Efficient Detection of All Pointer and Array Access Errors

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Outline

- Memory Access Errors
- Motivation
- Basic Methodology
- Check Optimization
- Experimental Evaluation
- Summary and Future Work

Memory Access Errors

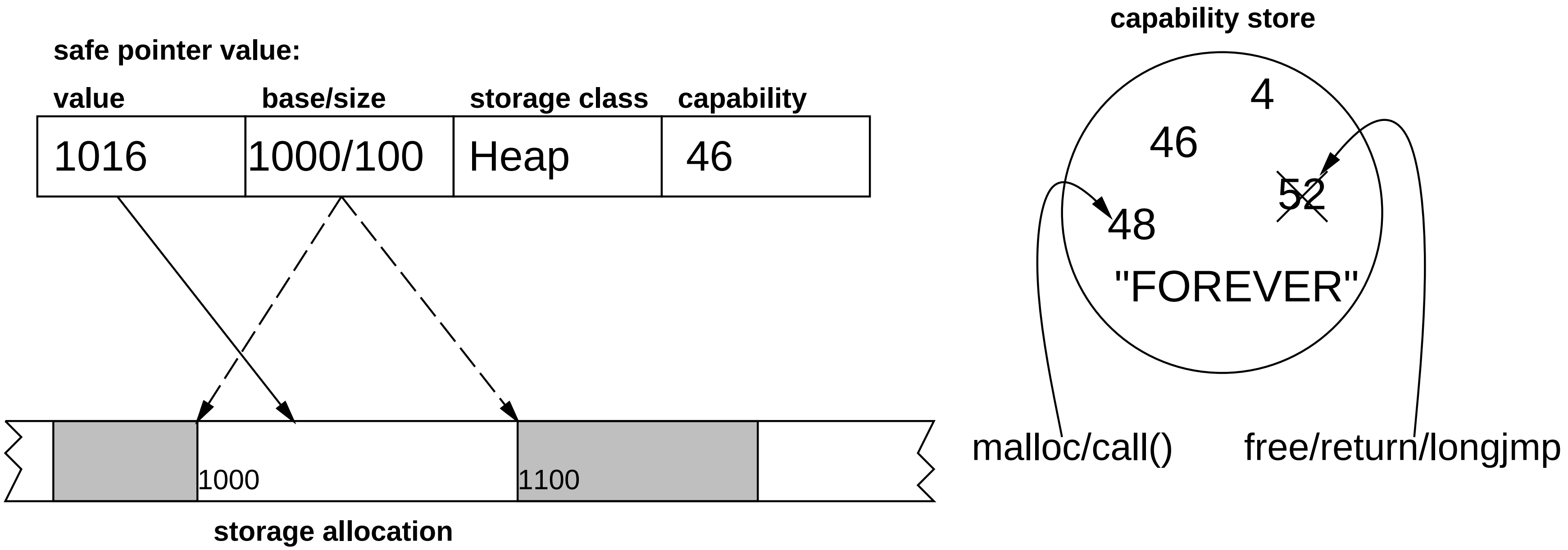
A *memory access error* is any dereference which accesses storage outside of the intended referent.

- *spatial access error*, outside of referent address bounds
- *temporal access error*, outside of referent lifetime
- *intended referent*, the memory object used to create the pointer value (in C, reference created with `malloc()` or `‘&’`)

Motivation

- programming errors are costly
- aggravated by abstraction, parallel programming, and programming in the large
- memory access errors are difficult to find and fix
  - arise under exceptional conditions
  - difficult to reproduce
  - difficult to correlate fault to error
- therefore: need both efficiency and complete coverage

Safe Pointer Abstraction



safe pointer value:

value	**base/size**	**storage class**	**capability**
1016	1000/100	Heap	46

1000

1100

storage allocation

capability store

4

46

~~52~~

48

"FOREVER"

malloc/call()

free/return/longjmp

Valid Dereference:

$$(capability \in capStore) \wedge (base \leq value \leq base + size - sizeof(*value))$$

