Finding Races in the Heap

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Data Races

Definition (Race condition)

An unintended indeterminism due to the lack of proper ordering constraints in the program.

- Lead to subtle and dangerous bugs.
- Violate Murphy's Law $\Rightarrow$ hard to test!

Famous Examples

- Therac-25 radiation therapy machine
    - Killed 3 people!
    - Race condition only occurred if setup was changed quickly; testers were not as fast.
- North American Blackout of 2003
    - Two processes got write accesses to a shared resource and corrupted it.
    - Alarm subsystem looped indefinitely.
    - The race had a window of only milliseconds!

Outline of Talk

1. Coarse-grained locking (static locks)
    - The Lockset Algorithm
2. Fine-grained (per-element locking)
    - JAVA: Conditional Must-Not Aliasing
    - C: Existentially Typed Flow (requires annotations)
    - C: Interprocedural Must-Alias Analysis
3. Medium-grained (per-bucket locking)
    - JAVA: Disjoint Reachability Analysis
    - C: Region Analysis
4. Unified Approach^{TM} to Race Detection

The Lockset Analysis

- For each program point
  - Compute set of locks that must be held.
  - `lock`$(\mathtt{l})$ adds the lock that $\mathtt{l}$ must point to.
  - `unlock`$(\mathtt{l})$ removes locks that $\mathtt{l}$ may point to.
- For each expression e in the program
  - Check if e may point to a shared variable.
  - Write down the access with set of mutexes held.
- Shared var has no common lock $\Rightarrow$ race!

Simple Example (no race)

$$\begin{aligned} T_1: &\ \texttt{lock}(\&l_1); \\ & v = v + 1; \\ & \texttt{unlock}(\&l_1); \end{aligned}$$

$$\begin{aligned} T_2: &\ \texttt{lock}(\&l_1); \\ & v = v + 1; \\ & \texttt{unlock}(\&l_1); \end{aligned}$$

- List of accesses:
  $\langle v, \{l_1\}, \text{write}, \texttt{file.c} : 2\rangle$
  $\langle v, \{l_1\}, \text{write}, \texttt{file.c} : 5\rangle$
- $\mathtt{v}$ is protected by $\{l_1\}$.

Simple Example (race!)

$T_1:$ $\texttt{lock}(\&l_1);$

$v = v + 1;$

$\texttt{unlock}(\&l_1);$

$T_2:$ $\texttt{lock}(\&l_2);$

$v = v + 1;$

$\texttt{unlock}(\&l_2);$

- List of accesses:
  $\langle v, \{l_1\}, \text{write}, \texttt{file.c} : 2\rangle$
  $\langle v, \{l_2\}, \text{write}, \texttt{file.c} : 5\rangle$
- No common lock!

Complications

- Context-Sensitivity
- Path-Sensitivity
- Synchronization-Sensitivity

- Dynamic Memory Allocation

Dynamic Data, Static Locks

$\mathtt{p} = \mathtt{malloc}();$
$\mathtt{lock}(\&\mathtt{l});$
$\mathtt{p} \rightarrow \mathtt{d} = 5;$
$\mathtt{unlock}(\&\mathtt{l});$

- List of accesses: $\langle \text{alloc@1.d}, \{\mathtt{l}\}, \ldots \rangle$
- Blob all elements allocated at that point.
- Can be handled as before.

Dynamic Data, Dynamic Locks

```
p = q = malloc();
lock(&p→l);
q→d = 7;
unlock(&p→l);
```

- List of accesses: $\langle \mathrm{alloc@1.d}, \{\mathrm{alloc@1.l}\}, \ldots \rangle$
- Is it the same element in the blob?
- Must-equality analysis!

Finding Races in the Heap

- Keep a symbolic lockset

$$\{p.l\}$$

- Use address must-equalities to match symbolic locksets with accesses.

$$\models p = q$$

- Use may points-to analysis to associate inferred invariant with memory locations.

