Towards a Globally Scalable Semantics-based Static Analysis

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(co-work with my students and postdocs)

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A Fundamental Challenge in SW

How can we reduce/eliminate errors in software?

- statically: before execution, before sell/embed
- automatically: against explosive sw size
- to find bugs or verify their absence

Our approach:

- "semantics-based static analysis"
- *abstract interpretation*, *type system*, *program logics*, *programming language theories*
- and hodge-podge of engineering

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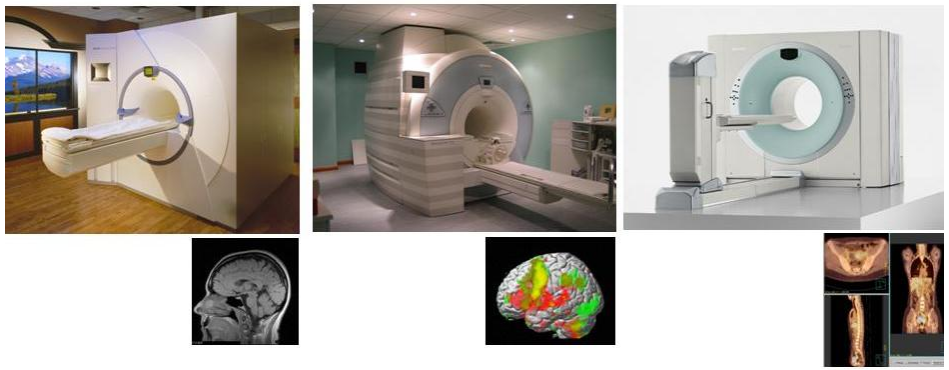
Our Goal

R&D of static software analysis tools:

"SW MRI" "SW fMRI" "SW PET"



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Our Activities

We publicize our works in:

- POPL('06, '11), CAV('08), VMCAI('10, '11), ICSE('11), SAS, OOPSLA, FSE, etc.
- ACM TOPLAS, TCS, JFP, SP&E, Acta Informatica, etc.

A commercialization:

Sparrow
The Early Bird

Research areas: *static analysis, abstract interpreation, programming languge theory, type system, & whatever relevant*

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Talk Outline

1. Short overview of SPARROW: scalable yet non-global bug finder for C
2. New localization technology for scalable & global SPARROW
3. Concluding remark

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Sparrow System

Motivation

- prove by ourselves that static analysis is "useful in real world"

Status

- *shallow property, full automation, scalable*
  - C's buffer overrun, memory leak, null deref., / by zero, $\cdots$
- for *non domain-specific* C code
- detection ratio: $\sim$6/KLOC, speed: $\sim$100Loc/sec

From the elusive three (deep property, scalability, automation)

– deep property

\+ domain-independence

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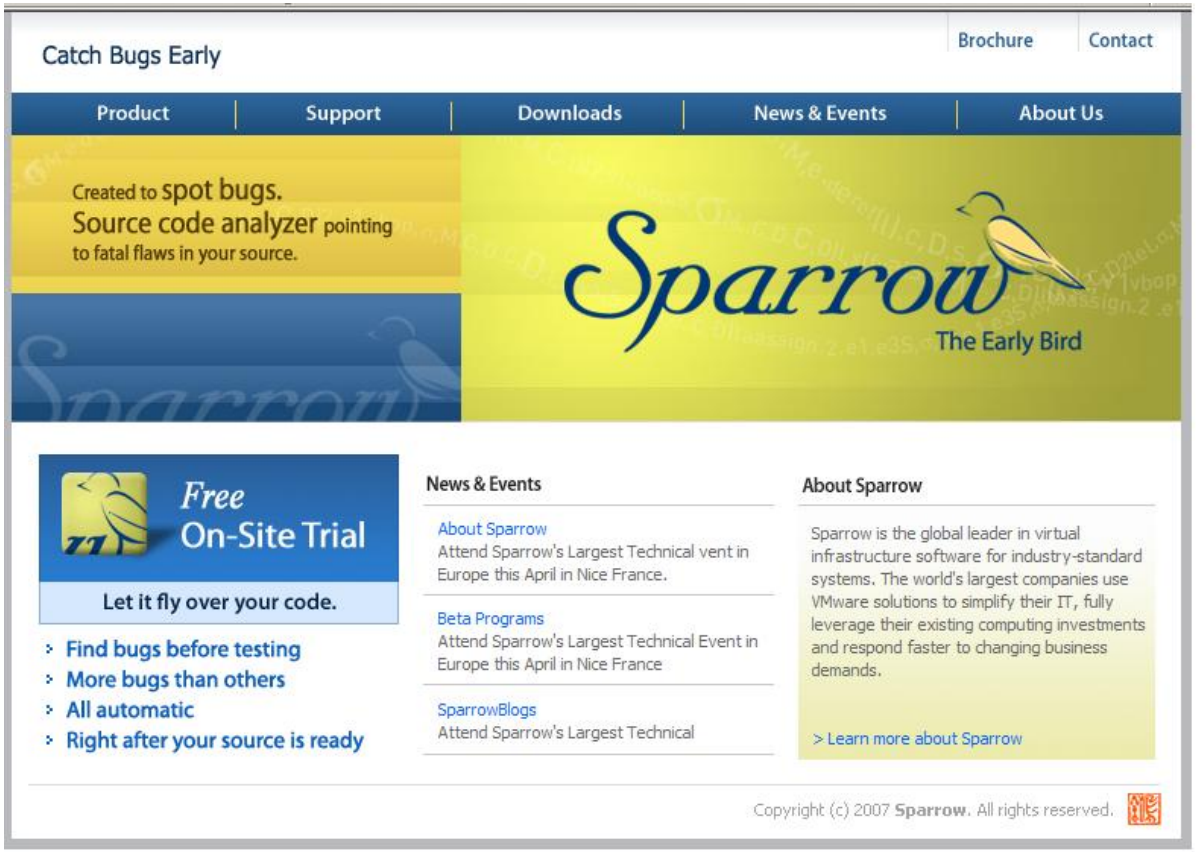
spa-arrow.com