Safe Pointer Creation, Manipulation, and Use

malloc(sizeof(struct Foo)) **==>**

value	base/size	storage class	capability
2000	2000/32	Heap	52

&p−>next−>status **==>**

value	base/size	storage class	capability
4032	4032/4	Local	36

value	base/size	storage class	capability
1010	1000/100	Heap	46

+ 6 **==>**

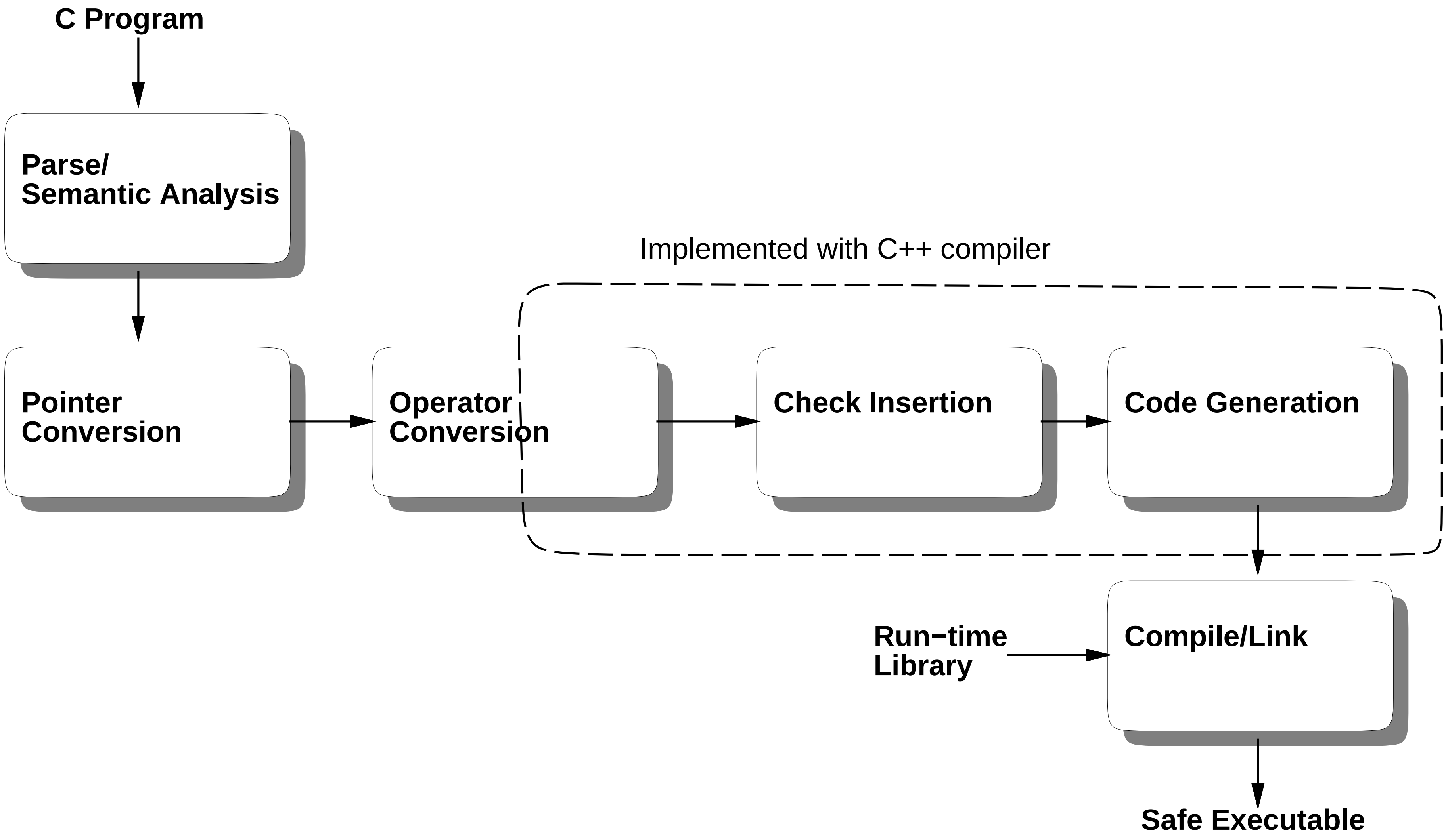
value	base/size	storage class	capability
1016	1000/100	Heap	46

