Dr. Memory Uncovered

Derek Bruening

Memory Bugs Are Hard

Internal corruption may not be externally visible

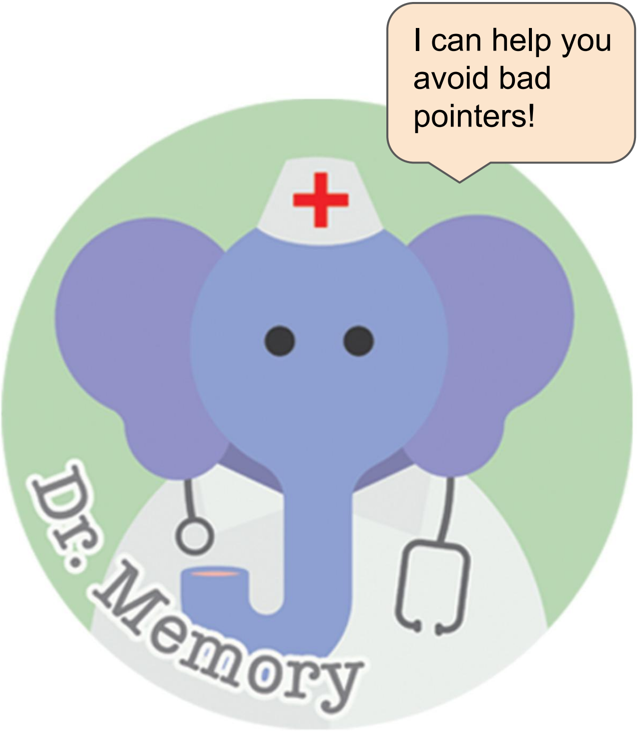
Observable symptoms are often delayed and non-deterministic

Testing usually relies on randomly happening to hit visible symptoms

Often remain in shipped products and can show up in customer usage

Outline

- Introduction
- Memory Bugs, Part 1: Bad Pointers
  - a.k.a. Unaddressable Accesses
- Memory Bugs, Part 2: Bad Values
  - a.k.a. Uninitialized Reads
- Memory Bugs, Part 3: Lost Pointers
  - a.k.a. Memory Leaks
- Implementation
- Related Tools
- History



Approach: Look for Known-Bad Behavior

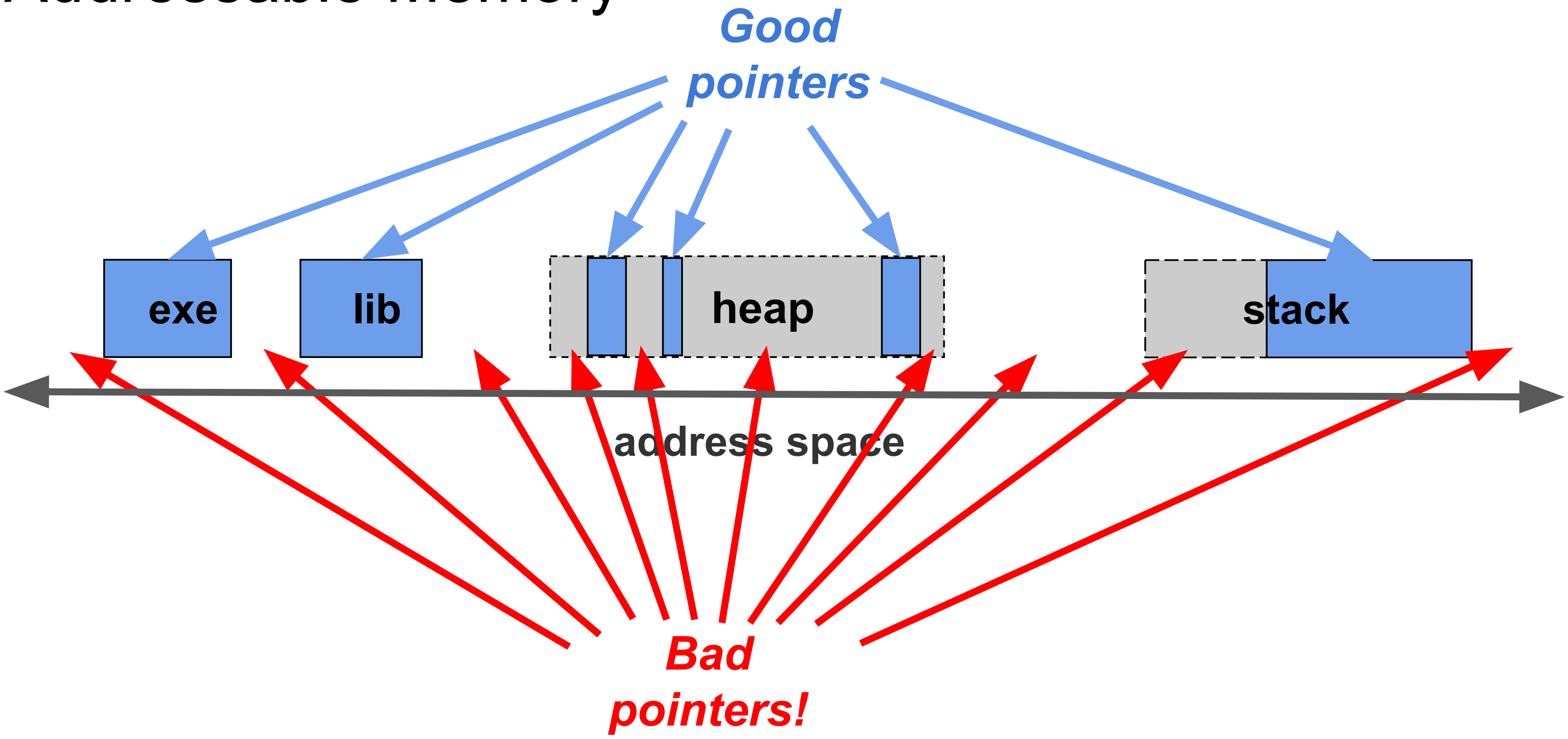
Tracking which pointer corresponds to which variable/object is hard

