Universe Types for Race Safety

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Race Conditions

Race conditions:

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

```cpp
sync (???) {
  ...
  e.f = 10;
  ...
}
```
Enforcing synchronisation is the key:

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

Enforcing synchronisation is the key:

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

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

\[ \vdash gb e : l \]
\[ \vdash gb e' : l \]
General Approach

Enforcing synchronisation is the key:

```plaintext
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

Universe Types for Race Safety
Type System (for illustrative purposes only!)

\[ \emptyset \vdash \text{this} \]

(Var)
Type System (for illustrative purposes only!)

\[
\begin{align*}
\emptyset \vdash \text{this} & \quad \text{(Var)} \\
\emptyset \vdash e & \quad \text{(Field)} \\
gb \vdash e : l & \\
l \in \mathbb{L} & \\
\mathbb{L} \vdash e.f
\end{align*}
\]
Type System (for illustrative purposes only!)

\[\emptyset \vdash \text{this}\]

\[\text{Var} \quad \begin{array}{c}
\mathbb{L} \vdash e \\
\vdash gb e : l \\
l \in \mathbb{L}
\end{array} \quad (\text{Field})
\]

\[\mathbb{L} \cup \{l\} \vdash e \quad (\text{Sync})
\]

\[\mathbb{L} \vdash e' \\
\vdash gb e' : l
\]

\[\mathbb{L} \vdash \text{sync } e' e\]
Type System (for illustrative purposes only!)

\[
\begin{align*}
\emptyset \vdash \text{this} & \quad \text{(Var)} \quad \emptyset \vdash \text{this} \\
\vdash_{gb} \ e : l & \quad \text{(Field)} \quad \vdash_{gb} \ e' : l \\
\mathbb{L} \vdash e & \quad \mathbb{L} \vdash e' \\
\vdash \mathbb{L} \cup \{l\} \vdash e & \quad \mathbb{L} \vdash \text{sync} \ e' \ e \\
\mathbb{L}' \vdash e & \quad \text{(Sub)} \quad \mathbb{L}' \vdash e \\
\mathbb{L}' \subseteq \mathbb{L} & \quad \mathbb{L}' \subseteq \mathbb{L} \\
\mathbb{L} \vdash e & \quad \mathbb{L} \vdash e
\end{align*}
\]
Type System (for illustrative purposes only!)

\[
\begin{align*}
&\emptyset \vdash \text{this} & &\text{(Var)}\\
&\emptyset \vdash e & &\text{Var}\\
&\vdash_{gb} e : l & &\text{(Field)}\\
&l \in \mathbb{L} & &\text{Field}\\
&\mathbb{L} \vdash e.f & &\text{Field}\\
&\mathbb{L} \vdash e' & &\text{(Sync)}\\
&\vdash_{gb} e' : l & &\text{Sync}\\
&\mathbb{L} \cup \{l\} \vdash e & &\text{Sync}\\
&\mathbb{L} \vdash \text{sync } e' e & &\text{Sync}\\

\end{align*}
\]

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.
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$\triangleright x.f.g$
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Paths are sequences of field accesses starting from a variable e.g.

- $x.f.g$
- `this.first.next.next`
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Suppose the programmer wrote: `sync (p) { ... p.f=20 }`
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Suppose the programmer 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

\[
\begin{align*}
\emptyset \vdash x & \quad \text{(var)} \\
\vdash x : x & \quad \text{(path)} \\
\{x, x.f\} \vdash x & \quad \text{(sub)} \\
\vdash x.f : x.f & \quad \text{(path)} \\
\{x, x.f\} \vdash x.f & \quad \text{(field)} \\
\vdash x : x.f & \quad \text{(field)} \\
\{x, x.f\} \vdash x.f.g = 10 & \quad \text{(field)} \\
\{x\} \vdash \text{sync}(x.f) \{x.f.g = 20\} & \quad \text{(sync)}
\end{align*}
\]
A problem

\[ \emptyset \vdash \text{sync } (x) \{ \; x=y \; ; \; x.f=20 \; \} \]
A problem

\[ \emptyset \vdash \text{sync } (x) \{ \ x=y \ ; \ x.f=20 \ \} \]

↑

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?
A problem

\[
\emptyset \vdash \text{sync (x) \{ x=y ; x.f=20 \} }
\]

↑ accesses the object y
A problem

\[ \emptyset \vdash \text{sync } (x) \{ x=y ; x.f=20 \} \]

\[ \uparrow \text{ accesses the object } y \]

similarly...

\[ \{x\} \vdash \text{sync } (x.f) \{ x.f=y ; x.f.g=20 \} \]
A problem

∅ ⊢ sync (x) \{ x=y ; x.f=20 \}

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$$\emptyset \vdash \text{sync} \ (x) \begin{cases} \ x=y \ ; \ x.f=20 \\
\uparrow \text{accesses the object } y \end{cases}$$

similarly...

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

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∅ ⊢ sync (x) { x=y ; x.f=20 }

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similarly...

{x} ⊢ 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?
class Node { Node next; int cargo }

Node i = ...;
sync(i) {
    while (i!=null) {
        i.cargo = 20;
        i = i.next;
    }
}
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. \( (\vdash_{gb} p : p) \)
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- When iterating over a list, \(n\) nodes may be accessed.
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- When iterating over a list, $n$ nodes may be accessed.
- Should we be taking $n$ locks?
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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.
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- No, we should associate one lock for all the nodes.
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- Need to be careful with assignment.
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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.
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- 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:
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Other work has used a programmer-supplied set, e.g. \{\texttt{RED}, \texttt{BLUE}\}.

The source code looks like:

\begin{verbatim}
RED Object r = new RED Object();
BLUE Object b = new BLUE Object();
\end{verbatim}
Other work has used a programmer-supplied set, e.g. \{RED, BLUE\}

The source code looks like:

