Static Lock Capabilities for Deadlock-Freedom

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Joint work with Michael D. Ernst and Dan Grossman

Verifying Deadlock Freedom

Deadlock

A cycle of threads, each blocked waiting for a resource held by the next thread in the cycle.

$$T_1 \to T_2 \to \ldots \to T_n, \qquad T_1 = T_n$$

Goal

Statically verify deadlock freedom for fine-grained locking

- Balanced binary trees
- Resizable hash tables
- Array elements
- Circular lists

Approach

A static (capability) type system

Deadlock-Free Code

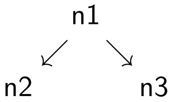
Assuming n2 == n1.left and n3 == n1.right:

Thread1 : sync n2 {}

Thread2 : sync n3 {}

Thread3 : sync n1 {sync n1.left {sync n1.right {}}}

Thread4 : sync n1 {sync n1.right {sync n1.left {}}}



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n1
$\swarrow$ $\searrow$
n2 n3

Prior static approaches require either:

- A total ordering on `n1`'s children (rejects T3 or T4), or
- Disallow interior pointers (`n2`, `n3`, rejecting T1 and T2)

> Lock capabilities impose neither restriction.

Lock Capabilities

Lock Capability

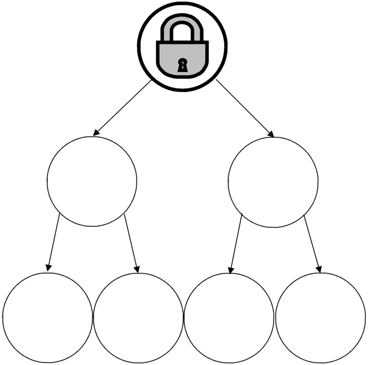
A static capability that permits acquiring additional locks

- Baked into a type-and-effect system
- Proved sound (they prevent deadlock)
- Straightforward extensions
- Scale to handle a set of diverse structures
  - with the help of some extensions to plumb singleton types

Intuition: Tree-Based Ordering

Fine-grained locking in a binary tree:

- Acquiring one lock while holding none avoids deadlock;
  "First lock is free"



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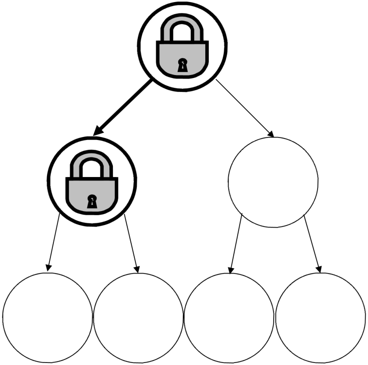

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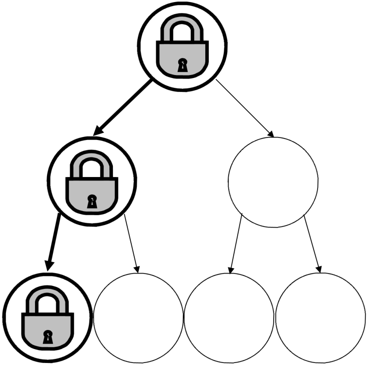

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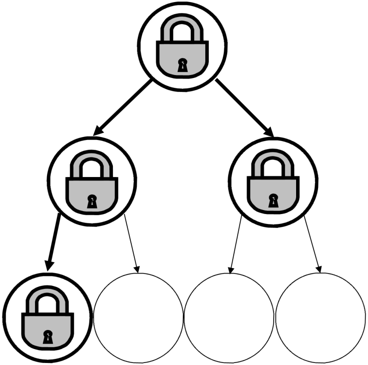

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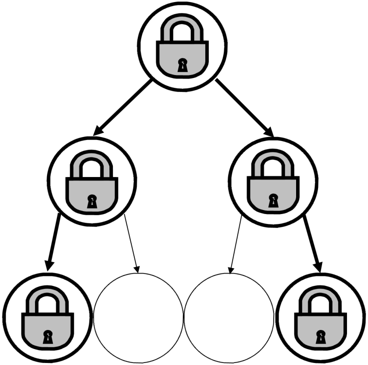

Generalizing Beyond Trees

Trees → Tree-shaped Partial Orders

In an *immutable* tree-shaped partial ordering, a thread may acquire a lock l when:

