Accelerating Dynamic Detection of Uses of Undefined Values with Static Value-Flow Analysis

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Outline

- What are undefined values?
- Related work and our contributions
- Methodology
- Evaluation
- Conclusion

Use of undefined values

- Undefined values are caused by memory allocations without initialization
    - Stack variables and malloc() heaps in C
- Definedness is transitive
- May cause serious problems when used by some critical operations
    - Conditional jumps
    - Pointer dereferences

undefined / defined

```
void foo() {
     int a, b, c;
     a = 1 + 2;
     b = 0;
     ...
     b = c + 3;
l1:  if (a > b)
        ...
     ...
     int *p;
l2:  *p = a;
}
```

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Dynamic analysis

- Instrumentation via shadow memory

- Binary-based instrumentation
  - Insert code on the binary
  - e.g. Valgrind (>10X slowdown)

- Source-based instrumentation
  - Insert code at compile-time
  - e.g. MSan (typical 3X slowdown)

undefined / defined

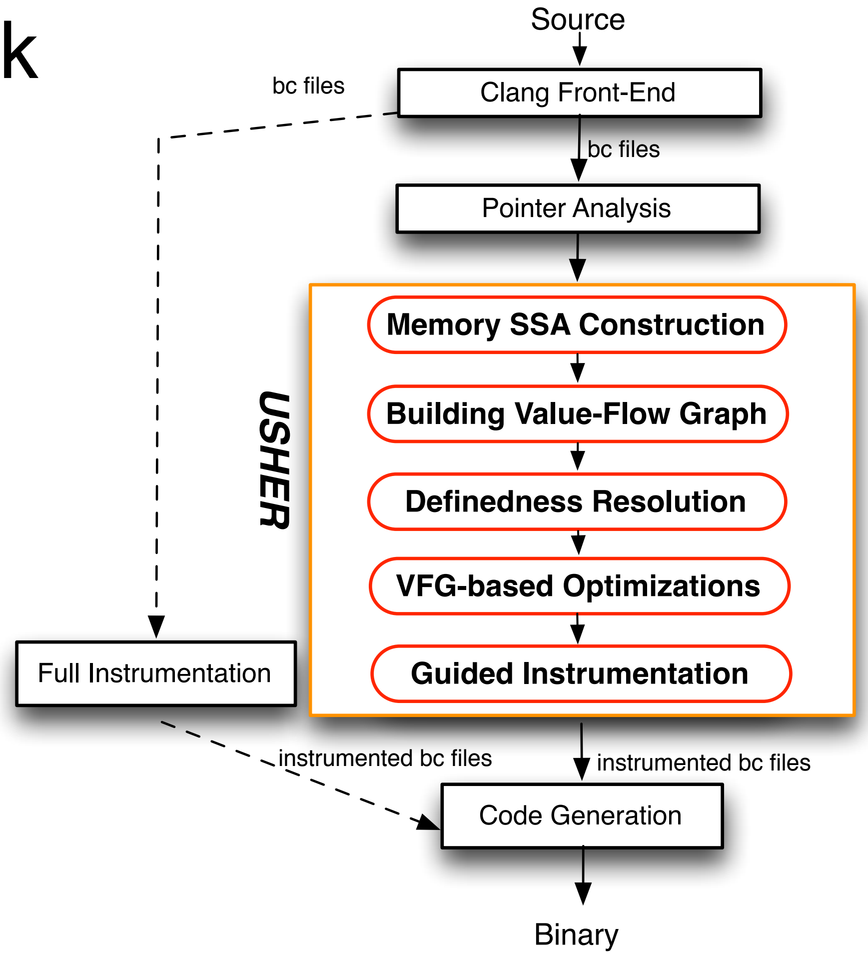
void foo() {	
int a, b, c;	**a_s= F; b_s= F; c_s= F;**
a = 1 + 2;	**a_s = T & T;**
b = 0;	**b_s= T;**
...	**...**
b = c + 3;	**b_s= c_s & T;**
I1: if (a > b)	**check (a_s& b_s);**
...	**...**
...	**...**
int *p;	**p_s = F;**
I2: *p = a;	**check (p_s);**
}	

