Modular Heap Abstraction-Based Memory Leak Detection for Heap-Manipulating Programs

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Outline

- Motivation
- Field-sensitive heap abstraction
- Memory leak detection
- Implementation and experiments
- Conclusion

Motivation

Motivation

Dynamic allocated data structures

- examples: lists, trees, etc.
- widely used in practice
  - e.g., operating systems, device drivers, etc.
- **error-prone**
  - memory leak
    - degrade preformance
    - cause memory-intensive or long-time running software to crash
  - dangling reference
  - double free
  - null pointer dereference
  - ...

Motivation

```
typedef struct list{
    int d;
    struct list* n;
}List;

void f(){
1:   List* x=(List*) malloc(sizeof(List));
2:   x→n =(List*) malloc(sizeof(List));
3:   free(x);
}
```

Memory leak on $x \to n$

Field sensitive analysis of heap manipulating programs

- **problem**: high cost for exact memory layout
- **solution**: abstraction to make the problem tractable
  - proper abstraction according to properties to check $\to$ simplify the problem & be precise enough

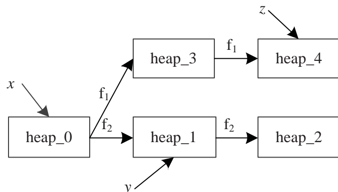
Field-sensitive heap abstraction

Concrete heap state

Shape graph $\langle H, S \rangle$

- the topological structure of heap memory can be described by a directed graph $H = \langle V, E \rangle$ where
  - V denotes the set of heap cells
  - $E : V \xrightarrow{F} V$ denotes the points-to relations between cells via their fields F
- $S : PVar \to V$ where $PVar$ denotes the set of pointer variables

$$PVar = \{x, y, z\}$$
$$V = \{heap_0, heap_1, heap_2, heap_3, heap_4\}$$
$$S = \{\langle x, heap_0\rangle, \langle y, heap_1\rangle, \langle z, heap_4\rangle\}$$
$$E = \{heap_0 \xrightarrow{f_1} heap_3, heap_0 \xrightarrow{f_2} heap_1, heap_1 \xrightarrow{f_2} heap_2, heap_3 \xrightarrow{f_1} heap_4\}$$



It may cause high memory cost! $\Rightarrow$ abstraction

Field-sensititive heap abstraction

An abstract domain of member-access distances $\langle D, +, - \rangle$

- elements: a set of abstract distances $D = \{0, 1, 2\}$
  - 0: the current cell **itself** (p)
  - 1: member-access with depth **1** ($p \to f$)
  - 2: member-access with depth **more than 1** ($p \to f \to^{\star}$).
- operations: $+, -$ over D (defined in Table 1)

Table 1: Operations over D

$+$	0	1	2
0	{0}	{1}	{2}
1	{1}	{2}	{2}
2	{2}	{2}	{2}

$-$	0	1	2
0	$\bot$	$\bot$	$\bot$
1	{1}	{0}	$\bot$
2	{2}	{1,2}	$\top$

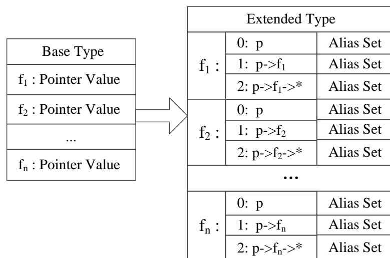
($\bot$: the operator cannot be applied to these operands; $\top$: $\{0, 1, 2\}$)

Field-sensititive heap abstraction

An extended pointer structure of a pointer p

$$\tau_p^\sharp \triangleq \{f_1 : \langle D, 2^{PVar} \rangle;\ f_2 : \langle D, 2^{PVar} \rangle;\ \ldots;\ f_n : \langle D, 2^{PVar} \rangle\}$$