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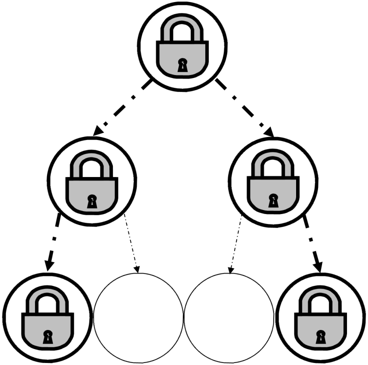
Harder:

- Early lock releases
- Modifying the partial order

Lock Capabilities



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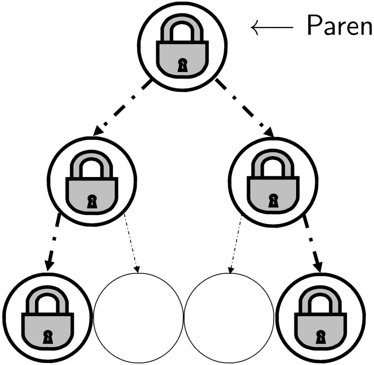

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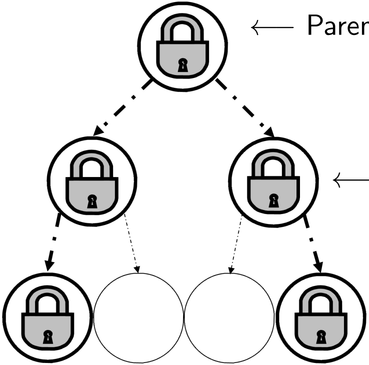

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⟵ Child type includes the *guarding capability*:
$x.right$: guardedBy$\langle x \rangle$ TreeNode

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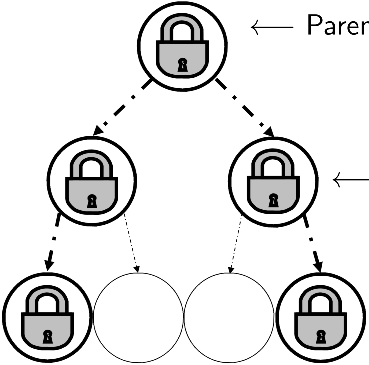

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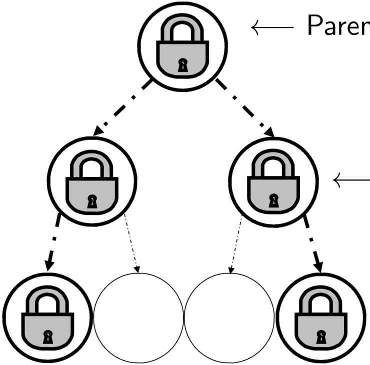

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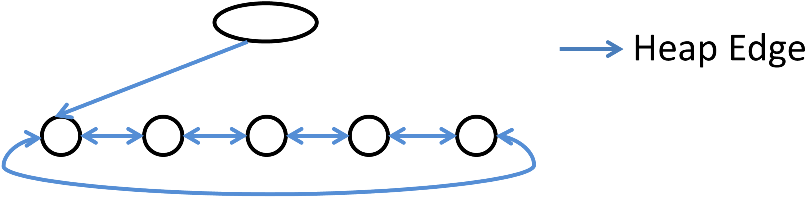
Deadlock freedom follows from the *capability granting relation* being a forest

Structures with Cycles

A forest-shaped capability granting relation doesn't require forest-shaped data structures. For example, here is a circular list:



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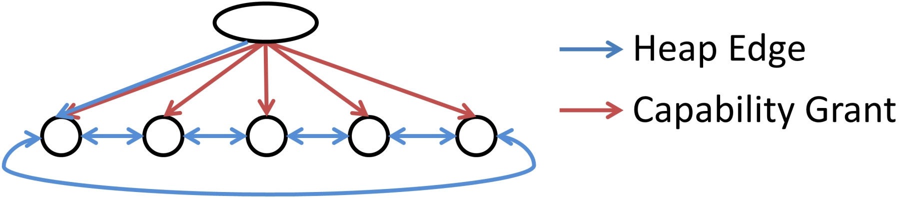