Thus, knowing where a pointer **should** point is hard

But, knowing where a pointer **should not** point is feasible

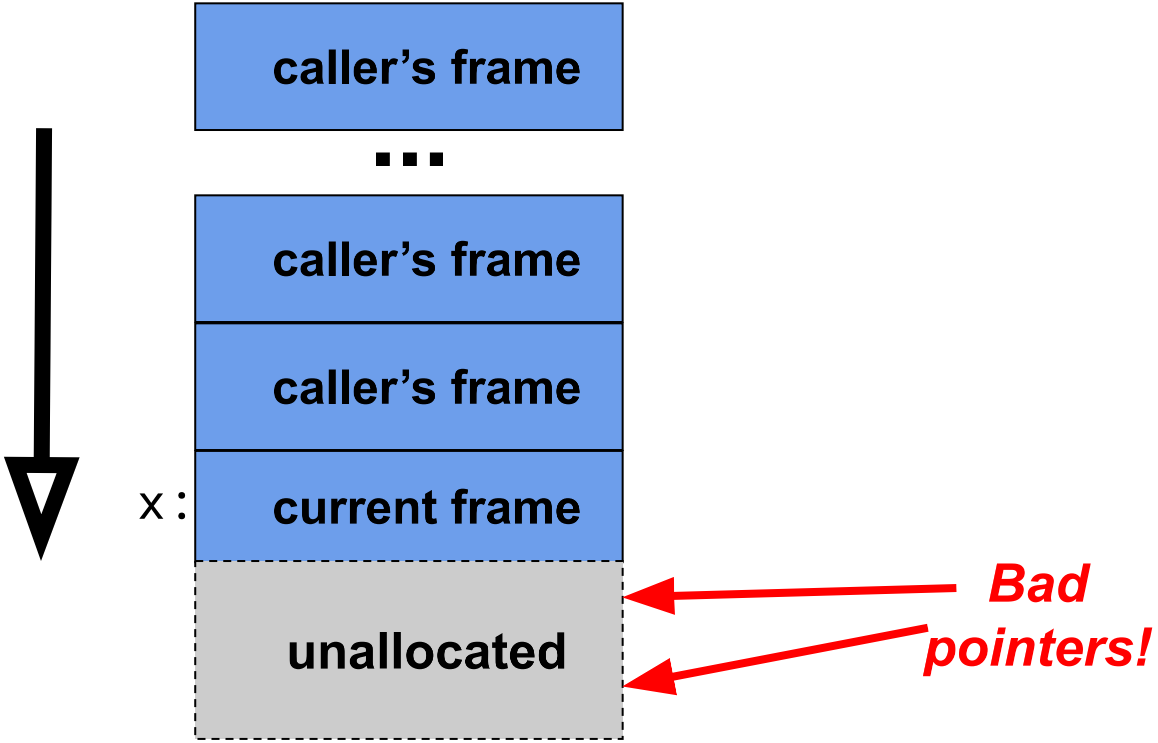
Probabilistic error detection!

