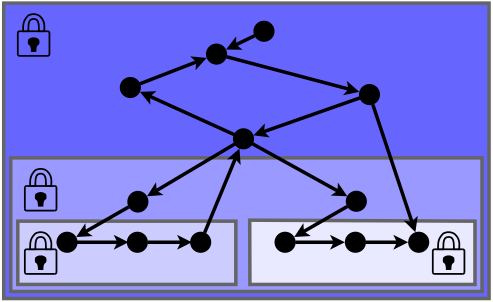
Carving the Heap Again

Ownership types impose a heap hierarchy:



Carving the Heap Again

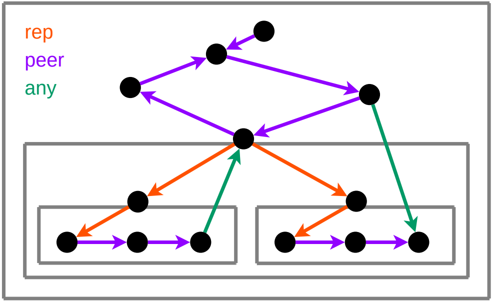
Ownership types impose a heap hierarchy:



Can use the "owner" of an object as its lock.

Universes

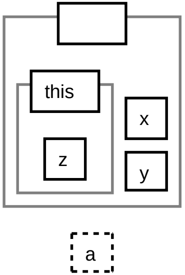
Universes form this hierarchy with 3 keywords



The keywords indicate the relative position of the referenced object.

Example

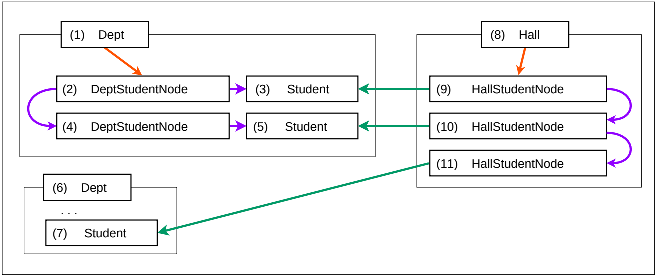
```
class C {
   peer Object m(peer Object x) {
      peer Object y = new peer Object();
      rep Object z = new rep Object();
      x = y;
      x = z; // not allowed
      any Object a = z;
      z = a; // not allowed
      return y;
   }
}
rep Object o = new rep C().m(new rep Object());
```



Background of Universes

Universes

- are an ownership type system (see Peter Müller's thesis).
- have the `any` type (unique to universes).
- are simple.
- are used in the JML (verification) tools.



Synchronisation

Let's assume have a sound universe type system $\Gamma \vdash e : u$

(where $u \in \{\texttt{rep}, \texttt{peer}, \texttt{any}\}$)

Synchronisation

Let's assume have a sound universe type system $\Gamma \vdash e : u$

(where $u \in \{\texttt{rep}, \texttt{peer}, \texttt{any}\}$)

We can use this to define: $\dfrac{\Gamma \vdash e : u}{\Gamma \vdash_{gb} e : u}$

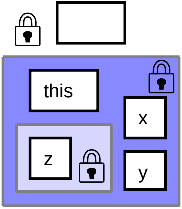
Synchronisation

Let's assume have a sound universe type system $\Gamma \vdash e : u$

(where $u \in \{\texttt{rep}, \texttt{peer}, \texttt{any}\}$)

We can use this to define: $\dfrac{\Gamma \vdash e : u}{\Gamma \vdash_{gb} e : u}$

```
peer Object x = new peer Object();
peer Object y = new peer Object();
rep Object z = new rep Object();
sync (x) { y.f := 20 } // OK
sync (x) { z.f := 20 } // error!
```



Iteration

```
class Node { peer Node next ; int cargo }
rep Node i = ...;
sync (i) {
     while (i!=null) {
          i.cargo = 20;
          i = i.next;
     }
}
```

Problem with `any`

Problem:

A pair of `any` objects may exist in different ownership domains.

Problem with any

Problem:

A pair of any objects may exist in different ownership domains.

```
any Object x = new peer Object();
any Object z = new rep Object();
sync (x) { z.f := 20 } // OK, but race condition!
```

Problem with any

Problem:

A pair of any objects may exist in different ownership domains.

```
any Object x = new peer Object();
any Object z = new rep Object();
sync (x) { z.f := 20 } // OK, but race condition!
```

Solution:

$$\frac{\Gamma \vdash e : u \qquad u \neq \texttt{any}}{\Gamma \vdash_{gb} e : u}$$

Problem with any

Problem:

A pair of any objects may exist in different ownership domains.

```
any Object x = new peer Object();
any Object z = new rep Object();
sync (x) { z.f := 20 } // OK, but race condition!
```

Solution:

$$\frac{\Gamma \vdash e : u \quad u \neq \texttt{any}}{\Gamma \vdash_{gb} e : u} \qquad \frac{}{\Gamma \vdash_{gb} p : p}$$

Examples

```
peer getPeer() { ... }
any getAny() { ... }

any Object x = ...;
peer Object y = ...;
rep Object z = ...;

sync (x) { x.f } // OK (path)
sync (y) { y.f } // OK (path) (universes)
sync (y) { z.f } // error!
sync (getPeer()) { y.f } // OK (universes)
sync (getAny()) { x.f } // error!
sync (x) { x=... ; x.f } // error!
sync (x) { x.f ; x=... } // error! (not flow sensitive)
```

Conclusion

Advantages of ownership:

- Locks scale with size of program

Conclusion

Advantages of ownership:

- Locks scale with size of program

Disadvantages of ownership:

- Require ownership annotations

Conclusion

Advantages of ownership:

- Locks scale with size of program

Disadvantages of ownership:

- Require ownership annotations

Notions of ownership also used by

- C. Flanagan et al (ESOP'99, CONCUR'99, PLDI'00, LICS'00, TLDI'03, PLDI'03, SAS'04, POPL'04, SPIN'04, TLDI'05, ECOOP'05)
- C. Boyapati et al (OOPSLA'01,OOPSLA'02)
- **Autolocker** – B. McCloskey et al (POPL'06)

Summary

We have

- given a race-safety type system that uses a $\vdash_{gb}$ judgement.
- given a simple path-based $\vdash_{gb} p : p$
- put objects into boxes and restricted assignment
  - with a static set of regions, and
  - with dynamic set of universes that grows at runtime

  in order to build a more powerful $\vdash_{gb}$.
- used the simple path-based $\vdash_{gb}$ with the universes $\vdash_{gb}$, to allow locking of `any`.

Atomicity

A race-safe block of code is atomic if its sync. is two-phase:

```
// GOOD
atomic {
    sync (x) {
        sync (y) {
            ...
            ...
        }
    }
}

// BAD
atomic {
    sync (x) { ...  }
    sync (y) { ...  }
}
```

```
// UGLY (but good, and useful too)
atomic {
    sync (x) {
        sync(y) {
            sync (x) {
                ...
            }
            sync (y) {
                ...
            }
        }
    }
}
```