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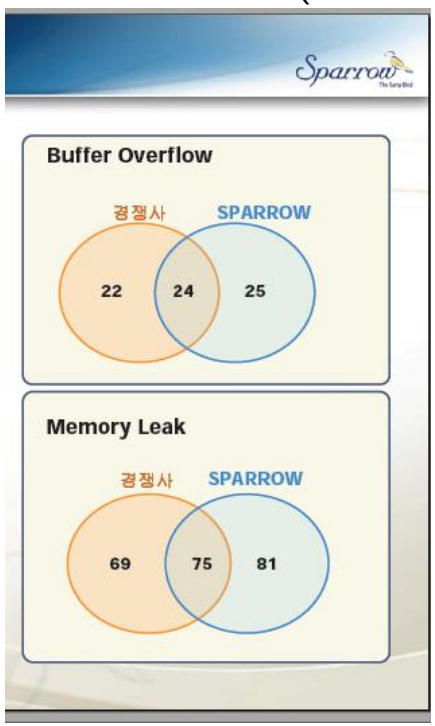
Customers

Domestic market at the moment

- electronics companies: Samsung, LG, $\cdots$
- network switching system sw developers
- other embedded sw developers
- bank system sw developers
- etc.

Complementing others (Coverity, GrammaTech, Klockworks, Polyspace).

- BMT at a site (a network device OS, $\sim$ 700KLOC):



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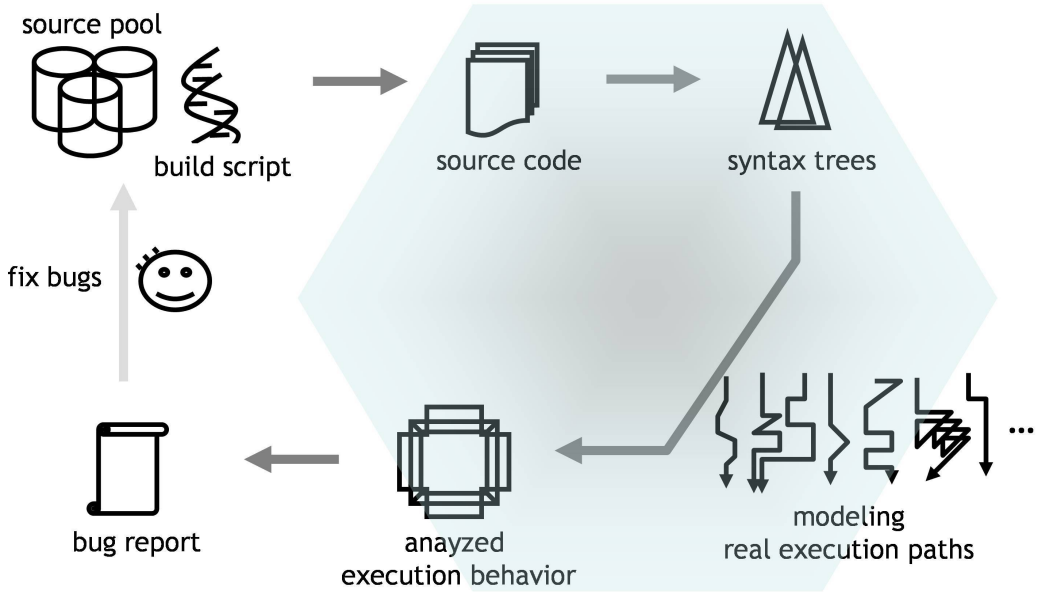
Steps of Sparrow

Sparrow is a one-button solution with four steps:



Performance Numbers (1/2)

Memory leak detection (SPEC2000 and open sources)

Programs	Size KLOC	Time (sec)	True Alarms	False Alarms
art	1.2	0.68	1	0
equake	1.5	1.03	0	0
mcf	1.9	2.77	0	0
bzip2	4.6	1.52	1	0
gzip	7.7	1.56	1	4
parser	10.9	15.93	0	0
ammp	13.2	9.68	20	0
vpr	16.9	7.85	0	9
crafty	19.4	84.32	0	0
twolf	19.7	68.80	5	0
mesa	50.2	43.15	9	0
vortex	52.6	34.79	0	1
gap	59.4	31.03	0	0
gcc	205.8	1330.33	44	1
gnuchess-5.07	17.8	9.44	4	0
tcl8.4.14	17.9	266.09	4	4
hanterm-3.1.6	25.6	13.66	0	0
sed-4.0.8	26.8	13.68	29	31
tar-1.13	28.3	13.88	5	3
grep-2.5.1a	31.5	22.19	2	3
openssh-3.5p1	36.7	10.75	18	4
bison-2.3	48.4	48.60	4	1
openssh-4.3p2	77.3	177.31	1	7
fftw-3.1.2	184.0	15.20	0	0
httpd-2.2.2	316.4	102.72	6	1
net-snmp-5.4	358.0	201.49	40	20
binutils-2.13.1	909.4	712.09	228	25

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Performance Numbers (2/2)

Buffer overrun detection (SPEC2000 and open sources)