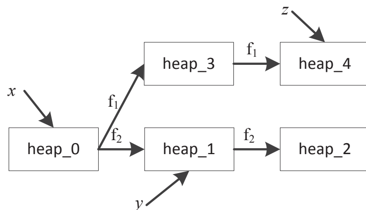
- $f_1, f_2, \ldots, f_n$ denote the n pointer fields of the structure that p points to
- $D = \{0, 1, 2\}$ denotes the set of abstract distances
- 2^{PVar} denotes the alias set of accessing field f_i of pointer p with distance $d \in D$



Field-sensititive heap abstraction

Example:

$PVar = \{x, y, z\}$
$V = \{heap_0, heap_1, heap_2, heap_3, heap_4\}$
$S = \{\langle x, heap_0\rangle, \langle y, heap_1\rangle, \langle z, heap_4\rangle\}$
$E = \{heap_0 \xrightarrow{f_1} heap_3, heap_0 \xrightarrow{f_2} heap_1, heap_1 \xrightarrow{f_2} heap_2, heap_3 \xrightarrow{f_1} heap_4\}$



$\tau_x^\sharp : \{f_1 : \langle 0, \emptyset\rangle, \langle 1, \emptyset\rangle, \langle 2, \{z\}\rangle; \quad f_2 : \langle 0, \emptyset\rangle, \langle 1, \{y\}\rangle, \langle 2, \emptyset\rangle\}$
$\tau_y^\sharp : \{f_1 : \langle 0, \emptyset\rangle, \langle 1, \bot\rangle; \quad f_2 : \langle 0, \emptyset\rangle, \langle 1, \emptyset\rangle, \langle 2, \bot\rangle\}$
$\tau_z^\sharp : \{f_1 : \langle 0, \emptyset\rangle, \langle 1, \bot\rangle; \quad f_2 : \langle 0, \emptyset\rangle, \langle 1, \bot\rangle\}$

Field-sensititive heap abstraction

Definition (Abstract Heap State)

The abstract heap state $\mathbb{S}^\sharp$ at each program point of a program *HP* consists of a set of extended structures of all pointer variables:

$$\mathbb{S}^\sharp = \{\tau^\sharp_{p_i} | p_i \in PVar(HP)\}$$

The number of abstract heap states: finite

$$\leq (fn \times 3 \times (2^{pn-1} + 1))^{pn}$$

- *pn*: the number of pointer variables
- *fn*: the maximum number of pointer fields

Field-sensititive heap abstraction

Alias bit-vector: using **bit-vector** to encode **alias set**

- maintain a variable ordering for all variables in *PVar*
- a alias bit-vector $\overrightarrow{r}^{\sharp}_{x} \in \{0,1\}^{|PVar|}$ is defined as
  $\overrightarrow{r}^{\sharp}_{p}(f_m, d)[i] = 1 \Leftrightarrow v_i$ is an alias of accessing f_m of p with distance d

Example: $PVar = \{x, y, z\}$ with variable ordering: $x \prec y \prec z$

$$\overrightarrow{r}^{\sharp}_{x} : \{f_1 : \langle 0,0\rangle, \langle 1,0\rangle, \langle 2,001\rangle;\ f_2 : \langle 0,0\rangle, \langle 1,010\rangle, \langle 2,0\rangle\}$$
$$\overrightarrow{r}^{\sharp}_{y} : \{f_1 : \langle 0,0\rangle, \langle 1,\bot\rangle;\ f_2 : \langle 0,0\rangle, \langle 1,0\rangle, \langle 2,\bot\rangle\}$$
$$\overrightarrow{r}^{\sharp}_{z} : \{f_1 : \langle 0,0\rangle, \langle 1,\bot\rangle;\ f_2 : \langle 0,0\rangle, \langle 1,\bot\rangle\}$$

Field-sensititive heap abstraction

Abstract heap state with a canonical form

Definition (Saturated abstract state)

An abstract state $\mathbb{S}^\sharp$ is *saturated* iff it satisfies:

1. **Anti-reflexivity**. $\forall p_i . \overrightarrow{r}^\sharp_{p_i}(f_m, 0)[i] = 0$.
2. **Symmetry**. $\forall p_i, p_j . \overrightarrow{r}^\sharp_{p_i}(f_m, 0)[j] = 1 \rightarrow \overrightarrow{r}^\sharp_{p_j}(f_m, 0)[i] = 1$.
3. **Transitivity**. $\forall p_i, p_j, p_t . \overrightarrow{r}^\sharp_{p_i}(f_m, d_1)[j] = 1 \wedge \overrightarrow{r}^\sharp_{p_j}(f_m, d_2)[t] = 1$ $\rightarrow \overrightarrow{r}^\sharp_{p_i}(f_m, d_1 + d_2)[t] = 1$.