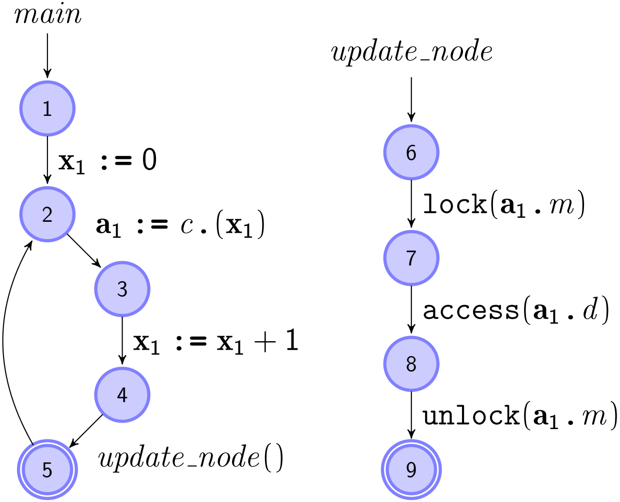
$$p \mapsto \{\mathrm{alloc@1}\}$$

Per-element locking

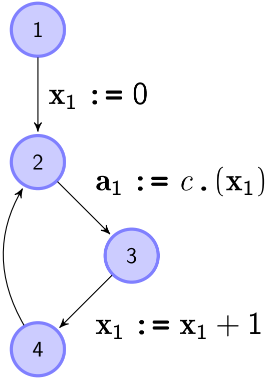
```
typedef struct {
  int datum;
  char filename[80];
  pthread_mutex_t mutex;
} node;

node cache[100];
```

Traverse cache



Valid Must-Equalities



1. No equalities hold!
2. No equalities hold!
3. $\mathbf{a}_1 \doteq c\,.\,(\mathbf{x}_1)$.
4. $\mathbf{a}_1 \doteq c\,.\,(-1 + \mathbf{x}_1)$.

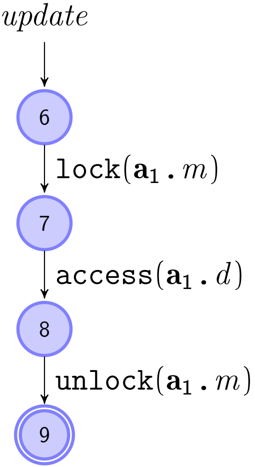
Abstract domain

$$\begin{tikzcd}
 & & \mathsf{true} & & \\
 & 8 - 4\mathbf{x}_1 \doteq 0 \arrow[ur, Rightarrow] & \cdots \arrow[u, Rightarrow] & \mathbf{a}_1 \doteq c\,\mathbf{.}\,(2) \arrow[ul, Rightarrow] & \\
\cdots \arrow[ur, Rightarrow] & & (4 - 2\mathbf{x}_1 \doteq 0) \wedge (\mathbf{a}_1 \doteq c\,\mathbf{.}\,(\mathbf{x}_1)) \arrow[ul, Rightarrow] \arrow[u, Rightarrow] \arrow[ur, Rightarrow] & & \cdots \arrow[ul, Rightarrow] \\
 & & \mathsf{false} \arrow[ull, Rightarrow] \arrow[u, Rightarrow] \arrow[urr, Rightarrow] & &
\end{tikzcd}$$

How do we compute $\mathrm{E}_1 \Rightarrow \mathrm{E}_2$?

Is this a complete lattice?

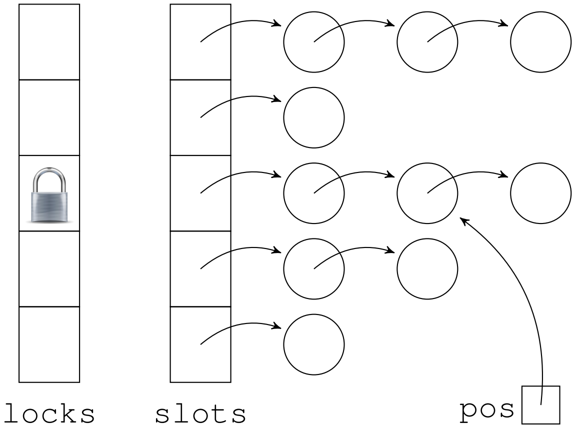
Back to Race detection



- We obtain the lockset: $\{c \,.\, (-1 + \mathbf{x}_1) \,.\, m,\ \mathbf{a}_1 \,.\, m\}$
- Lockset must equal held locks at the access!
- Correlate $\mathbf{a}_1 \,.\, d$ to $\mathbf{a}_1 \,.\, m$.
- Associate invariant with array c.