Programs	Size KLOC	Time (sec)	True Alarms	False Alarms
art	1.2	0.45	0	0
equake	1.5	2.89	0	1
mcf	1.9	0.33	0	0
bzip2	4.6	10.90	23	29
gzip	7.7	3.38	18	24
parser	10.9	260.94	4	13
twolf	19.7	8.59	0	0
ammp	13.2	10.20	6	0
vpr	16.9	11.15	0	3
crafty	19.4	139.80	1	5
mesa	50.2	47.88	2	10
vortex	52.6	40.12	2	0
gap	59.4	28.48	0	2
gzip-1.2.4	9.1	8.55	0	17
gnuchess-5.07	17.8	179.58	1	8
tcl8.4.14/unix	17.9	585.99	1	14
hanterm-3.1.6	25.6	52.25	34	1
sed-4.0.8	26.8	49.34	2	11
tar-1.13	28.3	57.98	1	10
grep-2.5.1a	31.5	47.26	0	1
bison-2.3	48.4	281.84	0	18
openssh-4.3p2	77.3	97.69	0	9
fftw-3.1.2	184.0	102.17	9	4
httpd-2.2.2	316.4	265.43	10	33
net-snmp-5.4	358.0	899.73	3	36

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Sparrow-detected Overrun Errors (1/3)

- in Linux Kernel 2.6.4

```
625       for (minor = 0; minor < 32 && acm_table[minor]; minor++);
...       ...
713       acm_table[minor] = acm;
```

- in a proprietary code

```
if (length >= NET_MAX_LEN)
   return API_SET_ERR_NET_INVALID_LENGTH;
...
buff[length] |= (num << 4);
```

- in a proprietary code

```
imi_send_to_daemon(PM_EAP, CONFIG_MODE, set_str, sizeof(set_str));
...
imi_send_to_daemon(int module, int mode, char *cmd, int len)
{
...
        strncpy(cmd, reply.str, len);
        cmd[len] = 0;
```

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Sparrow-detected Leak Errors (2/3)

- in sed-4.0.8/regexp_internal.c

```
948:   new_nexts = re_realloc (dfa->nexts, int, dfa->nodes_alloc);
949:   new_indices = re_realloc (dfa->org_indices, int, dfa->nodes_alloc);
950:   new_edests = re_realloc (dfa->edests, re_node_set, dfa->nodes_alloc);
951:   new_eclosures = re_realloc (dfa->eclosures, re_node_set,
952:       dfa->nodes_alloc);
953:   new_inveclosures = re_realloc (dfa->inveclosures, re_node_set,
954:  dfa->nodes_alloc);
955:   if (BE (new_nexts == NULL || new_indices == NULL
956:   || new_edests == NULL || new_eclosures == NULL
957:   || new_inveclosures == NULL, 0))
958:     return -1;
```

- in proprietary code

```
line = read_config_read_data(ASN_INTEGER, line,
                             &StorageTmp->traceRouteProbeHistoryHAddrType,
                             &tmpint);
...
line = read_config_read_data(ASN_OCTET_STR, line,
                             &StorageTmp->traceRouteProbeHistoryHAddr,
                             &StorageTmp->traceRouteProbeHistoryHAddrLen);
...
if (StorageTmp->traceRouteProbeHistoryHAddr == NULL) {
     config_perror
         (``invalid specification for traceRouteProbeHistoryHAddr'');
     return SNMPERR_GENERR;
}
```

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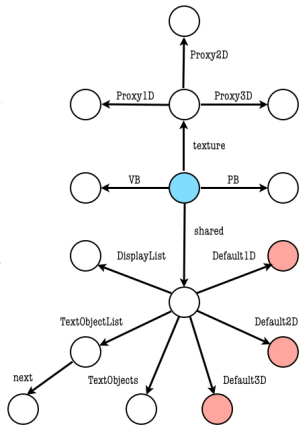
SPARROW-detected Leak Errors (3/3)

- in `mesa/osmesa.c`(in SPEC 2000)

```
276:   osmesa->gl_ctx = gl_create_context( osmesa->gl_visual );
...
287:     gl_destroy_context( osmesa->gl_ctx );
------------------
1164: GLcontext *gl_create_context( GLvisual *visual,
                            GLcontext *share_list,
                            void *driver_ctx )
...
1183:  ctx = (GLcontext *) calloc( 1, sizeof(GLc
...
1211:     ctx->Shared = alloc_shared_state();
---------------------
476: static struct gl_shared_state *alloc_shared
477: {
...
489: ss->Default1D = gl_alloc_texture_object(ss,
490: ss->Default2D = gl_alloc_texture_object(ss,
491: ss->Default3D = gl_alloc_texture_object(ss, 0, 3);
----------------------
1257: void gl_destroy_context( GLcontext *ctx )
1258: {
      ...
1274: free_shared_state( ctx, ctx->Shared );
```



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Sparrow Approach: Pure Soup + Impure Catalysts

Pure soup

- firm formalization of basis: a simple & "sound" abstract interpretation

Impure catalysts

- unorthodox & unsound techniques to refine the bug-finding performance

As a pragmatic approach to find prevalent true errors

- miss rare true cases, reduce many false alarms

Towards Globally Scalable Sparrow

A New Localization Technology of Abstract Memories

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Motivation

Big cost of global analysis by SPARROW

Program	LOC	Time	Mem
bc-1.06	13,093	13,879s	335MB
twolf	19,700	27,230s	1,199MB
less-382	23,822	137,827s	1,480MB