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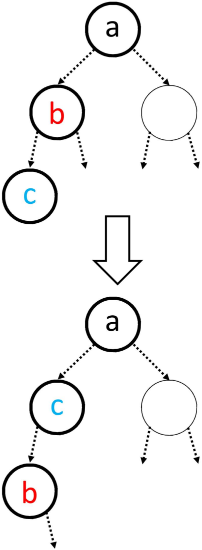
Supporting Mutable Structures



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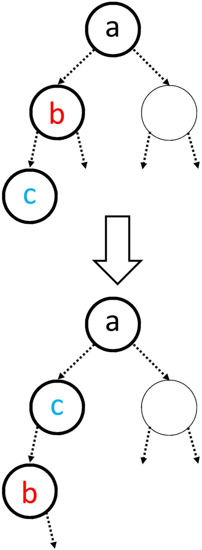

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- Strong Updates

  $\Longrightarrow$ weakened form of uniqueness

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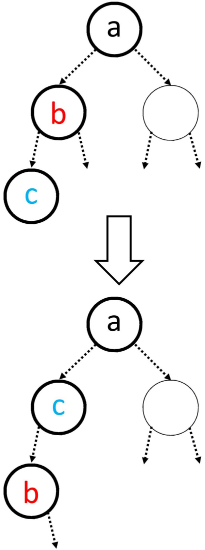

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  $\Longrightarrow$ track shape of capability-granting relation

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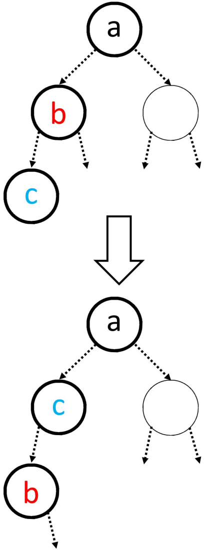

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  $\Longrightarrow$ restrictions on lock acquisition

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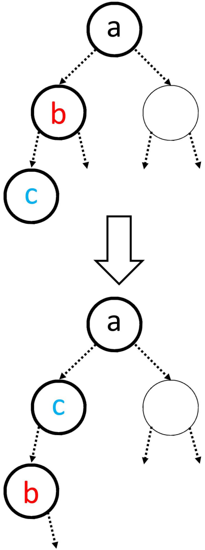

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- Preserving Acyclicity
  - $\Longrightarrow$ track shape of capability-granting relation
- Releasing Out-Of-Order
  - $\Longrightarrow$ restrictions on lock acquisition
  - ▸ No time to discuss out-of-order releases

Changing Capability Grants

The *capability granting relation* that determines each lock's guard must allow changes.

Partial Uniqueness

A single reference carries the guard information for an object

1	u_guardedBy$\langle x \rangle$ TreeNode	"Unique" with guard information
∞	guardless TreeNode	Duplicable, no guard information

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Partial Strong Updates

Guard information is isolated, enabling strong updates to the guard

$$x : \text{u\_guardedBy}\langle y\rangle\ \text{TreeNode} \longrightarrow x : \text{u\_guardedBy}\langle z\rangle\ \text{TreeNode}$$

