# Lecture 5

# Towards a Verifying Compiler: Multithreading

Wolfram Schulte
Microsoft Research
Formal Methods 2006

Race Conditions, Locks,
Deadlocks, Invariants, Locklevels
Access Sets

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Joint work with Rustan Leino, Mike Barnett, Manuel Fähndrich, Herman Venter, Rob DeLine, Wolfram Schulte (all MSR), and Peter Müller (ETH), Bart Jacobs (KU Leuven) and Bor-Yuh Evan Chung (Berkley) .

## Review: Pure Methods and Model Fields

Data abstraction is crucial to express functional correctness properties

- Verification methodology for model fields
  - *Model fields are reduced to ordinary fields with automatic updates*
- Verification challenges for model fields and pure methods
  - *Consistency*
  - *Weak purity*
  - *Heap dependence (and frame properties)*

## Multi-threading

- **Data race prevention**
- Invariants and ownership trees
- Deadlock prevention

# Multithreading

Multiple threads running in parallel, reading and writing shared data

A *data race* occurs when a shared variable is written by one thread and concurrently read or written by another thread

How to guarantee that there are no data races?

```
class Counter {
  int dangerous;
  void Inc() {
    int tmp = dangerous;
    dangerous = tmp + 1; }
}

Counter ct = new Counter();
new Thread(ct.Inc).Start();
new Thread(ct.Inc).Start();
//  What is the value of
//   ct.dangerous after both
//   threads have terminated?
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## Mutexes: Avoiding Races

- *Mutual exclusion* for shared objects is provided *via locks*

- Locks can be obtained using a *lock block*. A thread may enter a lock (o) block only if no other thread is executing inside a lock (o) block; else, the thread waits

- When *a thread holds a lock on object o*, *C#/Java*
  - do prevent other threads from locking o but
  - *do not prevent other threads from accessing o's fields*

# Program Method for Avoiding Races

Our program rules enforce that
*a thread* t *can only access a field of object* o *if* o *is either thread local or* t *has locked* o

We model accessibility using *access sets*:

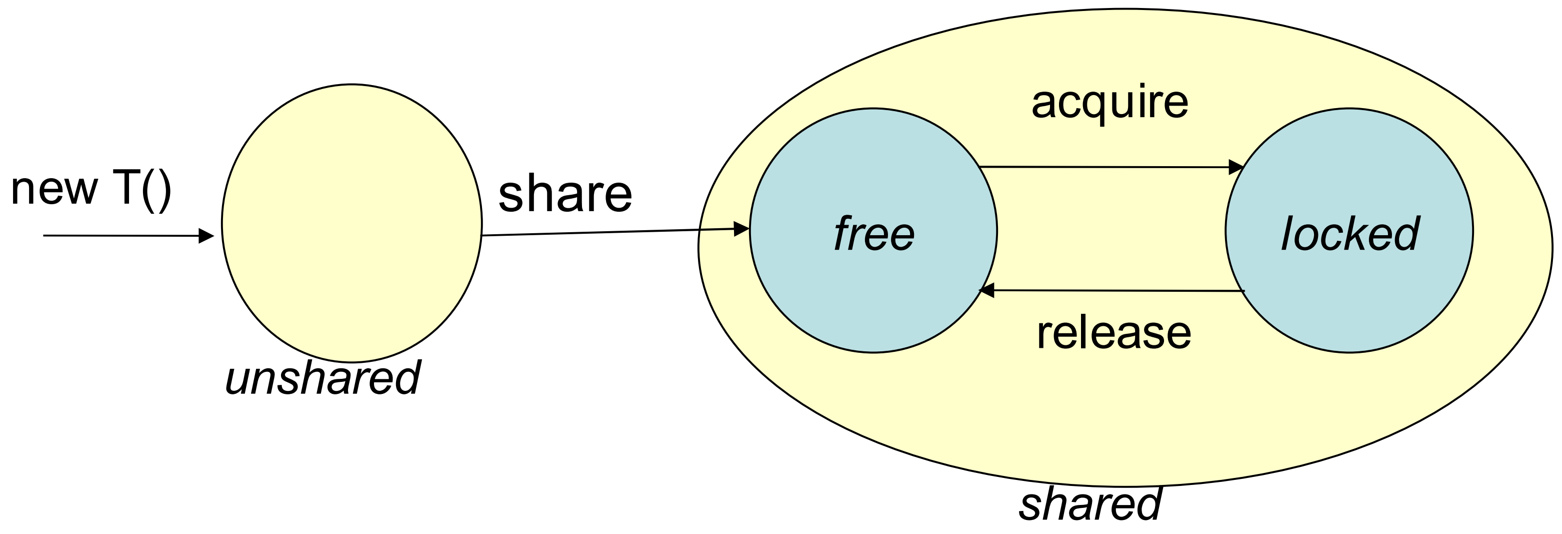
- A thread's access set consists of all objects it has created but not shared yet or whose lock it holds.
- Threads are only allowed to access fields of objects in their corresponding access set

Our program rules prevent data races by ensuring that *access sets of different threads never intersect*.

## Annotations Needed to Avoid Races

- Threads have access sets
  - t.A is a new ghost field in each thread t describing the set of accessible objects
- Objects can be shared
  - o.shared is a new boolean ghost field in each object o
  - share(o) is a new operation that shares an unshared o
- Fields can be declared to be shared
  - Shared fields can only be assigned shared objects.

# Object Life Cycle



## Verification via Access Sets