Memory leak detection

Syntax of heap-manipulating programs

$p, \ q \in PVar$
$f_1, \ f_2, \ \ldots \ f_i \ \ldots, \ f_m \in Fields$
$AsgnStmt := \ p = null | \ p \rightarrow f_i = null | \ p = q |$
$\qquad p = q \rightarrow f_i | \ p \rightarrow f_i = q | \ p = malloc() | \ p = free()$
$SwitchStmt := \ switch \ e \ \{c_1 : n_1, \ \ldots, \ c_j : c_j, \ \ldots, \ c_k : n_k, \ \ldots\}$
$CallStmt := \ e = g(e_1, \ \ldots, \ e_k)$
$ReturnStmt := \ return \ \ e$
$Stmt := \ AsgnStmt | \ SwitchStmt | \ CallStmt | \ ReturnStmt$
$SequenceStmt := \ Stmt; Stmt$

Abstract semantics

1. $[[p_u = null]](\mathbb{S}^\sharp) = \{\mathbb{S}^\sharp[\overrightarrow{r}^\sharp_{p_v}(f_m, d)[u] \leftarrow 0, \overrightarrow{r}^\sharp_{p_u}(f_m, d) \leftarrow \bot] | v \neq u\}$
   if $\exists w \neq u \wedge l \in D.\ \overrightarrow{r}^\sharp_{p_w}(f_m, l)[u] \neq 0 \vee \overrightarrow{r}^\sharp_{p_u}(f_m, 0) = \bot$
   $\{$**memory_leak**$\}$ otherwise
2. $[[p_u \rightarrow f_i = null]](\mathbb{S}^\sharp) = \{\mathbb{S}^\sharp[\overrightarrow{r}^\sharp_{p_v}(f_m, 2) \leftarrow \overrightarrow{r}^\sharp_{p_v}(f_m, 2) \overrightarrow{-} \overrightarrow{r}^\sharp_{p_u}(f_i, l) \overrightarrow{+} \overrightarrow{r}^\sharp_{p_u}(f_j, l) | v \in \{v | \overrightarrow{r}^\sharp_{p_v}(f_m, 1)[u] = 1 \vee \overrightarrow{r}^\sharp_{p_v}(f_m, 2)[u] = 1\} \wedge l \in \{1, 2\} \wedge f_j \in Fields - \{f_i\}, \overrightarrow{r}^\sharp_{p_u}(f_i, l) \leftarrow \bot | l \in \{1, 2\}, \overrightarrow{r}^\sharp_{p_w}(f_i, l) \leftarrow \bot | l \in \{1, 2\} \wedge w \in \{w | \overrightarrow{r}^\sharp_{p_u}(f_m, 0)[w] = 1]\}\}$
   if $\overrightarrow{r}^\sharp_{p_u}(f_i, 1) \neq 0$
   $\{$**memory_leak**$\}$ otherwise
3. $[[p_u = p_v]](\mathbb{S}^\sharp) = \{\mathbb{S}^\sharp_1[\overrightarrow{r}^\sharp_{p_u}(f_m, d) \leftarrow \overrightarrow{r}^\sharp_{p_v}(f_m, d)] | \mathbb{S}^\sharp_1 \in [[p_u = null]]\mathbb{S}^\sharp\}$
   if $\exists w \neq u \wedge l \in D. \overrightarrow{r}^\sharp_{p_w}(f_m, l)[u] \neq 0 \vee \overrightarrow{r}^\sharp_{p_u}(f_m, 0) = \bot$
   $\{$**memory_leak**$\}$ otherwise
4. $[[p_u = p_v \rightarrow f_i]](\mathbb{S}^\sharp) = \{\mathbb{S}^\sharp_1[\overrightarrow{r}^\sharp_{p_u}(f_m, 0) \leftarrow \overrightarrow{r}^\sharp_{p_v}(f_m, 1), \overrightarrow{r}^\sharp_{p_v}(f_m, 1)[u] \leftarrow 1] | \mathbb{S}^\sharp_1 \in [[p_u = null]]\mathbb{S}^\sharp\}$
   if $\exists w \neq u \wedge l \in D. \overrightarrow{r}^\sharp_{p_w}(f_m, l)[u] \neq 0 \vee \overrightarrow{r}^\sharp_{p_u}(f_m, 0) = \bot$
   $\{$**memory_leak**$\}$ otherwise