Other analysis

- Static analysis
  - Dataflow analysis
  - Compilers (gcc, clang)
  - HDL, typestate verification, IFDS
- Static + dynamic
  - Nguyen *et al. CC '03*
    - For Fortran (5X slowdown)
  - Necula *et al. TOPLAS '05*
    - CCured applies only to pointers (requiring source code modification)

The *Usher* framework

- Instrumentation
  - Full *vs* Guided (selective)



Source

Clang Front-End

bc files

bc files

Pointer Analysis

USHER

Memory SSA Construction

Building Value-Flow Graph

Definedness Resolution

VFG-based Optimizations

Guided Instrumentation

Full Instrumentation

instrumented bc files

instrumented bc files

Code Generation

Binary

Our contributions

- Usher is a new static + dynamic analysis to detect undefined value uses in C programs
  - Inspired by our previous work (Sui *et al.* ISSTA ’12)
  - Guide instrumentation by solving a graph reachability problem

- Our value-flow representation allows optimizations to be developed to further reduce the instrumentation

- Usher reduces the slowdowns of MSan from 212% – 302% to 123% – 140% for 15 benchmarks

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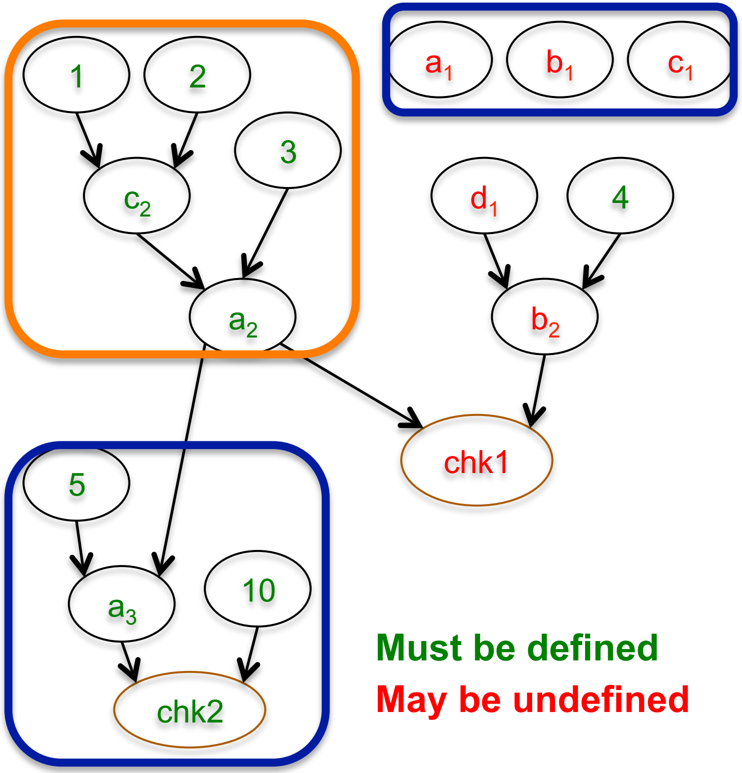
A motivating example



Must be defined

May be undefined

void foo() {	a_s= F; b_s= F; c_s= F;
int a_1, b_1, c_1, d_1;	d_s= F;
$c_2 = 1 + 2$;	$c_s = T \& T$;
$a_2 = 3 + c_2$;	$a_s = T \& c_s$;
$b_2 = d_1 + 4$;	$b_s = d_s \& T$;
I1: if ($a_2 > b_2$) ...;	check($a_s \& b_s$);
...	
$a_3 = a_2 + 5$;	$a_s = a_s \& T$;
I2: if ($a_3 > 10$) ...;	check($a_s \& T$);
}	