Addressable Memory



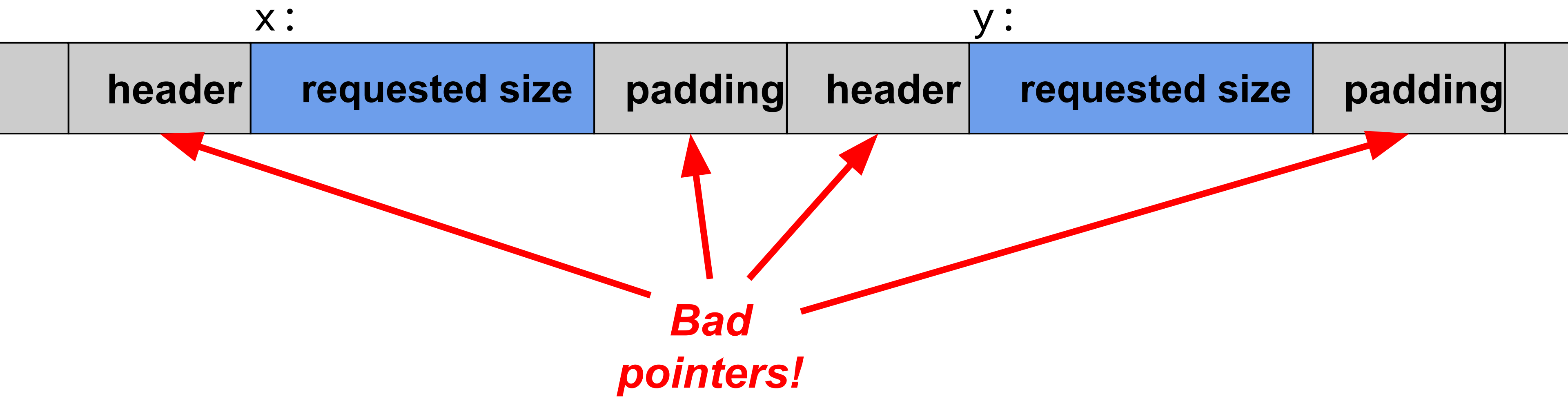
Stack Layout

`int x[16];`



Heap Layout

```
int *x = new int;
int *y = new int;
```



x:

y:

header

requested size

padding

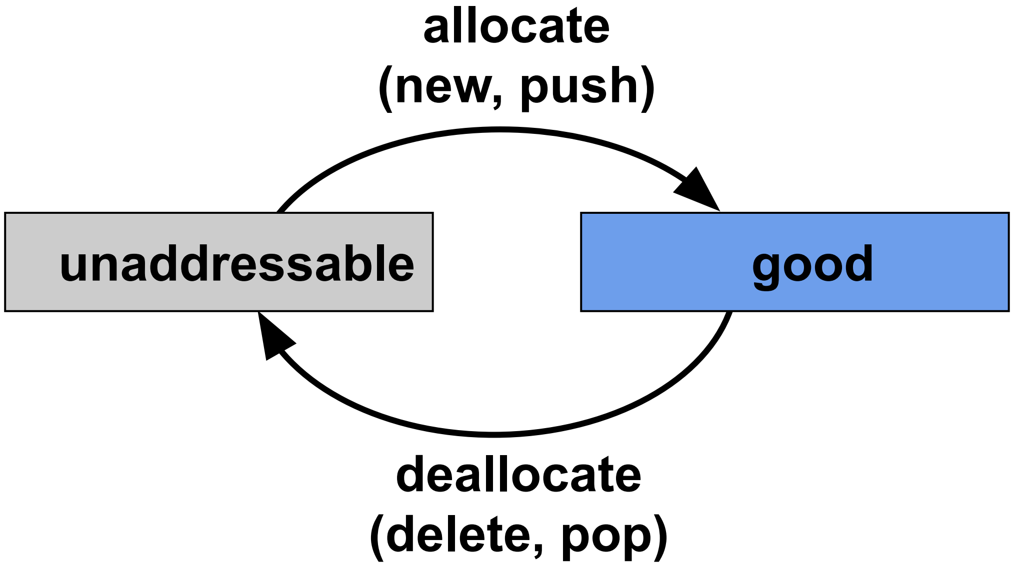
header

requested size

padding

Bad pointers!

Track Good Versus Bad Memory



allocate
(new, push)

unaddressable

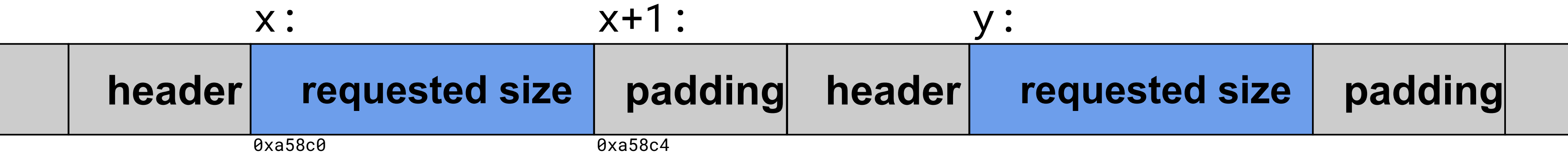
good

deallocate
(delete, pop)