```
Tr[[o = new C();]] = …
  o.shared:= false;
  tid.A[o]:= true

Tr[[x = o.f;]] = …
  assert tid.A[o];
  x :=o.f;

Tr[[o.f = x;]] = …
  assert tid.A[o];
  if (f is declared shared)
    assert x.shared;
  o.f :=x;
```

```
Tr[[share(o)]] = …
  assert tid.A[o];
  assert ! o.shared;
  o.shared :=true;
  tid.A[o] :=false;

Tr[[lock (o) S  ]] = …
  assert ! tid.A[o];
  assert o.shared;
  havoc o.*;
  tid.A[o]:=true;
 Tr[[S]];
  tid.A[o]:= false
```

# A Note on havoc in the Lock Rule

When a thread (re) acquires o, o might have been changed by another thread.

```
int x;
lock (o) {
  x = o.f;
}
lock (o) {
  assert x == o.f;   // fails
}
```

So we have to “forget all knowledge about o’s fields”. We do so by assigning an arbitrary value to all of o’s field, expressed as

havoc o.*

## Example for Data Race Freedom

```
Counter ct = new Counter();
share(ct);
new Thread(delegate () { lock (ct) ct.Inc(); }).Start();
new Thread(delegate () { lock (ct) ct.Inc(); }).Start();
```

# Example for Data Race Freedom

```
// thread t0
  Counter ct = new Counter();
  share(ct);
  Session s1 =new Session(ct,1);
  Session s2 =new Session(ct,2);
  // transfers s1 to t1
     t1 = new Thread(s1.Run);
  // transfers s2 to t2
     t2 = new Thread(s2.Run);
  t1.Start();
  t2.Start();
```

```
class Session {
  shared Counter ct ;
  int id;

  Session(Counter ct , int id)
    requires ct.shared;
    ensures tid.A[this] ∧ ! this.shared;
  { this.ct=ct; this.id=id; }

  void Run()
     requires tid.A[this];
  { for (; ; )
       lock (this.ct)
          this.ct.Inc();
  }
}
```

## Soundness

Theorem

- $\forall$ threads t1,t2 :: $t1 \neq t2 \Rightarrow t1.A \cap t2.A = \emptyset$
- $\forall$ object o, thread t :: o.shared && $o \in t.A \Rightarrow$ t holds o’s lock

- Proof sketch for Theorem
  - new
  - share (o)
  - Entry into lock (o)
  - Exit from lock (o)

Corollary

- Valid programs don’t have data races

## Multi-threading

- Data race prevention
- **Invariants and ownership trees**
- Deadlock prevention

## Invariants and Concurrency

*Invariants*, whether over a single object or over an ownership tree, can be *protected via a single lock* (coarse grained locking)

For sharing and locking

- require an object *o to be valid when o becomes free*
- ensures o's invariant on entry to its locked state

For owned objects

- require that commited objects are unaccessable, but
  - unpack(o) adds o's owned objects to the thread's access set
  - pack(o) deletes o's owned objects from the thread's access set

# Verifying Multi-threaded Pack/Unpack