Goal: Type system infers strong updates without explicit guidance

Changing Tree Structure

```
public TreeNode {
    public u_guardedBy⟨this⟩ TreeNode left;
    public u_guardedBy⟨this⟩ TreeNode right;
}
...
guardless TreeNode a;
...
lock(a) {
  lock(a.left) {
    lock(a.left.left) {
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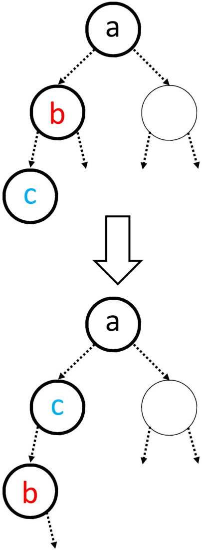


Destructive Reads

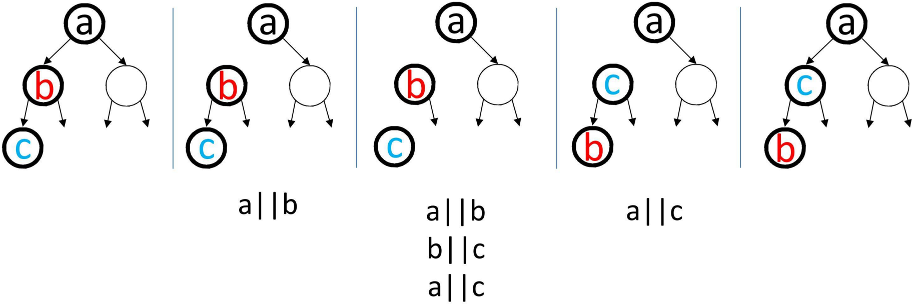
dread(p) atomically assigns null to path p and returns the old value, preventing duplication.

Preserving Acyclicity

Changes to the capability-granting relation must not create cycles.

We track disjointness of capability-granting trees in a flow-sensitive manner.

- Removing an edge produces two mutually disjoint trees
- Adding an edge between two mutually disjoint trees produces one tree



The Core Type System

Core typing judgement:

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Two theorems proven for basic lock capabilities with reordering:

1. Type Preservation
   - Long, straightforward
2. Deadlock Freedom Preservation
   - Extended semantics with capability-use log in graph form, modeling thread dependencies

Proposed Extensions

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- Combination with *lock levels*

Examples

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All handled cleanly by a single general approach.

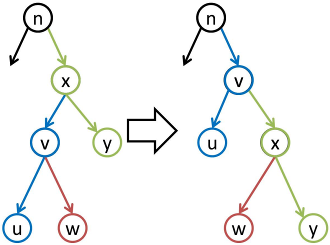
Contributions

- Introduced *lock capabilities*
  - New approach to verifying deadlock freedom
  - Well-suited to fine-grained locking
  - Suitable for any verification approach, we used types
- Proved soundness: lock capabilities ensure deadlock freedom
- Sketched useful, straightforward extensions
- Showed how lock capabilities can verify deadlock freedom for important, challenging examples

Backup Slides

Splay Tree Rotation

```
class Node {
    u_guardedBy<this>Node left;
    u_guardedBy<this>Node right;
}
...
  let final n = ... in
  lock (n) {
    let final x = n.right in
    if (x) {
      lock (x) {
        if (x.left) {
          let final v_name = x.left in
          lock (x.left) {
            let v = dread(x.left) in
            let final w_name = v.right in
            let w = dread(v.right) in
            // v.right := x
            v.right := dread(n.right);
            x.left := dread(w);
            n.right := dread(v);
  }}}}}
```



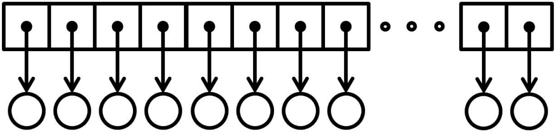
Differences from regular code are highlighted. Most can be inferred by a compiler.

Array-order Locking

Array-order locking is generally undecidable; lock capabilities enable a restricted form to be verified. In our core language extended with arrays and integers:

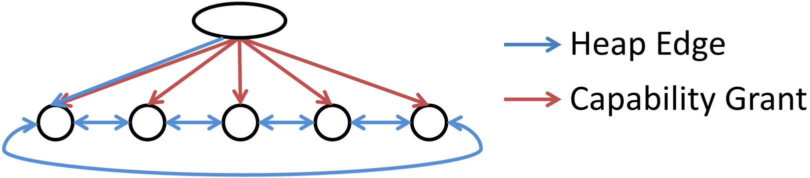
```
let final arr, unique a = new u_guardedBy Object[n] in
...
lock(arr) {
  lock(arr[i]) {
    lock(arr[j]) {
      ...
    }
  }
}
```

Note that we don't need to compare *i* and *j*!



Circular Lists

- The list of running processes in an OS kernel is *circular*
- It requires fine-grained locking for performance.
- Atomic resource transfer requires locking *multiple* processes.
- There is *no sensible ordering* on processes.



Orphaned Locks

Acyclic capability granting is only half of soundness:

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public TreeNode {
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guardless TreeNode a;
...
lock(a) {
  lock(a.left) {
    lock(a.left.left) {
      let b = dread(a.left) in
      let c = dread(b.left) in
      c.left := dread(b);
      a.left := dread(c);
    } // release c
    lock(a.left) { // lock c again
      // do stuff
    }
  }
}
```