Heap Overflow

```
86: int *x = new int;
87: int *y = new int;
88: *(x+1) = 42;
```

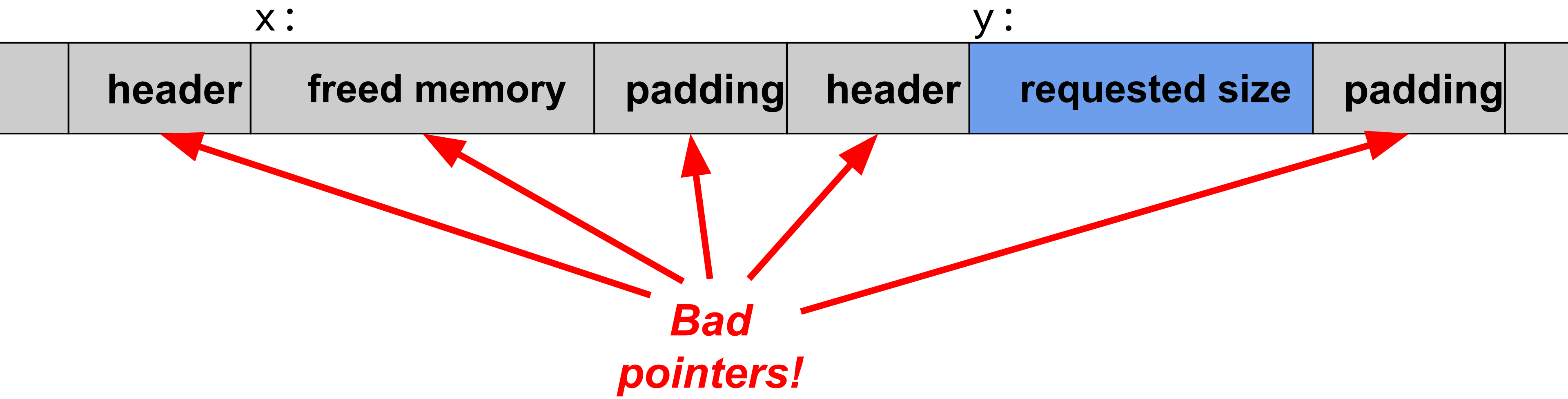
Error!



```
Error #1: UNADDRESSABLE ACCESS
Reading 4 bytes @ 0xa58c4 - 0xa58c8
Next lower object: 0xa58c0 - 0xa58c4
Offending code:
    myapp!main()   myapp.c:88
```

Freed Memory

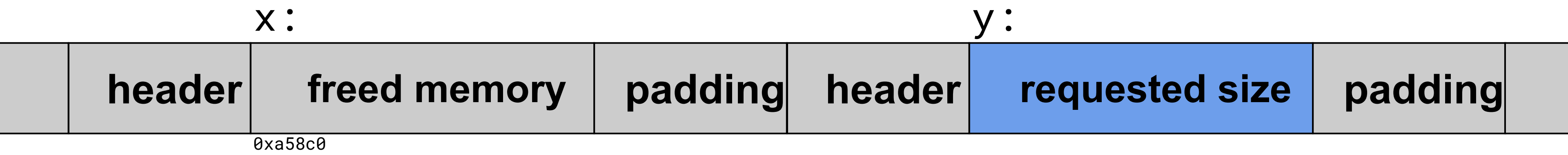
```
int *x = new int;
int *y = new int;
delete x;
```



Use After Free/Delete

```
86: int *x = new int;
87: int *y = new int;
88: delete x;
89: *x = 42;
```