1.6 days

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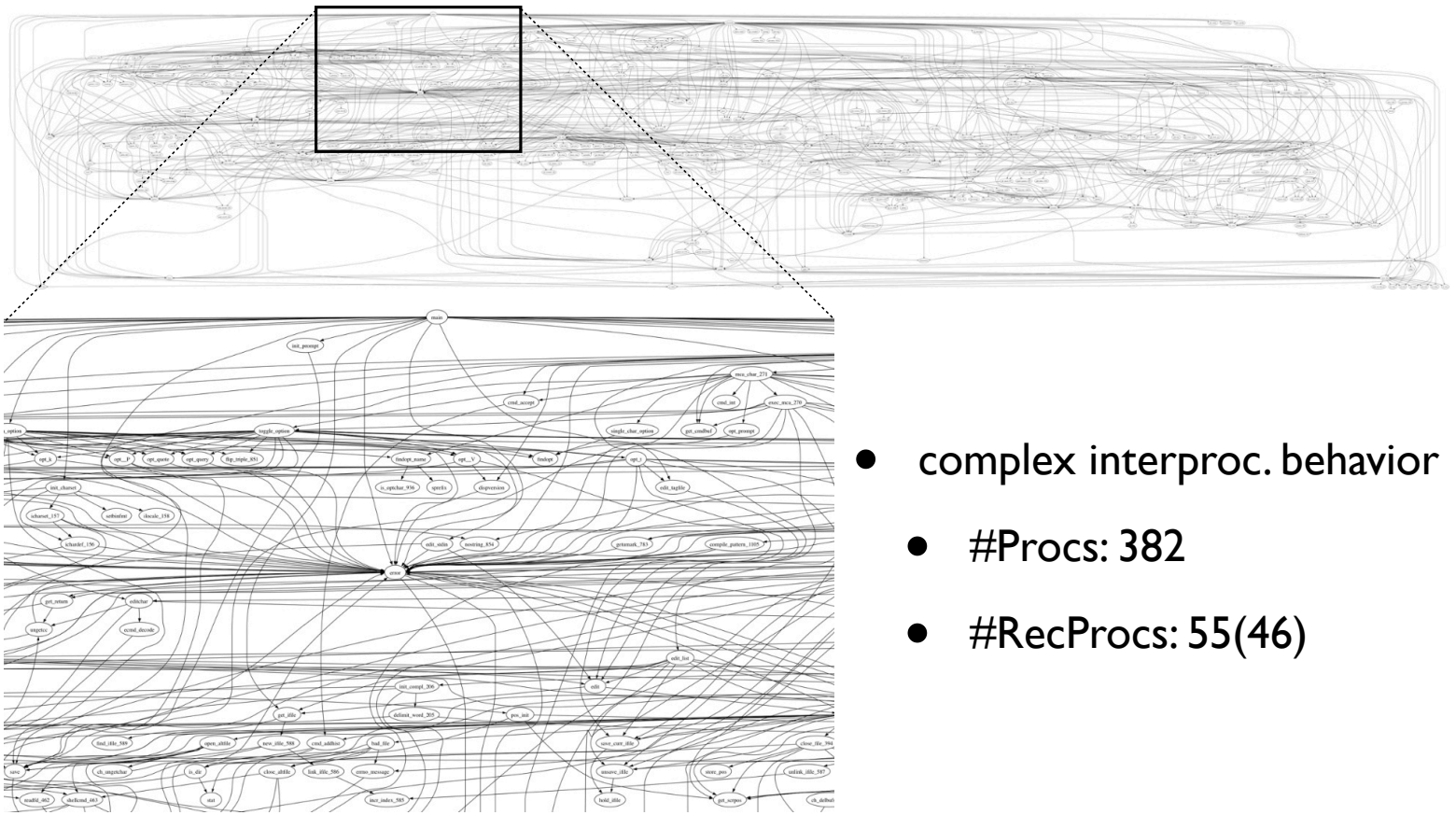
Real-World Programs

less-382, 23,822 LOC



- complex interproc. behavior
  - #Procs: 382
  - #RecProcs: 55(46)

Bottleneck: Re-analysis

- In global analysis, procedures are wastefully re-analyzed by changes to input states.

```
int f() {...}
int m() {
  g = 1; f();
  g = 2; f();}
```

Suppose f does not access g

Change of g has no impact on the analysis of f

- One major reason for big global analysis cost.

program	LOC	Repeated analyses of procedures
gzip	7,327	211
parser	10,900	601
bc	13,093	1,151
less	23,822	755

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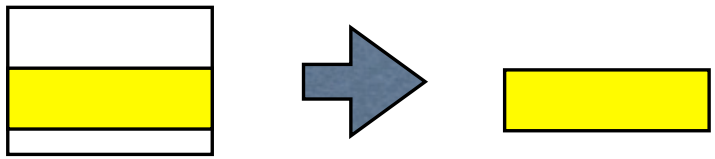
Solution

- When analyzing a procedure, pass only the memory parts that is necessary to analyze the procedure.



- Localization reduces re-analysis.

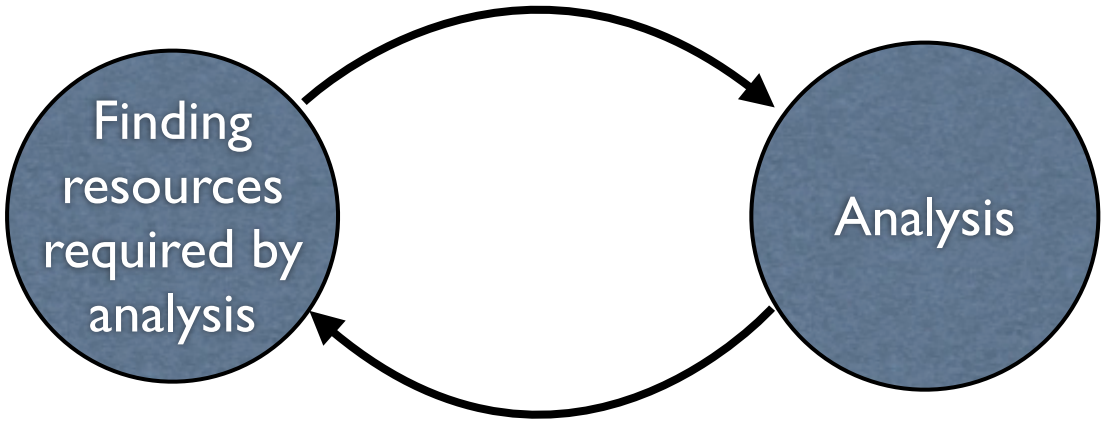
```
int f() {...}
int m() {
  g = 1; f();
  g = 2; f();}
```