deref

value	base/size	storage class	capability
1010	1000/100	Heap	46

==> **perform access check**

Program Transformations



C Program

Parse/
Semantic Analysis

Implemented with C++ compiler

Pointer Conversion

Operator Conversion

Check Insertion

Code Generation

Run−time Library

Compile/Link

Safe Executable

Requisites of Complete Coverage

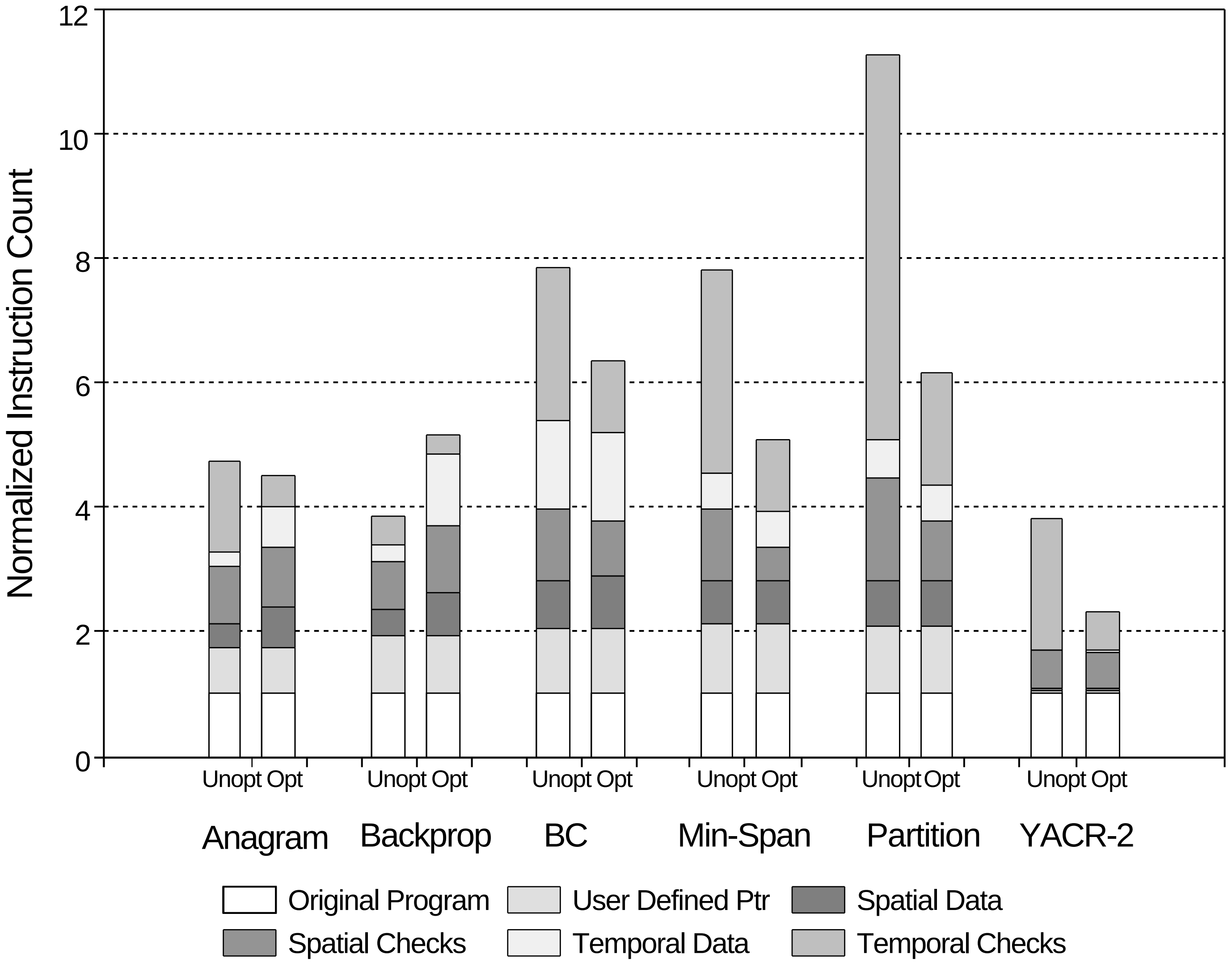
- storage management must be apparent
  - systems programmer can assist with API
- pointer constants must be well defined
  - NULL, functions, strings are ok, others use API
- object attributes must be preserved
  - cannot be manipulated by program
  - cannot be lost
  - “well behaved” programs can be checked efficiently