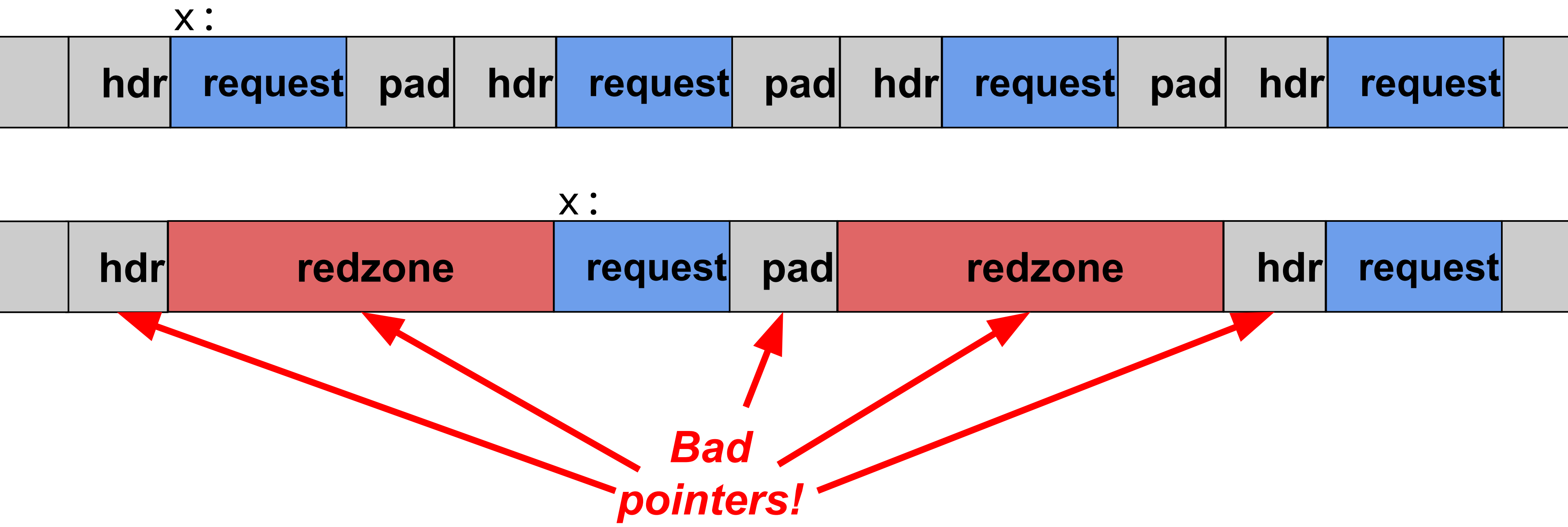
Error!



```
Error #1: UNADDRESSABLE ACCESS
Writing 4 bytes @ 0xa58c0 - 0xa58c4
Write overlaps freed 0xa58c0 - 0xa58c4
Offending code:
    myapp!main()    myapp.c:89
```

Redzones

```
int *x = new int;
std::cout << *(x+8);
```



Bad pointers!

Delayed Frees

When delete or free is called, do not return the memory for re-use.

Also called “quarantine”.

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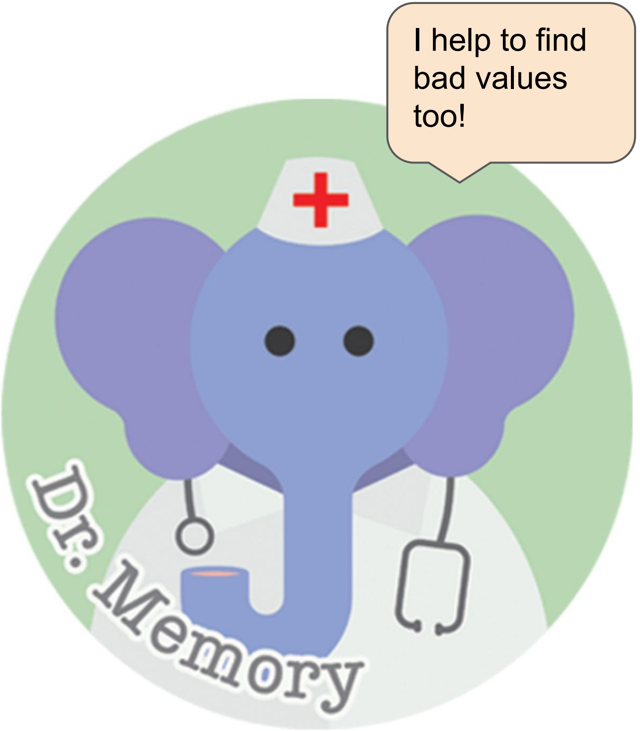