Assume f does not access g

Need not to analyze f again

A Catch 22 Situation

- How to find the memory parts that will be used during the *a*nalysis before the analysis



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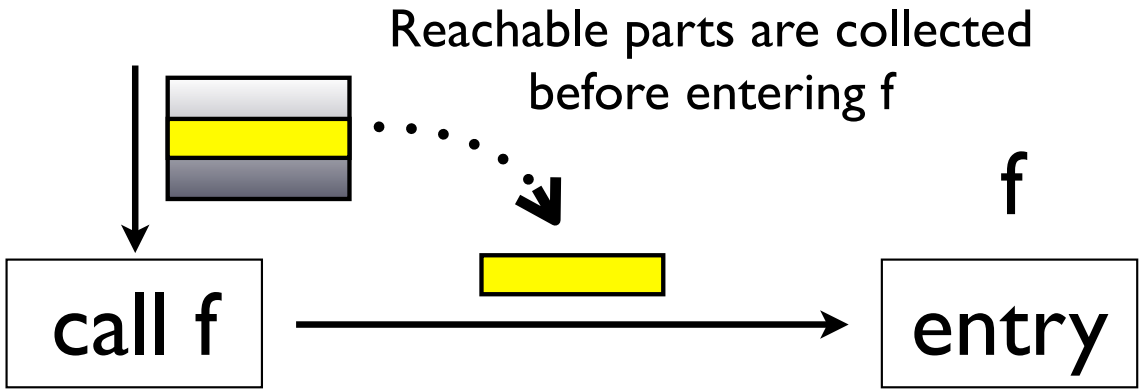
Status Quo: Reachability-based Approach (Abstract Garbage Collection)

- Approximate what will be used by removing the unreachable from parameters and globals
- Conventional in control flow analysis, shape analysis, ...



Safe, but Crude

- Accessed parts are a tiny subset of the reachable
  - ex) only a small number of globals are actually accessed in a procedure

Program	LOC	accessed memory / reachable memory
spell-1.0	2,213	5 / 453 (1.1%)
barcode-0.96	4,460	19 / 1175 (1.6%)
httptunnel-3.3	6,174	10 / 673 (1.5%)
gzip-1.2.4a	7,327	22 / 1002 (2.2%)
jwhois-3.0.1	9,344	28 / 830 (3.4%)
parser	10,900	75 / 1787 (4.2%)
bc-1.06	13,093	24 / 824 (2.9%)
less-290	18,449	86 / 1546 (5.6%)

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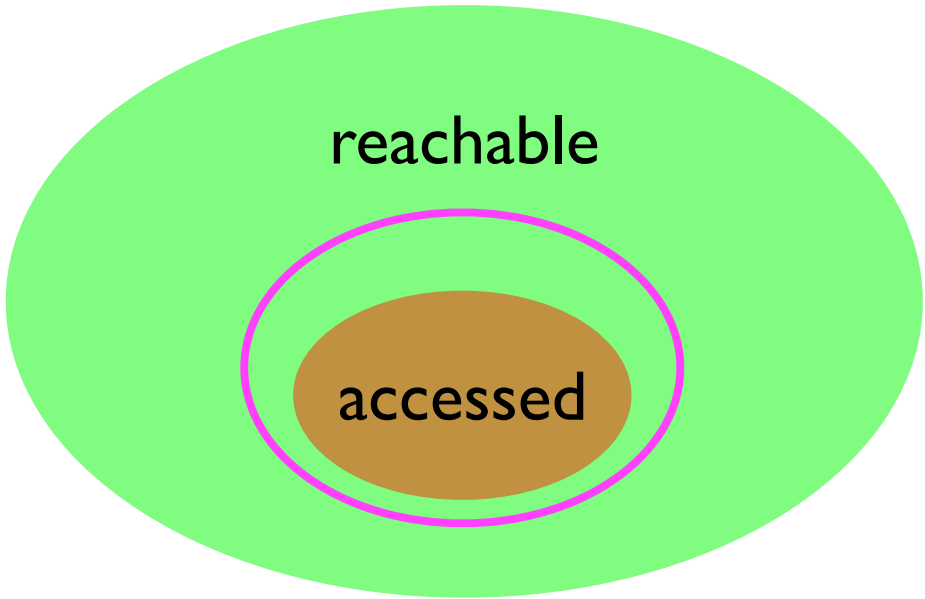
Our Approach

- More aggressive than reachability
  - Exclude some reachable that will not be accessed