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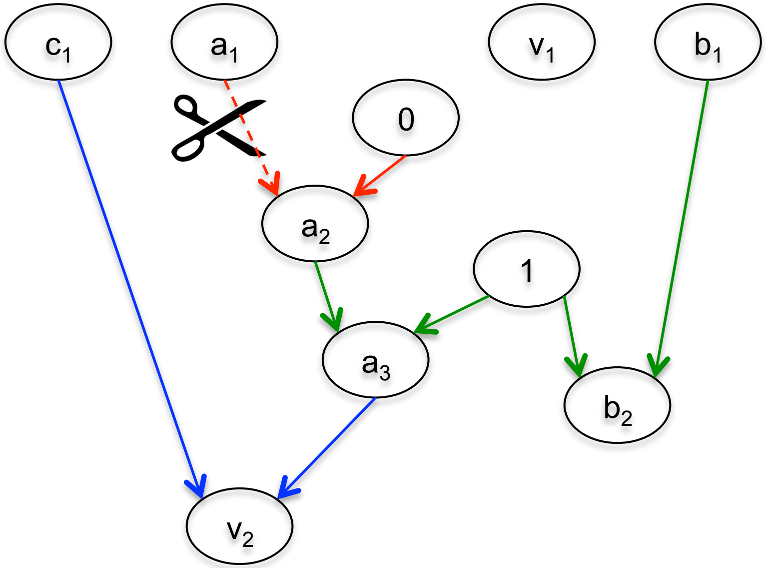
Value-flow graph (VFG)

- Sparseness is based on Static Single Assignment (SSA) form

- For top-level variables
  - e.g., x = y;, a = b + c;
  - SSA is straight forward (e.g. partial SSA in LLVM-IR)

- For address-taken variables
  - e.g., x = *p;,   *q = y;
  - Use pointer analysis results to build *Memory* SSA

VFG for address-taken variables



Points-to information:

$p_1 \rightarrow \{a\}$
$x_4 \rightarrow \{a, b\}$
$y_3 \rightarrow \{a, c\}$

```
void bar() {
    int a1, b1, c1, v1;
    int *p1, *x1, *y1;
    ...
   *p1 = 0;     [a2 = 0;]  //strong update
    ...
   *x4 = 1;     [a3=(1, a2);]  //weak update
                [b2=(1, b1);]
    ...
   v2 = *y3;    [v2=(a3, c1);]
}
```

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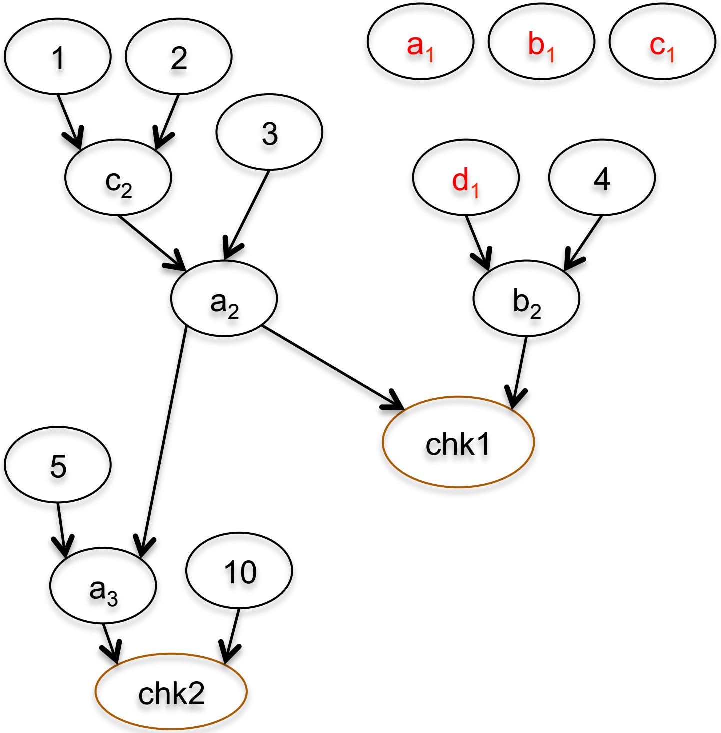
Guided instrumentation