Stack Layout

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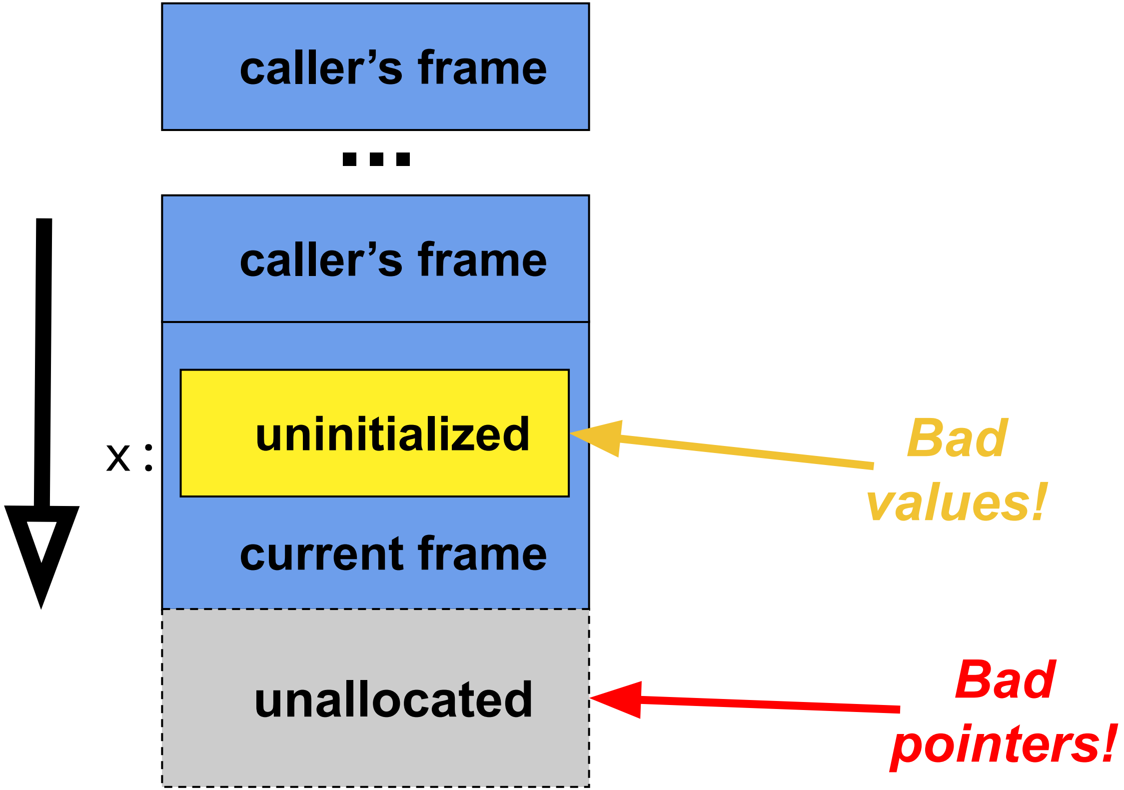
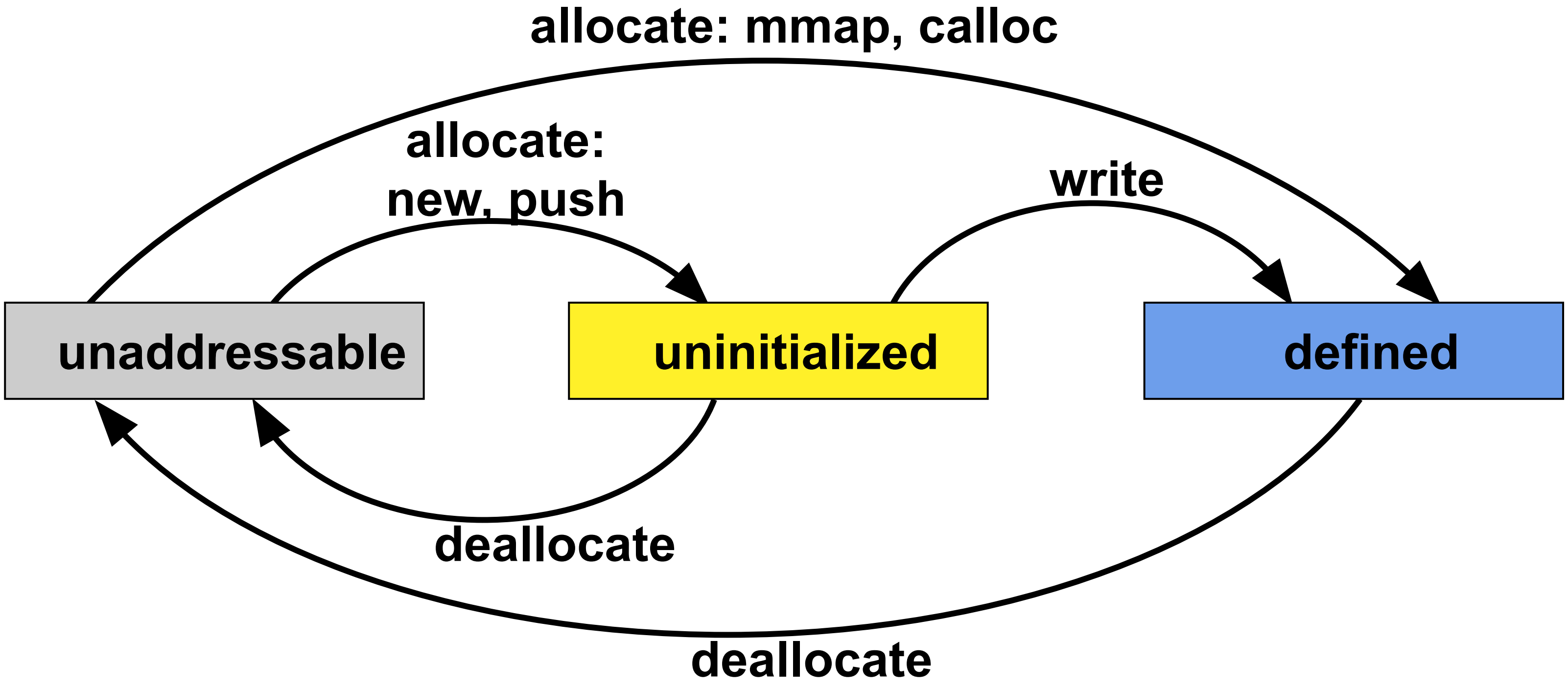
```

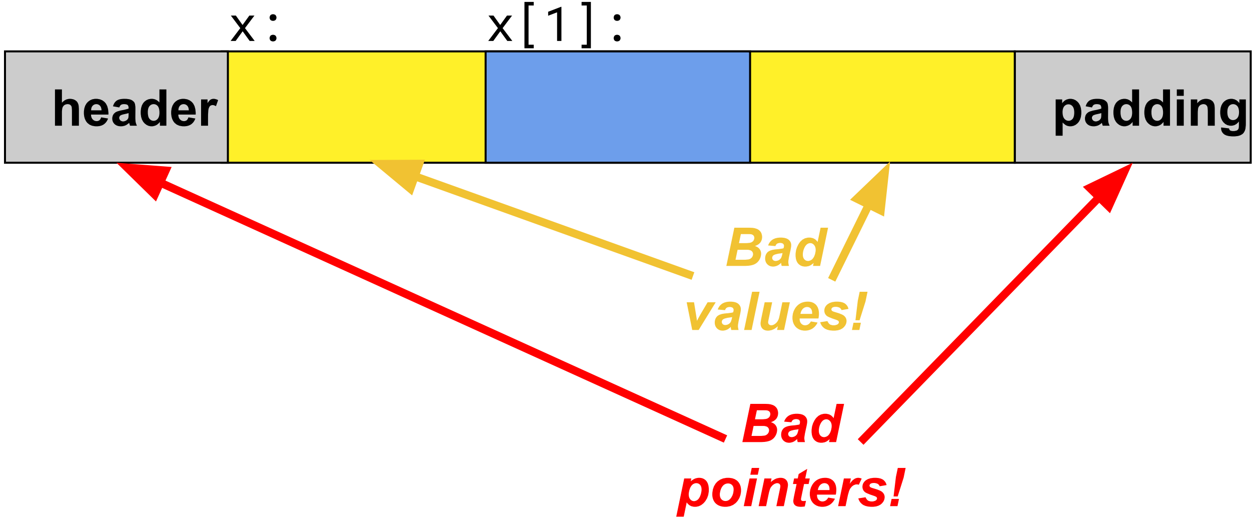


Track Three States of Memory



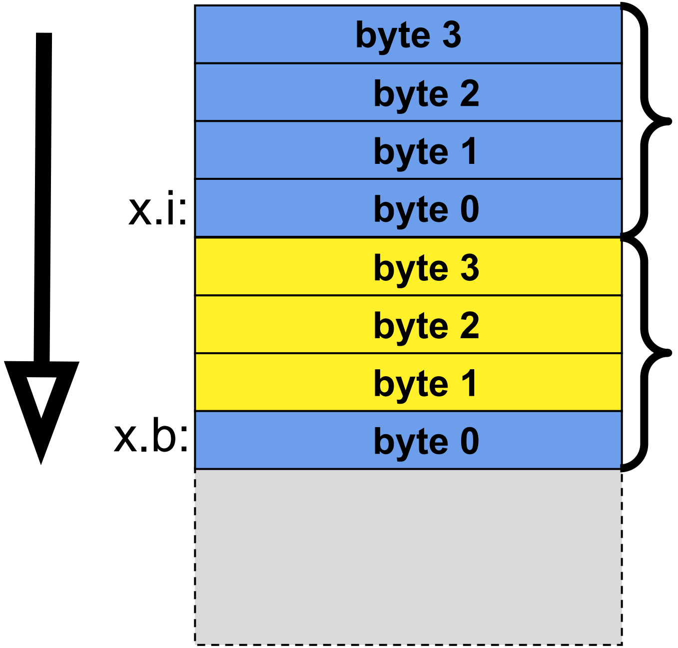
Heap Layout