```java
RED Object r = new RED Object();
BLUE Object b = new BLUE Object();
r = b; //not allowed
```
Other work has used a programmer-supplied set, e.g. \{\texttt{RED}, \texttt{BLUE}\}

The source code looks like:

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

The source code looks like:

```java
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

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\[
\Gamma \vdash e : R \\
\Gamma \vdash_{gb} e : R
\]

Note we now need a \( \Gamma \) in the other type system too: \( L, \Gamma \vdash e \).

Object \( r_1, r_2 = \ldots \)

BLUE Object \( b = \ldots \)

\[
\text{sync}(r_1) \\
\quad b.f = 10; // \text{not allowed} \\
r_2.f = 10; // \text{OK}
\]
Suppose we already have a region type system:

\[
\Gamma \vdash e : R \\
\Gamma \vdash_{gb} e : R
\]

Note we now need a \( \Gamma \) in the other type system too:

\( \mathbb{L}, \Gamma \vdash e \)
Regions as Locks

Suppose we already have a region type system:

\[
\Gamma \vdash e : R \\
\Gamma \vdash_{gb} e : R
\]

Note we now need a \( \Gamma \) in the other type system too:

\[
L, \Gamma \vdash e
\]

RED Object \( r_1, r_2 = \ldots \)
BLUE Object \( b = \ldots \)

\[
sync(r_1) \{
  b.f = 10; // not allowed
  r2.f = 10; // OK
\}
\]
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;
    }
}
Carving up the heap helps us verify safe locking:
Carving up the heap helps us verify safe locking:

\[ x.f = y ; x.f.g = 10 \]

Here we must lock \( l \) where \( \vdash_{gb} y : l \)
Summary

Carving up the heap helps us verify safe locking:

- \( x.f = y \); \( x.f.g = 10 \)
  Here we must lock \( l \) where ... \( \vdash_{gb} y : l \)

- The region type rule for assignment ensures ... \( \vdash_{gb} x.f : l \)
Carving up the heap helps us verify safe locking:

- $x.f = y \; ; \; x.f.g = 10$
  Here we must lock $l$ where ... $\vdash_{gb} y : l$
- The region type rule for assignment ensures ... $\vdash_{gb} x.f : l$
- Instead of restricting all assignments to field $f$, we only restrict assignments where the lock changes.
Carving up the heap helps us verify safe locking:

- `x.f = y ; x.f.g = 10`
  Here we must lock `l` where `⊢ gb y : l`
- The region type rule for assignment ensures `⊢ gb x.f : l`
- Instead of restricting all assignments to field `f`, we only restrict assignments where the lock changes.
- So soundness is preserved.
Advantages of carving with regions:
Summary 2

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

▸ Inference is possible (points-to analysis)

Disadvantages of regions:

▸ Unscalable (number of locks does not scale with program)
Advantages of carving with regions:

- Simple
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Disadvantages of regions:

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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)
Ownership types impose a heap hierarchy:

![Heap Hierarchy Diagram]

Universe Types for Race Safety
Ownership types impose a heap hierarchy:

Can use the “owner” of an object as its lock.
Universes form this hierarchy with 3 keywords:

- `rep`
- `peer`
- `any`

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.

Universe Types for Race Safety
Let’s assume have a sound universe type system $\Gamma \vdash e : u$

(\text{where } u \in \{\text{rep}, \text{peer}, \text{any}\})
Synchronisation

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

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

We can use this to define:

$$
\Gamma \vdash e : u \\
\Gamma \vdash_{gb} e : u
$$

Object $x = \text{new peer Object}();$
Object $y = \text{new peer Object}();$
Object $z = \text{new rep Object}();$

sync ($x$) {
    $y$.f := 20
} // OK

sync ($x$) {
    $z$.f := 20
} // error!
Synchronisation

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

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

We can use this to define: 

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

peer Object $x = \text{new peer Object}();$
peer Object $y = \text{new peer Object}();$
rep Object $z = \text{new rep Object}();$
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 \texttt{any}

\textbf{Problem:}

A pair of \texttt{any} objects may exist in different ownership domains.
Problem with any

Problem:

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

```java
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.

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

Solution:

\[ \Gamma \vdash e : u \]
\[ u \neq \text{any} \]
\[ \frac{}{\Gamma \vdash_{gb} e : u} \]
Problem with any

**Problem:**

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

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

**Solution:**

\[
\Gamma \vdash e : u \\
\frac{u \neq \text{any}}{\Gamma \vdash_{gb} e : u} \quad \Gamma \vdash_{gb} p : p
\]
Examples

```java
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

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- 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) {
        ...
      }
    }
  }
}

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