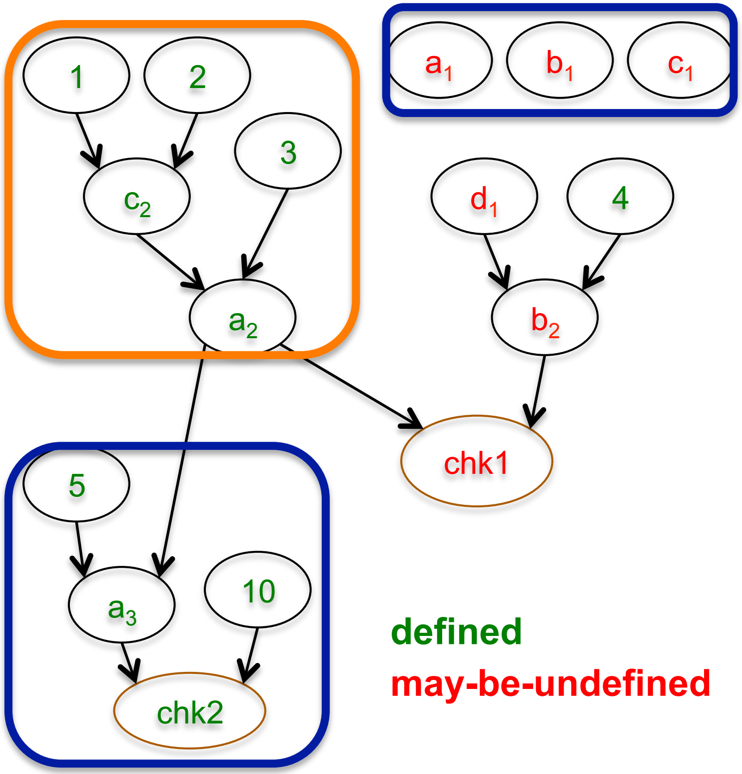
- Definedness resolution on VFG
  - Traverse from every undefined source node (stack, malloc())
    - Mark the reachable nodes as may-be-undefined
    - Mark the unreachable nodes as defined
  - Graph reachability in a context-sensitive manner
- Instrumentation
  - Rule out the nodes that never reach any may-be-undefined check node (critical operation)
  - For the remaining nodes
    - For may-be-undefined nodes, insert instrumentation code
    - For defined nodes,

Revisit the motivating example



void foo() {	a_s= F; b_s= F; c_s= F;
int a_1, b_1, c_1, d_1;	d_s= F;
$c_2 = 1 + 2$;	$c_s = T \& T$;
$a_2 = 3 + c_2$;	$a_s = T \& c_s$;
$b_2 = d_1 + 4$;	$b_s = d_s \& T$;
l1: if ($a_2 > b_2$) ...;	check($a_s \& b_s$);
...	
$a_3 = a_2 + 5$;	$a_s = a_s \& T$;
l2: if ($a_3 > 10$) ...;	check($a_s \& T$);
}	

Revisit the motivating example

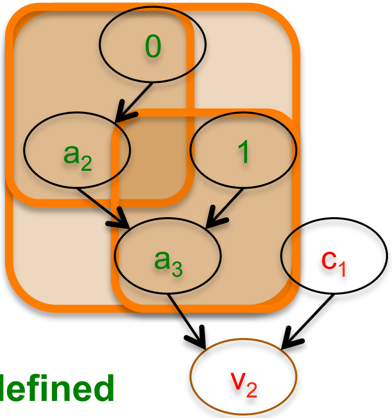


defined

may-be-undefined

void foo() {	a_s= F; b_s= F; c_s= F;
int a_1, b_1, c_1, d_1;	d_s= F;
c_2 = 1 + 2;	c_s = T & T;
a_2 = 3 + c_2;	a_s = T & c_s;
b_2 = d_1 + 4;	b_s = d_s & T;
l1: if (a_2 > b_2) ...;	check(a_s & b_s);
...	
a_3 = a_2 + 5;	a_s = a_s & T;
l2: if (a_3 > 10) ...;	check(a_s & T);
}	

