Checking and Inferring Local Non-Aliasing

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Introduction

- Aliasing: A long-standing problem
  - Pointers are hard to analyze

    ...*p = 3 ...   what is updated?

  - We need to know for
    - compilers (optimization)
    - software analysis tools (CQual, Cyclone, Vault, SLAM, ESP, ...)

Alias Analysis

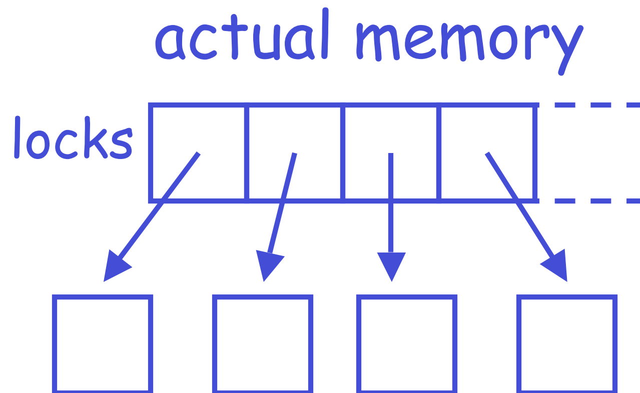
- What expressions may refer to same location?
  - To what memory locations do expressions point?

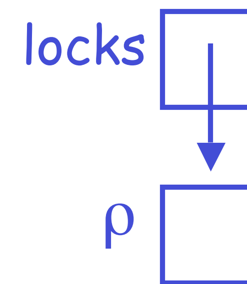
- Alias analysis abstracts memory with bounded set of locations
  - Choices affect subsequent analysis

- Programmer has little input to alias analysis

Example from CQual: Modeling Arrays

lock *locks[n]; // define array of n locks





- CQual: All elements of locks[] may alias
  - Represented with a single abstract location ρ

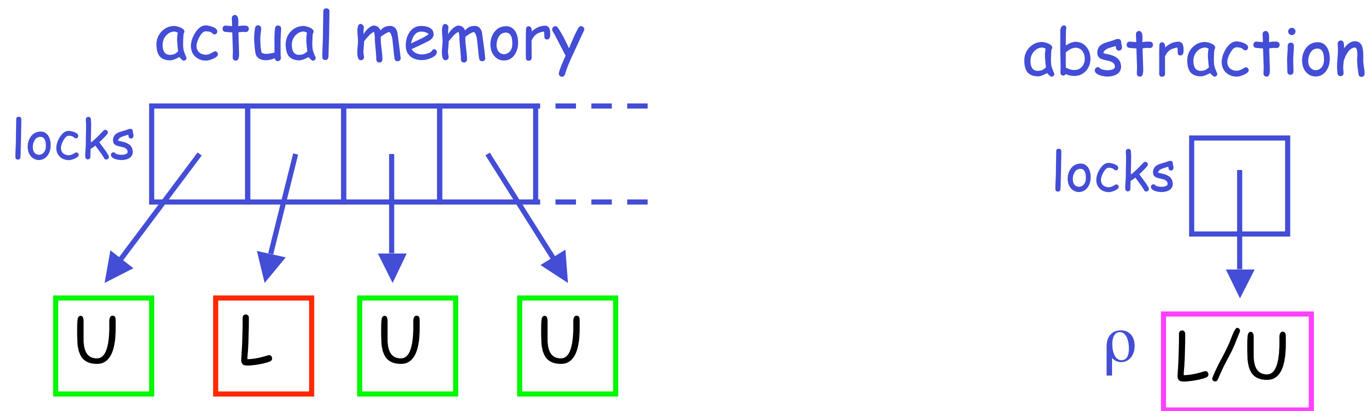
Example from CQual

```
void foo(int i) {
  do_with_lock(locks[i]);
}
void do_with_lock(lock *l) {
  spin_lock(l);
  work();
  spin_unlock(l);
}
```

ρ unlocked

?

Example from CQual: Weak Update



- After acquiring lock, ρ is locked *or* unlocked
  - This is a *weak update*

Example from CQual

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```

ρ unlocked

ρ locked or unlocked

ρ locked or unlocked

ρ locked or unlocked

Why This Design?