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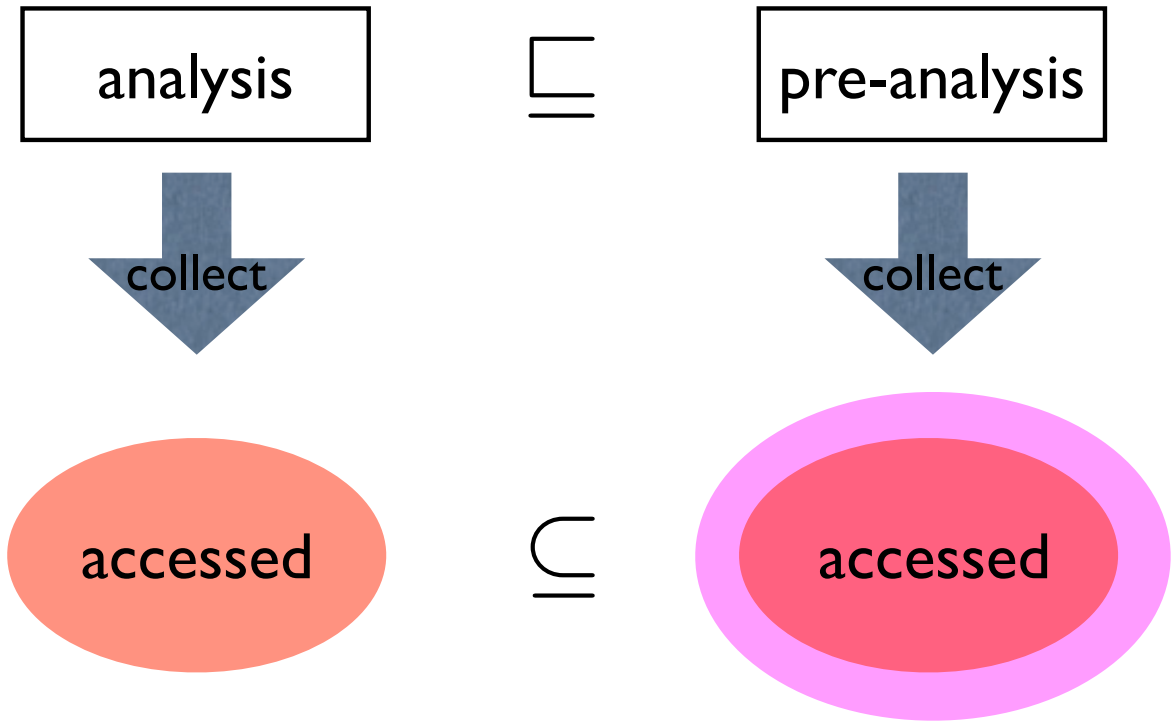
How?

- Basically, perform the analysis once more.
  - using a further abstraction of the analysis



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How to Get the Further Abstraction?

- Easy in our case, because the underlying analysis is designed as an abstract interpretation.
- Just apply conservative abstractions to the abstract semantics of the original analysis.

Original analysis

$$\hat{\mathcal{D}} = Node \to \hat{Mem}$$

$$\hat{\mathcal{F}} : \hat{\mathcal{D}} \to \hat{\mathcal{D}}$$
$$\hat{\mathcal{F}} = \lambda T.\lambda n.\hat{f}_n\ (\bigsqcup_{p \in \text{predof}(n)} T(p))$$

Pre-analysis

$$\hat{\mathcal{D}}_{pre} = \hat{Mem}$$

$$\hat{\mathcal{F}}_{pre} : \hat{\mathcal{D}}_{pre} \to \hat{\mathcal{D}}_{pre}$$
$$\hat{\mathcal{F}}_{pre} = \lambda m.(\bigsqcup_{n \in Node} \hat{f}_n(m))$$

ignore statements orders

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Collecting Abstract Locations

- Access functions collects accessed abstract locations.
  - naturally derived from the definitions of the abstract semantics

abstract semantics

$$
\begin{aligned}
\hat{\mathcal{V}}(n)(\hat{m}) &= \langle [n,n], \bot, \bot, \bot \rangle \\
\hat{\mathcal{V}}(e_1 \texttt{ + } e_2)(\hat{m}) &= \hat{\mathcal{V}}(e_1)(\hat{m}) \hat{+} \hat{\mathcal{V}}(e_2)(\hat{m}) \\
\hat{\mathcal{V}}(lv)(\hat{m}) &= \bigsqcup \{ \hat{m}(A\hat{d}dr) \mid \\
&\qquad A\hat{d}dr \in \hat{\mathcal{L}}(lv)(\hat{m}) \} \\
\hat{\mathcal{V}}(\&lv)(\hat{m}) &= \langle \bot, \hat{\mathcal{L}}(lv)(\hat{m}), \bot, \bot \rangle
\end{aligned}
$$

$$
\begin{aligned}
\hat{\mathcal{L}}(x)(\hat{m}) &= \{x\} \\
\hat{\mathcal{L}}(*e)(\hat{m}) &= \hat{\mathcal{V}}(e)(\hat{m}).2 \cup \{ l \mid \langle l, o, s \rangle \in \hat{\mathcal{V}}(e)(\hat{m}).3 \} \\
&\qquad \cup \{ \langle l, x \rangle \mid \langle l, \{x\} \rangle \in \hat{\mathcal{V}}(e)(\hat{m}).4 \} \\
\hat{\mathcal{L}}(e_1 \texttt{[}e_2\texttt{]})(\hat{m}) &= \{ l \mid \langle l, o, s \rangle \in \hat{\mathcal{V}}(e_1)(\hat{m}).3 \} \\
\hat{\mathcal{L}}(e\texttt{.}x)(\hat{m}) &= \{ \langle l, x \rangle \mid \langle l, \{x\} \rangle \in \hat{\mathcal{V}}(e)(\hat{m}).4 \}
\end{aligned}
$$

access functions

$$
\begin{aligned}
\hat{\mathcal{AV}}(n)(\hat{m}) &= \emptyset \\
\hat{\mathcal{AV}}(e_1 \texttt{ + } e_2)(\hat{m}) &= \hat{\mathcal{AV}}(e_1)(\hat{m}) \cup \hat{\mathcal{AV}}(e_2)(\hat{m}) \\
\hat{\mathcal{AV}}(lv)(\hat{m}) &= \hat{\mathcal{AL}}(lv)(\hat{m}) \cup \hat{\mathcal{L}}(lv)(\hat{m}) \\
\hat{\mathcal{AV}}(\&lv)(\hat{m}) &= \hat{\mathcal{AL}}(lv)(\hat{m})
\end{aligned}
$$

$$
\begin{aligned}
\hat{\mathcal{AL}}(x)(\hat{m}) &= \emptyset \\
\hat{\mathcal{AL}}(*e)(\hat{m}) &= \hat{\mathcal{AV}}(e)(\hat{m}) \\
\hat{\mathcal{AL}}(e_1 \texttt{[}e_2\texttt{]})(\hat{m}) &= \hat{\mathcal{AV}}(e_1)(\hat{m}) \\
\hat{\mathcal{AL}}(e\texttt{.}x)(\hat{m}) &= \hat{\mathcal{AV}}(e)(\hat{m})
\end{aligned}
$$