False positives with address-taken variables



defined

may-be-undefined

Points-to information

- **Statically**
  - $p_1 \rightarrow \{a\}$
  - $x_4 \rightarrow \{a, b\}$
  - $y_3 \rightarrow \{a, c\}$
- **At runtime**
  - $p_1 \rightarrow a$
  - $x_4 \rightarrow b$
  - $y_3 \rightarrow a$

void bar() {	
int a_1, b_1, c_1, v_1;	a_s= F; b_s= F;
int $*p_1$, $*x_1$, $*y_1$;	c_s= F; v_s= F;
...	...
I1: $*p_1$ = 0; [a_2 = 0;] //SU	$(*p)_s$ = T;
...	
I2: $*x_4$ = 1; [a_3=(1, a_2);] //WU	$(*x)_s$ = T;
[b_2=(1, b_1);]	
...	...
I3: v_2 = $*y_3$; [v_2=(a_3, c_1);]	v_s = $(*y)_s$;
I4: if (v_2) ...;	check (v_s);
}	

Exe	a_s / b_s / v_s	a_s / b_s / v_s	a_s / b_s / v_s
I1	F / F / F	F / F / F	T / F / F
I2	F / F / F	F / T / F	T / F / F
I3	F / F / F	F / T / F	T / F / T
I4	F / F / **F**	F / T / **F**	T / F / **T**

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Optimizations on the VFG

- VFG simplification
  - Reduce shadow propagation distance

- Redundant check elimination
  - If a value x_n is previously checked, then the following checks on it can be eliminated

Redundant check elimination

...

$c_1 = a_1 + b_1$;

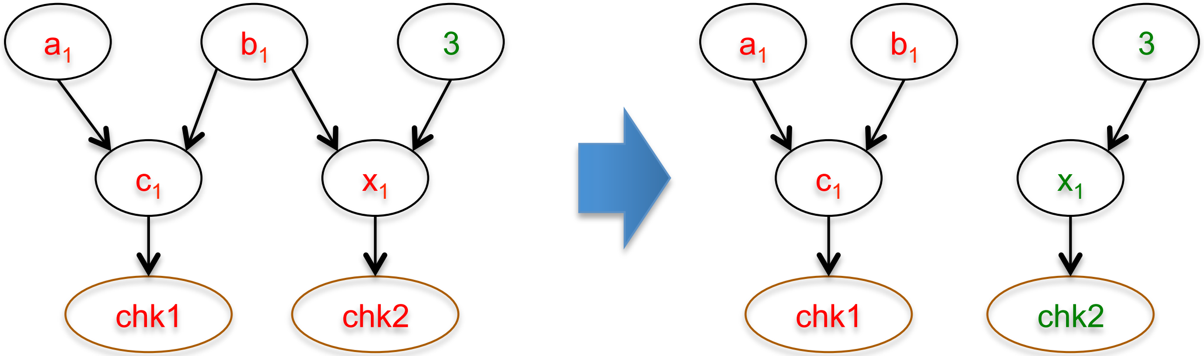
I1: if (c_1) ...

...

I2: $x_1 = b_1 + 3$;

if (x_1) ....

...



(1) Value V must flow to a checking statement at L;

(2) Value V is used in statement at L';

(3) L dominates L' in CFG.

If (1), (2) and (3) hold, cut the edge from V for L'