- Simple, efficient, scalable alias analysis
- More abstract locations =
  - Greater precision
  - Less efficiency
    - Need to model facts about more names at each state

- Observation: A little extra *local* information would make a big difference

Restrict

```
void do_with_lock(lock *restrict l) { ... }
```

- Let l point to lock a
- Within l's scope, all accesses to a are through l
  - (Approximately)

⇒In do_with_lock, no other aliases of a used

- Can use *strong updates* on state of l

Contributions of This Work

- Type and effect system for checking that uses of restrict are safe
  - Provably sound
  - Contrast to ANSI C: restrict annotation trusted
    - unchecked, with informal semantics
- New construct confine
  - Short-hand for common uses of restrict
  - Easier to use

Contributions of This Work (cont'd)

- Automatic inference of restrict and confine
- Experiment using confine inference in checking locking in Linux kernel
  - Recovered strong updates in 95% of cases
  - Enabled new deadlocks to come to light

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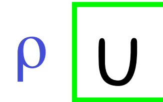

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ρ unlocked

copy ρ to η

Example from CQual

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copy ρ to η

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ρ unlocked

copy ρ to η

η locked

strong update

- η represents only one location
  - Safe to perform strong update (replacement)

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ρ unlocked

copy ρ to η

η locked

η unlocked

- η represents only one location
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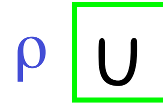

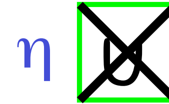

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ρ unlocked

copy ρ to η

η locked

η unlocked

copy η to ρ

- η represents only one location
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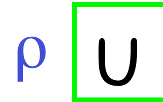
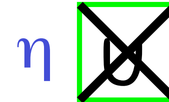
ρ 

η 

Example from CQual

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}
void do_with_lock(lock *restrict l) {
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  work();
  spin_unlock(l);
}
```

- ρ unlocked
- ρ unlocked
- copy ρ to η
- η locked
- η unlocked
- copy η to ρ

- η represents only one location
  - Safe to perform strong update (replacement)

Check Restrict with Type and Effect System

- Types extended with *abstract locations*
  - Flow-insensitive, unification-based may-alias analysis

τ ::= ...| ref$^{\rho}(\tau)$ pointer to abstract loc ρ

- Effects are sets of locations

$L ::= \emptyset \mid \{\rho\} \mid L1 \cup L2 \mid L1 \cap L2$

Type Rules

- $A \vdash e : \tau; L$
  - In environment A, expression e has type τ
  - evaluating e has effect L

$$\frac{A \vdash e : \mathrm{ref}^{\rho}(\tau); L}{A \vdash {*e} : \tau; L \cup \{\rho\}}$$

Restrict

- restrict x = e1 in e2
  - x is a pointer initialized to e1
  - x is in scope only within e2
  - within e2, only x and copies derived from x can be used to access *x
  - outside of e2, values derived from x cannot be used

Restrict Rule

$$\frac{A \mid e1 : ref^{\rho}(\tau 1);\ L1 \qquad A[ref^{\eta}(\tau 1)\backslash x] \mid e2 : \tau 2;\ L2 \qquad \rho \notin L2 \qquad \eta \notin locs(A, \tau 1, \tau 2)}{A \mid restrict\ x = e1\ in\ e2 : \tau 2;\ L1 \cup L2 \cup \{\rho\}}$$

Soundness

- Type system for checking restrict is sound
  - Well-typed program doesn't go wrong according to a formal semantics

  $\Rightarrow$ uses of restrict are safe

- Provable using standard subject-reduction techniques

Improving Restrict

- Must bind a variable name in restrict

```
spin_lock(locks[i]);
work();
spin_unlock(locks[i]);
```

Improving Restrict

- Must bind a variable name in restrict

```
restrict mylock = locks[i] in {
    spin_lock(mylock)
    work();
    spin_unlock(mylock);
}
```

  - Time consuming, need to manually check transformation is safe

Confine

- Short-hand for previous transformation