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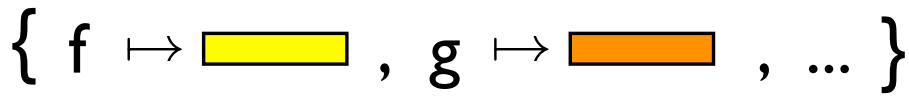
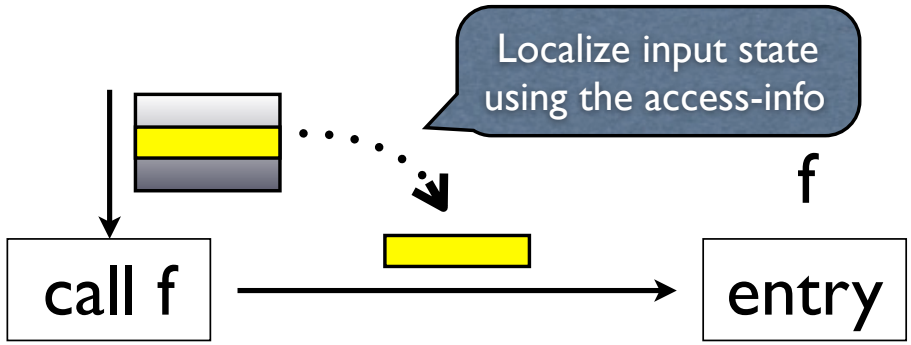
Access-based Localization at Procedure Calls

1. Access-analysis



2. Actual analysis



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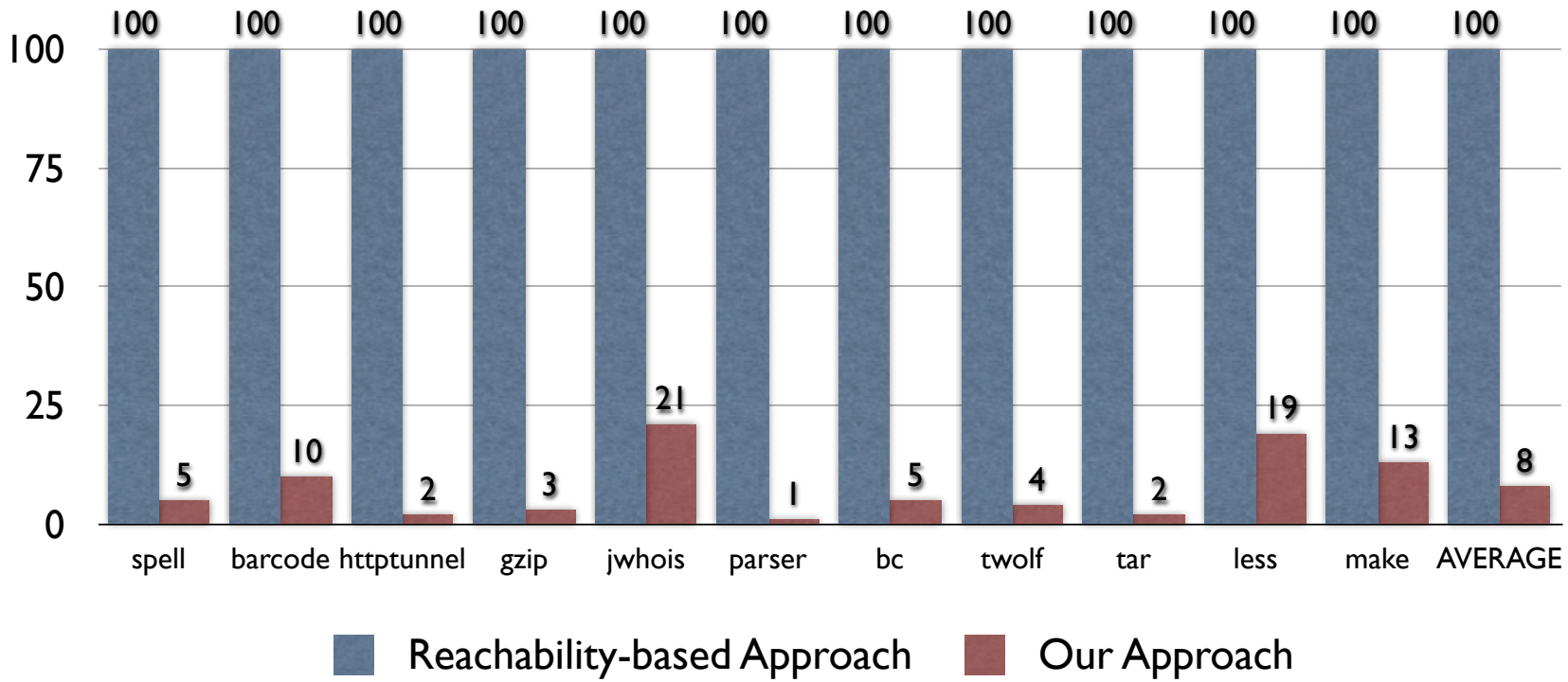
Performance