```
int *x = new int[3];
x[1] = 42;
```

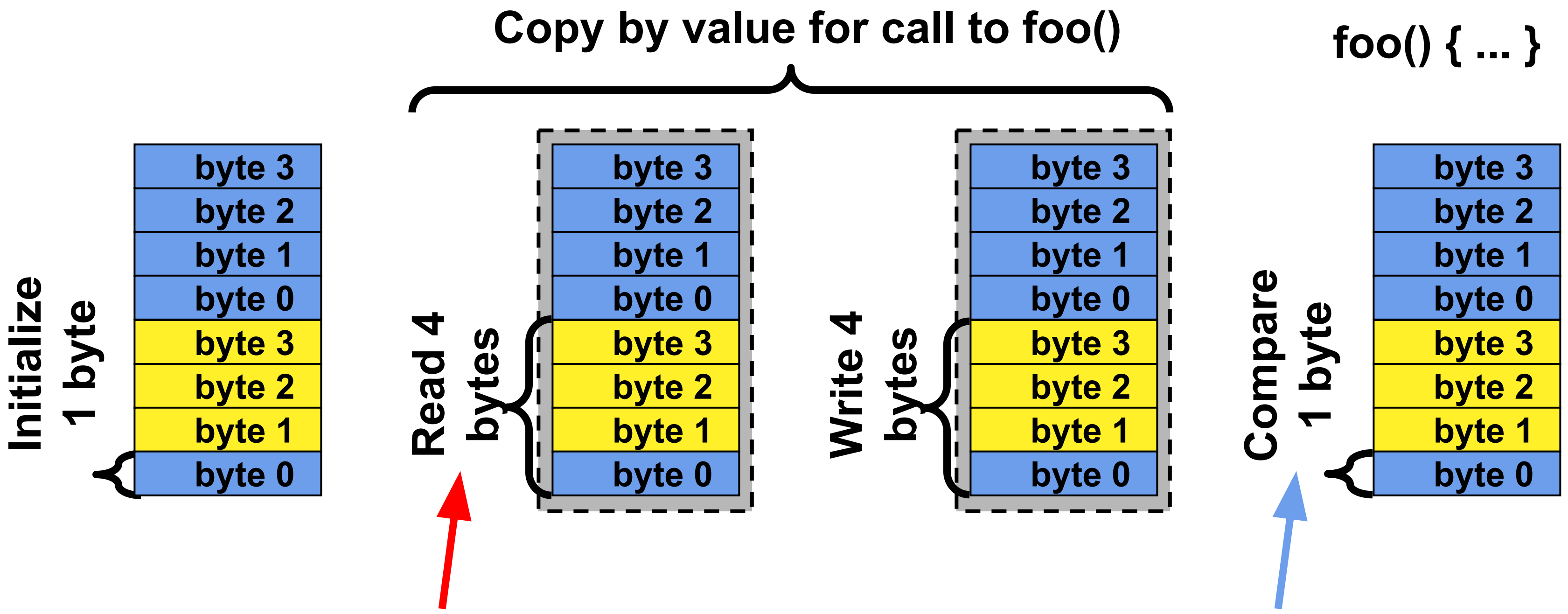


Word Granularity