Check Optimization

A check at a dereference of pointer value v may be elided at program pointer p if the previous, equivalent check executed on v has not been invalidated by some program action.

- run-time check optimization
  - more flexible, but more run-time overhead
  - eliding capability store searches: free counter
  - eliding range checks: memoization
- compile-time check optimization
  - less flexible, no run-time overhead
  - similar to common subexpression elimination

Execution Overheads



Results

- execution overheads are low enough for development environments (130-540%), not low enough for in-field releases
- greatest slowdown factors:
  - check insertion breaks traditional optimizations
  - C++ templates are problematic
  - safe pointers are not register allocated
- run-time optimization of spatial checks is ineffective
- run-time optimization of temporal checks works well
- text and data size overheads are quite low

Comparison to Other Checking Techniques

- How are intended referents tracked?
  - “fat” pointers vs. no tracking
- How is the state of active memory represented?
  - capability store vs. memory state map
- How is the program instrumented?
  - object- vs. source-level
- What optimizations are applied?
  - spatial and temporal check optimization

Summary

- technique capable of detecting **ALL** memory access errors
- source level program transformations
- works on existing codes, *e.g.*, those written in C/C++
- employs safe pointers → pointer value + referent details
- compile- and run-time access check optimization possible
- 540% overhead for *Partition* (3.7 insts/deref)

Current and Future Work

- re-target compiler from C++ to C
- compile-time check optimization
- run-time check improvements
- back-end integration
- parallel checking
- storage leak detection
- interface issues (libraries, system calls, unsafe code)

- availability: e-mail `austin@cs.wisc.edu`

Temporal Access Error Example

[x,x,x,x,NEVER]
[x,x,x,x,NEVER]
[2000,2000,10,Heap,1]
"
"
"
"

[x,x,x,x,NEVER]
[2000,2000,10,Heap,1]
"
"
"
[2000,2000,10,Heap,2]
"

p

q

capability store

```
char *p, *q;
p = malloc(10);
q = p+6;
*q; /* no error */
free(p);
p = malloc(10);
*q; /* error!!! */
```

{ }
{ 1 }
"
"
{ }
{ 2 }
"

[value, base, size, storageClass, capability]

Analyzed Programs

Program	Instructions		Insts per Dereference		Description
	Static	Dynamic	Static	Dynamic	
`Anagram`	`10.0K`	`19.4M`	`106.3`	`7.6`	`anagram generator`
`Backprop`	`10.8K`	`122.4M`	`148.5`	`8.9`	`neural net trainer`
`GNU BC`	`19.5K`	`12.2M`	`15.5`	`7.6`	`arbitrary precision calc`
`Min-Span`	`11.9K`	`13.3M`	`48.7`	`5.9`	`min spanning tree comp`
`Partition`	`13.5K`	`21.1M`	`62.4`	`3.7`	`graph partitioning tool`
`YACR-2`	`18.5K`	`546.2M`	`37.1`	`14.0`	`VLSI channel router`

Comparison to Other Checking Techniques

- How are intended referents tracked?
  - “fat” pointers (Safe-C, CodeCenter, RTCC, Bcc, UW-Pascal)
  - intended referents are not tracked (Purify)
- How is the state of active memory represented?
  - capability store (Safe-C)
  - memory state map (Purify, CodeCenter)
  - keys stored in heap node headers (UW-Pascal)
  - memory state is not tracked (RTCC, Bcc)
- How is the program instrumented?
  - object-level: (Purify)
  - source-level/compile-time: (Safe-C, RTCC, Bcc, UW-Pascal)
  - run-time: (CodeCenter)