($\overrightarrow{+}$: bitwise addition; $\overrightarrow{-}$: bitwise subtraction)

Abstract semantics

5. $[[p_u \rightarrow f_i = p_v]](\mathbb{S}^\sharp) = \{\mathbb{S}^\sharp_1[(\overrightarrow{r}^\sharp_{p_w}(f_i,1) \leftarrow \overrightarrow{r}^\sharp_{p_v}(f_m,0))[v] \leftarrow 1, \overrightarrow{r}^\sharp_{p_w}(f_m,2) \leftarrow \overrightarrow{r}^\sharp_{p_v}(f_m,1) \overrightarrow{+} \overrightarrow{r}^\sharp_{p_v}(f_m,2),$ $(\overrightarrow{r}^\sharp_{p_t}(f_m,2) \leftarrow \overrightarrow{r}^\sharp_{p_t}(f_m,2) \overrightarrow{+} \overrightarrow{r}^\sharp_{p_v}(f_m,0) \overrightarrow{+} \overrightarrow{r}^\sharp_{p_v}(f_m,1) \overrightarrow{+} \overrightarrow{r}^\sharp_{p_v}(f_m,2))[v] \leftarrow 1] | t \in \{t | \overrightarrow{r}^\sharp_{p_t}(f_m,1)[u] =$ $1 \vee \overrightarrow{r}^\sharp_{p_t}(f_m,2)[u] = 1\} \wedge w \in \{w | \overrightarrow{r}^\sharp_{p_u}(f_m,0)[w] = 1\} \cup \{u\} \wedge \mathbb{S}^\sharp_1 \in [[p_u \rightarrow f_i = null]](\mathbb{S}^\sharp)\}$
   if $\overrightarrow{r}^\sharp_{p_u}(f_i,1) \neq 0$
   $\{$**memory_leak**$\}$ otherwise
6. $[[p_u = malloc]](\mathbb{S}^\sharp) = \{\mathbb{S}^\sharp_1[\overrightarrow{r}^\sharp_{p_u}(f_m,d) \leftarrow 0] | \mathbb{S}^\sharp_1 \in [[p_u = null]]\mathbb{S}^\sharp\}$
   if $\exists w \neq u \wedge l \in D.\ \overrightarrow{r}^\sharp_{p_w}(f_m,l)[u] \neq 0 \vee \overrightarrow{r}^\sharp_{p_u}(f_m,0) = \perp$
   $\{$**memory_leak**$\}$ otherwise
7. $[[p_u = free()]](\mathbb{S}^\sharp) = \{\mathbb{S}^\sharp[\overrightarrow{r}^\sharp_{p_w}(f_m,d)[t] \leftarrow 0, \overrightarrow{r}^\sharp_{p_w}(f_m,d)[u] \leftarrow 0, \overrightarrow{r}^\sharp_{p_t}(f_m,d) \leftarrow \perp, \overrightarrow{r}^\sharp_{p_u}(f_m,d) \leftarrow \perp] | t \in$ $\{t | \overrightarrow{r}^\sharp_{p_u}(f_m,0)[t] = 1\} \wedge w \in \{w | \overrightarrow{r}^\sharp_{p_u}(f_m,0)[w] = 0 \wedge w \neq u\}\}$
   if $\overrightarrow{r}^\sharp_{p_u}(f_m,1) \neq 0 \vee \overrightarrow{r}^\sharp_{p_u}(f_m,1) = \perp$
   $\{$**memory_leak**$\}$ otherwise