- Why integer equalities?

Synchronized Hashtable



What do we need?

- Infer the locked addresses
  $\texttt{locks}[i]$
- Information about pointers
  $\texttt{pos} \in \texttt{slot}[i]$
- Disjointness information
  $\texttt{slot}[i] \cap \texttt{slot}[j] = \emptyset$

Region Analysis

- Heap Abstraction:

$$\Pi \times \mathrm{R}$$

- What are the disjoint regions?
- What region does each pointer belong to?

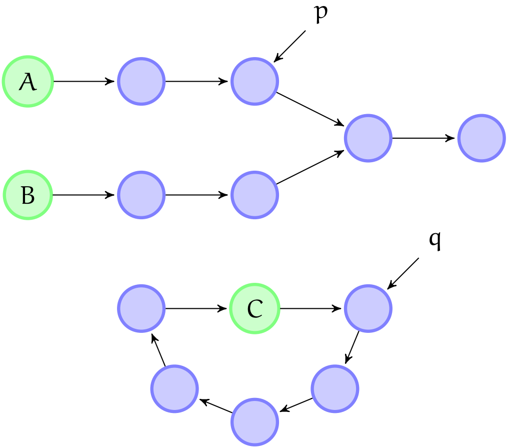
Region Analysis

- Heap Abstraction:

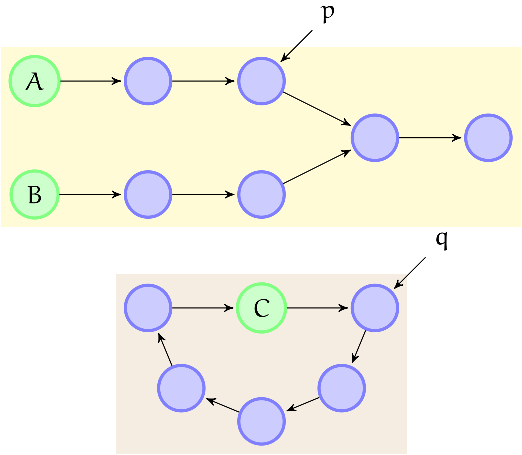
$$\Pi \times R$$

- lattice of partitions on A (owners)
- region mapping $R\colon V \to \mathcal{P}(A \cup \{\bullet\})$

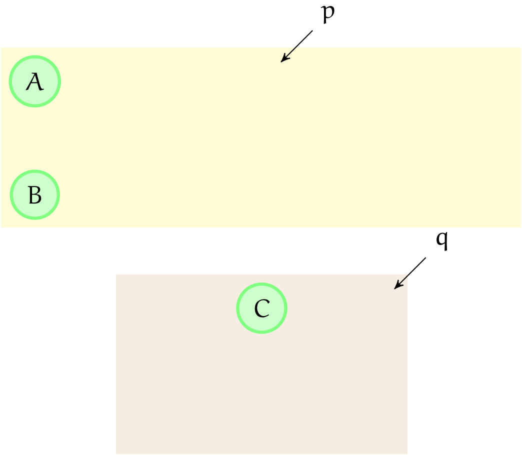
Abstraction



Abstraction



Abstraction



Abstraction

- Partitions: $\{A, B\}, \{C\}$
- Mapping:
  $p \mapsto \{A, B\}$
  $q \mapsto \{C\}$

Analysis

$$p = \texttt{malloc}();$$
$$q = \&A;$$
$$p \rightarrow n = q \rightarrow n;$$
$$q \rightarrow n = \&B;$$
$$\texttt{if}\ (\star)\ q = \&C;$$

- Partitions:
  $\{A\}, \{B\}, \{C\}$
- Mapping:
  $p \mapsto \emptyset$
  $q \mapsto \emptyset$