```
confine (locks[i]) in {
    spin_lock(locks[i])
    work();
    spin_unlock(locks[i]);
}
```

  - Only need to pick expression, introduce scope

Confine Inference

- Assume we know expression to confine
  - In experiment, given spin_lock(e) try confining e
- Algorithm
  - Introduce confine everywhere
  - Eliminate incorrect confines
  - Greedily combine adjacent confines
    - (confine e in e1 ; confine e in e2) = confine e in e1;e2
- Use heuristics in practice to speed up

PLDI'02 Results

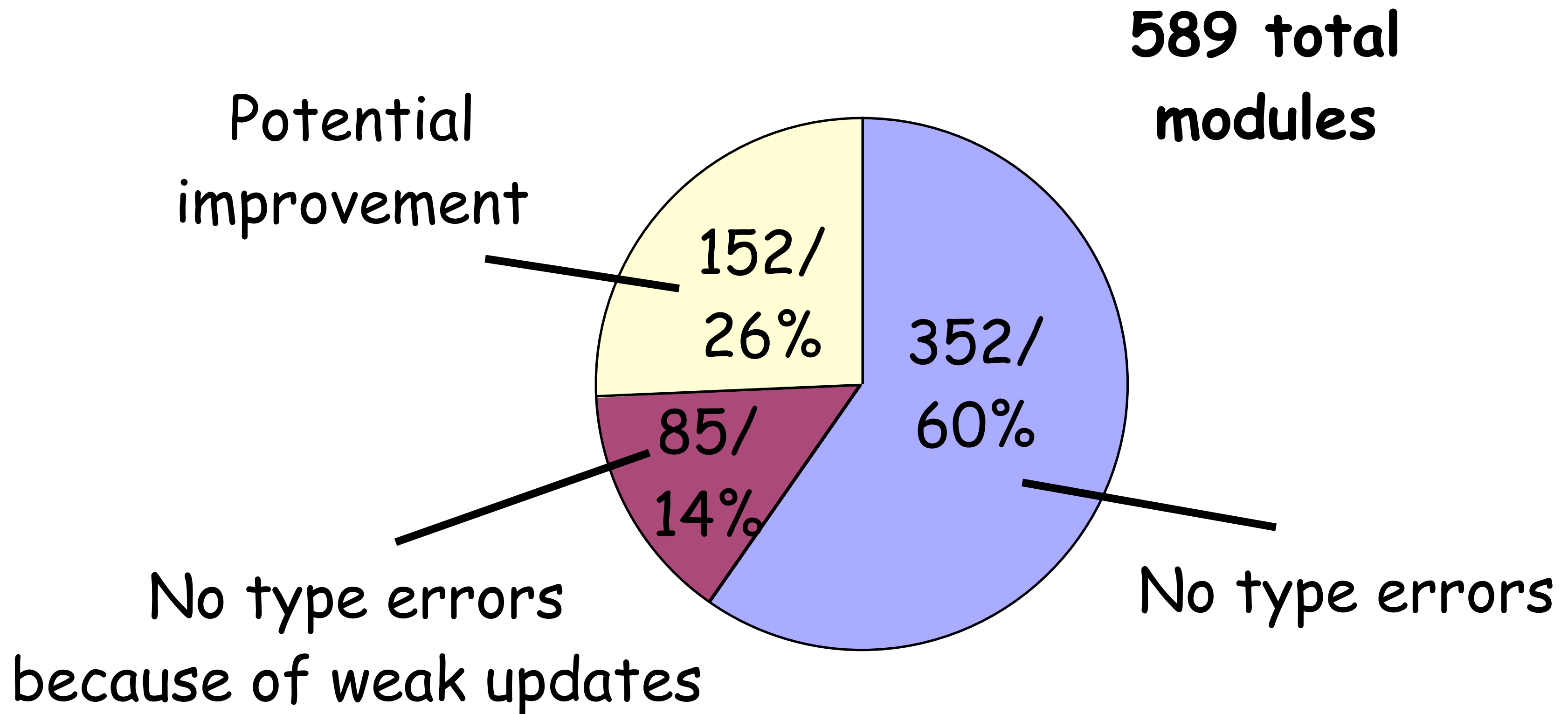
- Found a number of locking bugs in Linux kernel
  - Many weak updates with multi-file analysis
    - In CQual, weak updates to locks yield type errors
  - Makes it hard to find true locking bugs
- Can we eliminate weak updates with restrict?
  - Yes, but painful to put in by hand

New Experiment: Eliminating Weak Updates

- How many more strong updates with confine inference?

- Metric: # lock updates involved in error
  - Lower bound: Assume all updates are strong
    - But unsound!

Type Errors



Actual Improvement in Strong Updates

- 138/152: Same as assuming updates strong
  - Optimal result
- 14/152: Confine misses some strong updates
  - See paper for numbers

Experimental Summary

- Overall, confine inference gets 95% of cases
  - Could eliminate 3277 type errors
  - Does eliminate 3116 type errors
  - (Includes duplicates from duplicated modules)

- Remaining type errors
  - Deadlocks (found 4 new ones)
  - Aliasing conservatism and lack of path sensitivity

Conclusion

- restrict and confine successfully recover local strong updates
  - Can be used as programmer annotations to document aliasing properties
- Automatic confine inference works 95% of the time
  - Large improvement in quality of type errors