($\overrightarrow{+}$: bitwise addition; $\overrightarrow{-}$: bitwise subtraction)

Memory leak detection

Detecting memory leaks in assignments

(a) check whether there are other pointers that can access the cell pointed to by the current pointer (p_u), such as **Rule** 1, 3, 4, 6;

(b) check whether there are other pointers that points to the cell referenced by the pointer field of the current pointer $(p_u \rightarrow f_i)$, such as **Rule** 2, 5;

(c) check whether all pointer fields of the current pointer $(p_u \rightarrow f_i)$ are *null* or pointed to by other pointers, like **Rule** 7.

Example

1. $$[[p_u = null]](\mathbb{S}^\sharp) = \begin{cases} \{\mathbb{S}^\sharp[\overrightarrow{r}^\sharp_{p_v}(f_m, d)[u] \leftarrow 0, \overrightarrow{r}^\sharp_{p_u}(f_m, d) \leftarrow \bot] \mid v \neq u\} \\ \quad \text{if} \quad \exists w \neq u \wedge l \in D.\ \overrightarrow{r}^\sharp_{p_w}(f_m, l)[u] \neq 0 \vee \overrightarrow{r}^\sharp_{p_u}(f_m, 0) = \bot \\ \{\textbf{memory_leak}\} \quad \text{otherwise} \end{cases}$$

Interprocedural memory leak detection

Big-step abstract semantics

$\mathbb{S}^{\sharp}_{Of} = [[f(p_0, p_1, ..., p_{k-1})]](\mathbb{S}^{\sharp}_{If})$, wherein $\mathbb{S}^{\sharp}_{Of}$ is the postcondition after the running of the callee f under the precondition $\mathbb{S}^{\sharp}_{If}$.

Procedural summary: $\langle \mathbb{S}^{\sharp}_{If}, \mathbb{S}^{\sharp}_{Of} \rangle$

- $\mathbb{S}^{\sharp}_{If}$: abstract heap state over arguments and global pointers
- $\mathbb{S}^{\sharp}_{Of}$: abstract heap state over return variable and global pointers

Example

```
typedef struct list{
   int d;
   struct list* n;
}List;

List* l;

List* f1(List* p){
1   if(p!=NULL){
2      l=p;
3   }
4   p=(List*) malloc(sizeof(List));
5   p→n=(List*)malloc(sizeof(List));
6   return p;
}

void g1(){
1   l=NULL;
2   List* x=(List*)malloc(sizeof(List));
3   List* y=f1(x);
4   free(y);
5   free(l);
}

void g2(){
1   l=NULL;
2   List* x=NULL;
3   List* z=f1(x);
4   free(z);
}
```

Table 2: procedural summary for $f1$

Precondition	Postcondition
$\vec{r}^{\sharp}_{p} : \{n : \langle 0, \bot \rangle\}$ $\vec{r}^{\sharp}_{l} : \{n : \langle 0, \bot \rangle\}$	$\vec{r}^{\sharp}_{ret_{f1}} : \{n : \langle 0, \emptyset \rangle, \langle 1, \emptyset \rangle, \langle 2, \bot \rangle\}$ $\vec{r}^{\sharp}_{l} : \{n : \langle 0, \bot \rangle\}$
$\vec{r}^{\sharp}_{p} : \{n : \langle 0, \emptyset \rangle, \langle 1, \bot \rangle\}$ $\vec{r}^{\sharp}_{l} : \{n : \langle 0, \bot \rangle\}$	$\vec{r}^{\sharp}_{ret_{f1}} : \{n : \langle 0, \emptyset \rangle, \langle 1, \emptyset \rangle, \langle 2, \bot \rangle\}$ $\vec{r}^{\sharp}_{l} : \{n : \langle 0, \emptyset \rangle, \langle 1, \bot \rangle\}$
$\vec{r}^{\sharp}_{p} : \{n : \langle 0, \emptyset \rangle, \langle 1, \emptyset \rangle, \langle 2, \bot \rangle\}$ $\vec{r}^{\sharp}_{l} : \{n : \langle 0, \bot \rangle\}$	$\vec{r}_{ret_{f1}} : \{n : \langle 0, \emptyset \rangle, \langle 1, \emptyset \rangle, \langle 2, \bot \rangle\}$ $\vec{r}^{\sharp}_{l} : \{n : \langle 0, \emptyset \rangle, \langle 1, \emptyset \rangle, \langle 2, \bot \rangle\}$
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Fixpoint iteration algorithm for analysis