Analysis

$p = \texttt{malloc}();$

$q = \&A;$

$p \rightarrow n = q \rightarrow n;$

$q \rightarrow n = \&B;$

$\texttt{if}\ (\star)\ q = \&C;$

- Partitions:
  $\{A\}, \{B\}, \{C\}$
- Mapping:
  $p \mapsto \{\bullet\}$
  $q \mapsto \emptyset$

Analysis

$\mathtt{p} = \mathtt{malloc}();$

$\mathtt{q} = \&A;$

$\mathtt{p} \rightarrow \mathtt{n} = \mathtt{q} \rightarrow \mathtt{n};$

$\mathtt{q} \rightarrow \mathtt{n} = \&B;$

$\mathtt{if}\ (\star)\ \mathtt{q} = \&C;$

- Partitions:
  $\{A\}, \{B\}, \{C\}$
- Mapping:
  $\mathtt{p} \mapsto \{\bullet\}$
  $\mathtt{q} \mapsto \{A\}$

Analysis

$\mathtt{p} = \mathtt{malloc}();$

$\mathtt{q} = \&A;$

$\mathtt{p} \rightarrow \mathtt{n} = \mathtt{q} \rightarrow \mathtt{n};$

$\mathtt{q} \rightarrow \mathtt{n} = \&\mathrm{B};$

$\mathtt{if}\ (\star)\ \mathtt{q} = \&\mathrm{C};$

- Partitions:
  $\{A\}, \{B\}, \{C\}$
- Mapping:
  $\mathtt{p} \mapsto \{A\}$
  $\mathtt{q} \mapsto \{A\}$

Analysis

```
p = malloc();
q = &A;
p→n = q→n;
q→n = &B;
if (⋆) q = &C;
```

- Partitions:
  $\{A, B\}, \{C\}$
- Mapping:
  $p \mapsto \{A, B\}$
  $q \mapsto \{A, B\}$

Analysis

$\mathtt{p} = \mathtt{malloc}();$

$\mathtt{q} = \&A;$

$\mathtt{p} \rightarrow \mathtt{n} = \mathtt{q} \rightarrow \mathtt{n};$

$\mathtt{q} \rightarrow \mathtt{n} = \&B;$

$\mathtt{if}\ (\star)\ \mathtt{q} = \&C;$

- Partitions: $\{A, B\}, \{C\}$
- Mapping: $\mathtt{p} \mapsto \{A, B\}$ $\mathtt{q} \mapsto \{C\}$

Analysis

$p = \texttt{malloc}();$

$q = \&A;$

$p \rightarrow n = q \rightarrow n;$

$q \rightarrow n = \&B;$

$\texttt{if}\ (\star)\ q = \&C;$

- Partitions: $\{A, B\}, \{C\}$
- Mapping:
  $p \mapsto \{A, B\}$
  $q \mapsto \{A, B, C\}$

Dealing with the arrays

- Allow symbolic index expressions.
- If we need to join two regions with owners $A[e_1]$ and $A[e_2]$
  - If we $\models e_1 = e_2$, just keep one of them.
  - Otherwise, collapse the array.
- Partition lattice Π tracks collapsed arrays.
- If an array A has not collapsed in Π,
  the regions of $A[\mathrm{i}]$ and $A[\mathrm{j}]$ are disjoint ($\mathrm{i} \neq \mathrm{j}$).

Back to the example

- The symbolic lockset will be

  $$\{\texttt{locks.(}\texttt{i}\texttt{)}\}$$

- As we access `pos`, we have
  - Points-to analysis: `pos` $\mapsto$ {alloc@55}.
  - Region analysis: `pos` $\in$ `slots.(i)`.
- Associate the invariant with the array. Why?

Unified Approach to Race Detection

- Want to deal with dynamic regions.
    - List (instead of array) of regions.
    - Type-based regions for, e.g., per-device structures.
- Where to associate invariants?
    - Static names.
    - Allocation sites.
    - Types.
    - Regions.

Solution

- Under construction . . .
- All the ingredients are there.
- Implementation is making good progress.
- Where are the theorems?