On average 92% reduction in time



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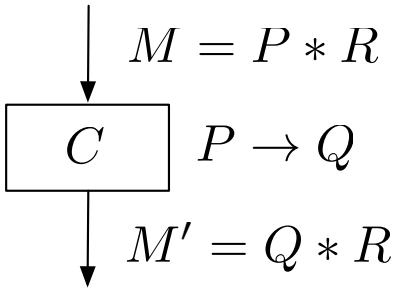
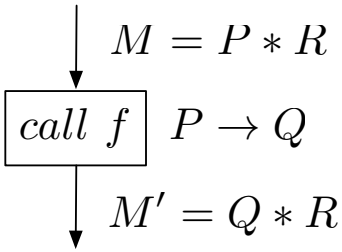
Access-based Localization at Everywhere

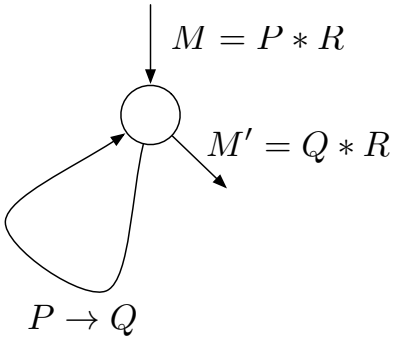
- We can apply access-based localization to any code block C.



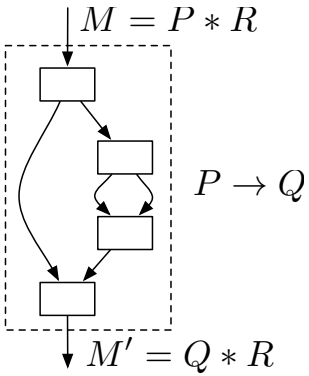
procedures



loops



branches



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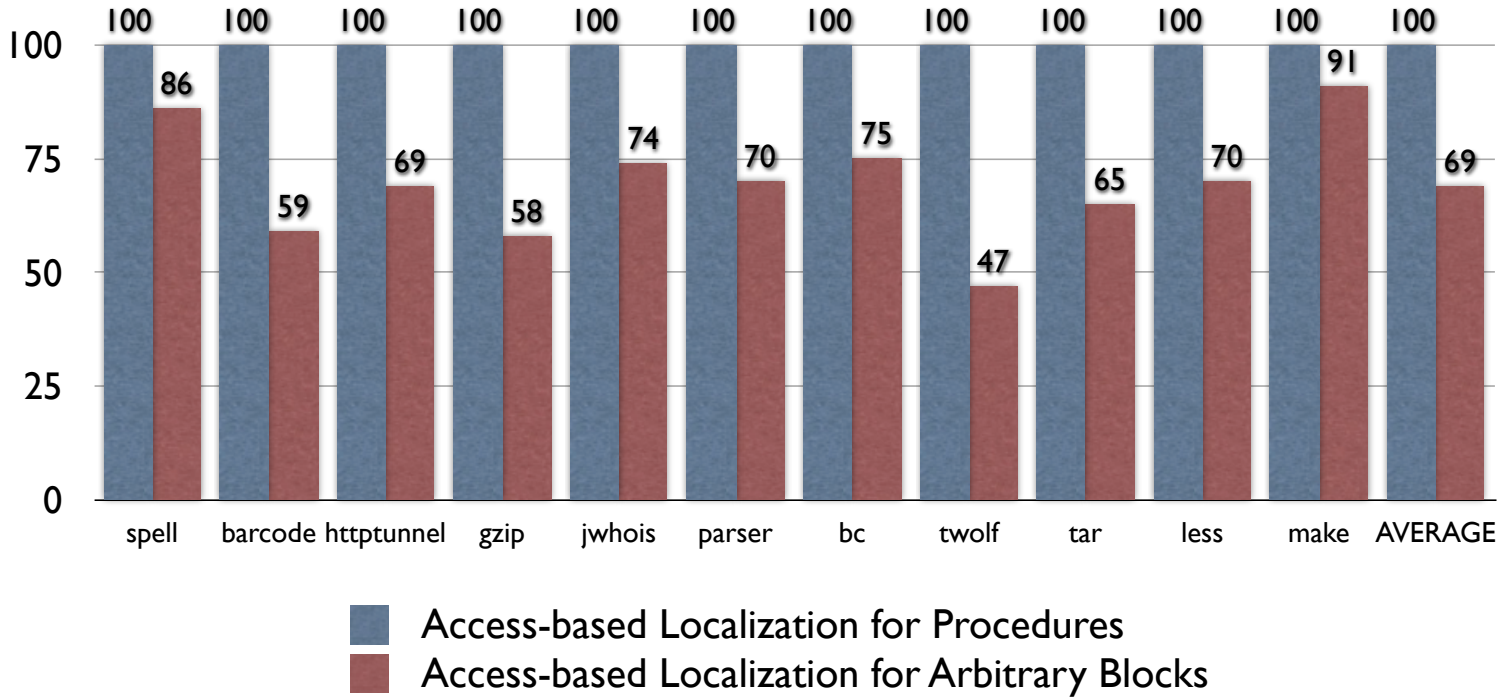
Performance

On average 31% further reduction in time



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Concluding Remark

- Semantics-based static analysis technology: mature to solve realistic problems for sequential C programs
- Our humble proof: SPARROW
- Practical, semantically-dense global analysis for 100 MLoc will soon be possible
- But lots of problems still remain
  - reducing false alarms: cost vs soundness vs reality vs specialization
  - alarm explanation: analysis internals too complex to understand
  - daunting properties to check/verify

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Thank you.

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