- to compute the abstract heap state for each program point
- worklist-based
- always terminate (without need of widening)
  - maximum number of heap abstract states: $(fn \times 3 \times (2^{pn-1} + 1))^{pn}$

Implementation and experiments

Prototype

Heapcheck

- a field and context sensitive interprocedural memory leak detector
- based on Crystal (a program analysis system for C) [1]
- preprocessing process
  - slicing
  - transforming the input program into a SSA-like form by instrumenting new pointer variables

Pointer assignments	SSA-like assignments
$p \rightarrow f_i = q \rightarrow f_j$	$pt_0 = q \rightarrow f_j;\ p \rightarrow f_i = pt_0$
$p = p \rightarrow f_i$	$pt_1 = p \rightarrow f_i;\ p = pt_1$
$p \rightarrow f_i = malloc$	$pt_2 = malloc;\ p \rightarrow f_i = pt_2$
$p = q \rightarrow f_i \rightarrow f_j$	$pt_3 = q \rightarrow f_i;\ p = pt_3 \rightarrow f_j$
$p \rightarrow f_i = free()$	$pt_4 = p \rightarrow f_i;\ pt_4 = free()$

[1] https://www.cs.cornell.edu/projects/crystal/

Experiments

Results on benchmark programs (memory leak)

Programs	Size (Kloc)	Preprocess time (Sec)	Analysis time (Sec)		Memory (MB)		Reported alarms (#*fp*/#*total*)
			Without sum.	Sum.-based	Without sum.	Sum.-based	
164.gzip	7.7	1.19	0.31	0.33	27	6	0
175.vpr	17	1.84	2.83	1.11	194	86.7	1/1
179.art	1.2	0.32	0.1	0.1	34.4	33	0
186.crafty	21.7	3.13	7.56	6.98	295	258	0
188.ammp	13.2	1.88	1.22	0.21	135	60.2	0
300.twolf	19.9	3.05	7.38	4.31	442	195	0/3
176.gcc	210	8.35	106.62	61.04	4596	920	2/17
tar-1.12	11.7	1.08	18.98	9.09	239	178	0/5
openssh	58.3	20.55	2.61	1.44	186	144.3	2/14
openssl	36	8.47	0.46	0.44	73.5	40.7	6/11

- Real bugs found ($\#totoal - \#fp$)
  1. ignoring judging whether all the **sub-level pointer fields** are null when deallocating the heap cell pointed to by a pointer
  2. the heap cell pointed to by a **local** pointer variable is not deallocated at the return site

Experiments

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- Precision
  - false positive rate: about 32% on openssh and openssl
    - compared with [B. Hackett, R. Rugina. Region-based shape analysis with tracked locations. POPL05]: about 64% (openssh: 16/26; openssh: 9/13)

Conclusion

Conclusion

Summary

- a field sensitive heap abstraction based on **member-access distances** and **alias bit-vector** domain
- a field and context sensitive interprocedural memory leak detection algorithm based on **summaries**
- experimental evaluations
  - our approach is scalable with satisfied precision in detecting **memory leaks** for large heap-manipulating programs

Thank you!

Questions?