```
Tr[[unpack o;]] =
    assert tid.A[o];
    assert o.inv;
    foreach (c | c.owner = o)
      { tid.A[c] := true; }
    o.inv := false;
```

```
Tr[[ pack o;]] =
    assert tid.A[o];
    assert ! o.inv;
    assert $\forall$c: c.owner = o $\Rightarrow$
         tid.A[c] $\wedge$ c.inv;
    foreach (c | c.owner = o)
        { tid.A[c] := false; }
    assert Inv( o );
    o.inv := true;
```

## Ownership: Verifying Lock Blocks

Finally, when locking we also have to “forget the knowledge about” owned objects

```
Tr[[lock (o) S;  ]] =
        assert o.shared;
        assert ! tid.A[o];
        foreach (p | !tid.A[p])  havoc p.*;
        tid.A[o]:=true;
        Tr[[S]] ;
        tid.A[o]:= false;
```

## Outline of the talk

- Data race prevention
- Invariants and ownership trees
- **Deadlock prevention**

## Multi-threading

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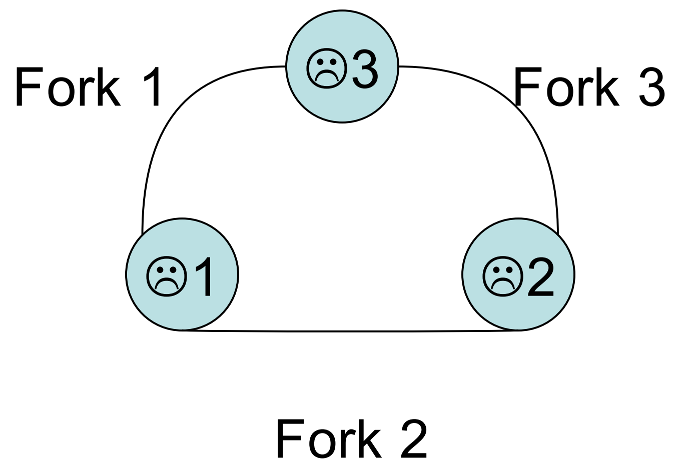
# Concurrency: Deadlocks

A *deadlock* occurs when a set of threads each wait for a mutex (i.e shared object) that another thread holds

Methodology:

- *partial order over all shared objects*
- in each thread, *acquire shared objects in descending order*

Dining Philosophers



☹1 has F1, waits for F2
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## Annotations Needed to Avoid Deadlocks

*We construct a partial order on shared objects, denoted by .*

- When o is shared, we add edges to the partial order as specified in the share command's where clause.

  (Specified lower bounds have to be less than specified upper bounds)

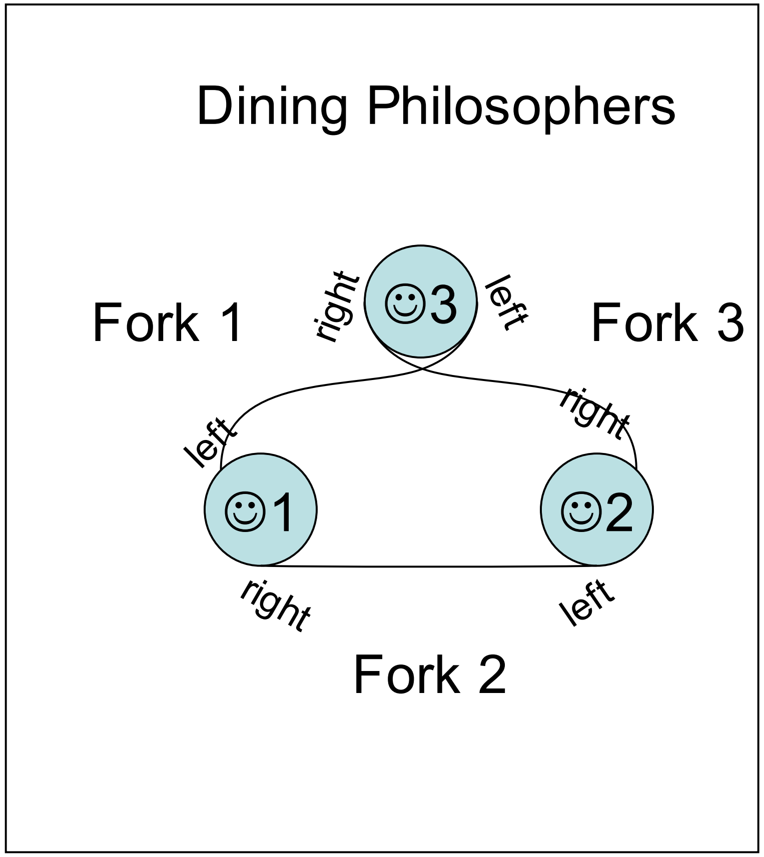
- Each thread has a new ghost field *lockstack*, holding the set of acquired locks

# Verification via Lock Ordering and Lockstacks