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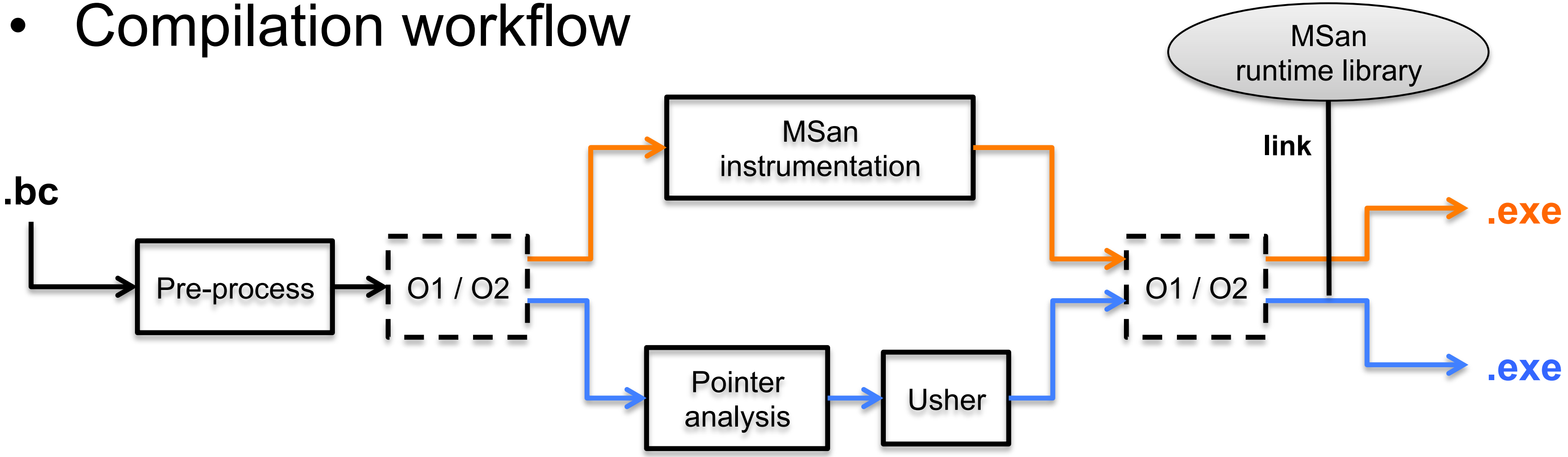
Evaluation

- Benchmarks
  - All 15 C programs of SPEC2K

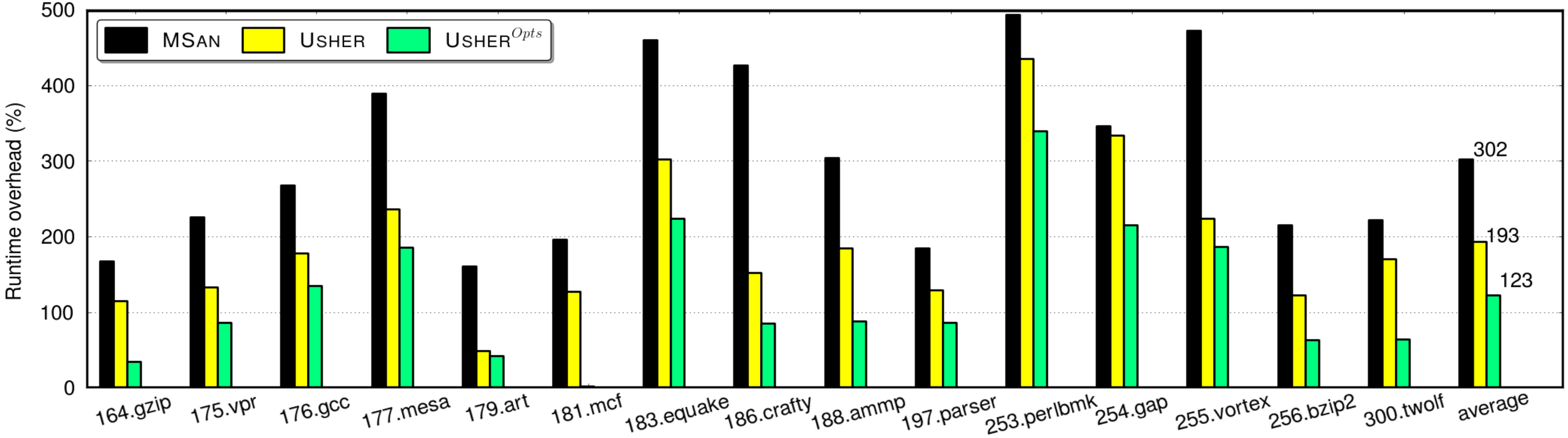
- Compilation workflow



Field-sensitive Andersen's analysis (Hardekopf and Lin, PLDI '07)

Results

- Static analysis
  - Most benchmarks <1s and <320MB
  - *176.gcc* (58s, 2.7GB) and *253.perlbmk* (54s, 1.4GB)
- Runtime overhead (WRT native code)



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Conclusion

- A new static + dynamic analysis for undefined value use detection in C programs
  - Sparse VFG analysis
  - VFG-based optimizations
  - Selective instrumentation
- For even better results?
  - Try more precise pointer analysis

Thank You!