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      // DEADLOCK!!!
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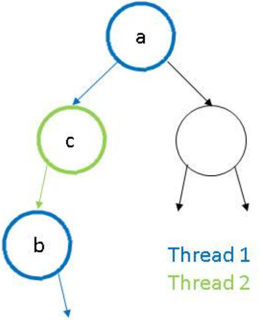



```
lock(n) {            // lock c
  lock(n.left) {     // lock b
    // DEADLOCK!!!
  }
}
```

Theorem: Type Preservation

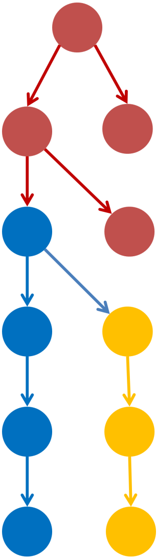
- Syntactic proof
- Extended typing rules add:
  - Heap typing Σ
  - Per-thread capability grants $\phi_i : \mathrm{Value} \rightarrow \mathrm{Variable}$ (or intuitively, $\mathrm{Lock} \rightarrow \mathrm{Lock}$)
- Requires many invariants
  - Most are natural (e.g. well-formed environments)
  - A few natural to preserve, subtle to state
    - e.g. relating multiple threads' assertions about the capability-granting relation
  - Full details in TR

Theorem: Deadlock Freedom Preservation

Deadlock freedom is a preservation proof:

- Build a labeled graph of how threads use capabilities
- Prove there is never a path between a single thread's locks using capabilities of multiple threads.

Detailed sketch in paper, full proof in TR.



Dining Philosophers

The problem:

- *The* canonical deadlock example
- n philosophers eating at a circular table
  - Only n chopsticks, one to each side of each philosopher
  - Must share chopsticks (locks) with neighbors
  - Philosophers are greedy and won't put down chopstick (release lock) until they've eaten
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With support for lock capabilities with unstructured locking:

- Capability-granting relation identical to the circular list
- With releasing "global" lock early:
  - Serializes acquisition
  - Allows parallelism between threads holding multiple locks
- *Verifiably* deadlock-free solution that allows some parallelism with simple code

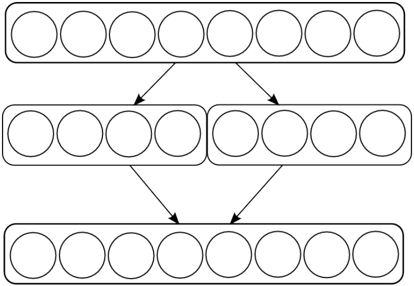
Background: Lock Levels

The program's locks are partitioned into *levels*, and the programmer specifies a partial order on levels.

Lock Levels Locking Protocol

A thread may acquire a lock *l* when:

- It holds no other locks, or
- *l* is in a lock level ordered *after* the level of *all* locks held



Limitations:

- Requires total ordering on any set of locks held concurrently.
- Can't deal with reordering, except for SafeJava and Chalice.

Comparing Lock Levels and Lock Capabilities

Fundamental philosophical difference: with lock levels, acquiring a lock *restricts* the set of locks the thread may then acquire, while with lock capabilities, acquiring a lock *extends* the set of locks the thread may then acquire.

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- Allow some locking without total orderings
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It is possible to integrate the two for a more expressive system.

Chalice (Leino & Müller, ESOP'09, '10)

Combines a clever variant of levels with fractional permissions:

- Uses a *dense lattice* of levels, not discrete
  - For any levels l_0, l_1, exists l' s.t. $l_0 \sqsubset l' \sqsubset l_1$
- Uses fractional permissions on a ghost field μ to reorder

These add great flexibility over other lock level systems.

```
class TreeNode {
  TreeNode left, right;
  // declare full permission
  // on left.μ, right.μ }
...
lock (n) {
  reorder n.left.μ after n.μ;
  lock (n.left) {
  reorder n.right.μ after n.left.μ;
  lock (n.right) {...}
} }
```

Approaches lock capabilities, but

- Requires explicit reordering
- Full permissions for reordering loses external references

Fails to exploit that this structure *doesn't need* ordering on children