```
Tr[[share o
      where p     o && o     q;]] =
  assert o ∈ tid.A;
  assert ! o.shared;
  tid.A[o] := false;
  o.shared := true;
  assert p     q;
  assume p     o && o     q;
```

```
Tr[[lock (o) S  ]] =
 assert o.shared;
 assert tid.lockstack != empty ⇒
    o     tid.lockstack.top();
  tid.lockStack.push(o);
  foreach (p | !tid.A[p])  havoc p.*;
  tid.A[o]:=true;
  Tr[[S]] ;
  tid.A[o]:= false;
  tid.lockstack.pop(o);
```

# Example: Deadlock Avoidance (contd.)



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f1 = new Fork(); share f1;
f2 = new Fork(); share f2 where f1    f2;
f3 = new Fork(); share f3 where f2    f3 ;

P1 = new Thread( delegate() {
     lock (f2) { lock (f1) { /*eat*/ }}});
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## Conclusion

- Clients can reason entirely as if world was single-threaded for non-shared objects
- Supports caller-side locking and callee-side locking
- Deadlocks are prevented by partially ordering shared objects

## The End

(for now)

Thank you!

http://research.micsoft.com/specsharp

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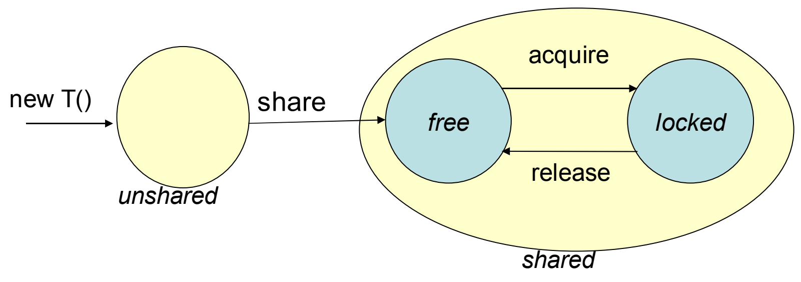

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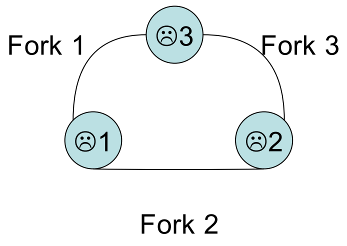

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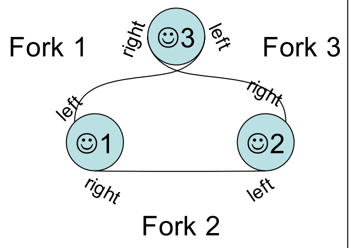

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