```
class mydata {
 public:
  bool b;
  int i;
};
void foo(mydata d);
mydata x;
x.b = true;
x.i = 42;
foo(x);
```



Uninitialized Reads Are Everywhere



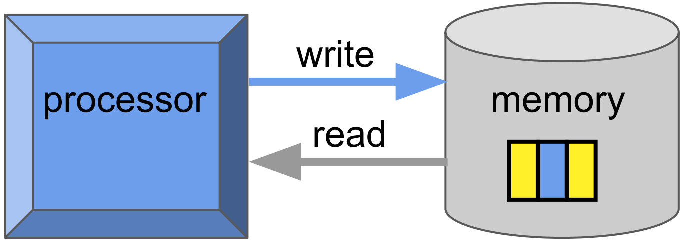
Is this uninitialized read an error?

No, foo() only uses the first byte.

Solution: Delayed Error Reporting

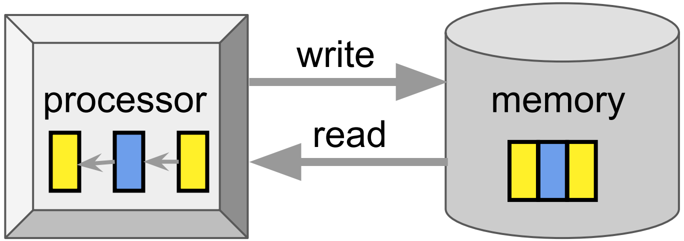
Report uninitialized read errors on "meaningful" reads only

- Conditional branch
- Pointer
- System call



Requires propagating state as data flows through the processor

- Expensive: now we need to track colors inside the processor, not just in memory!



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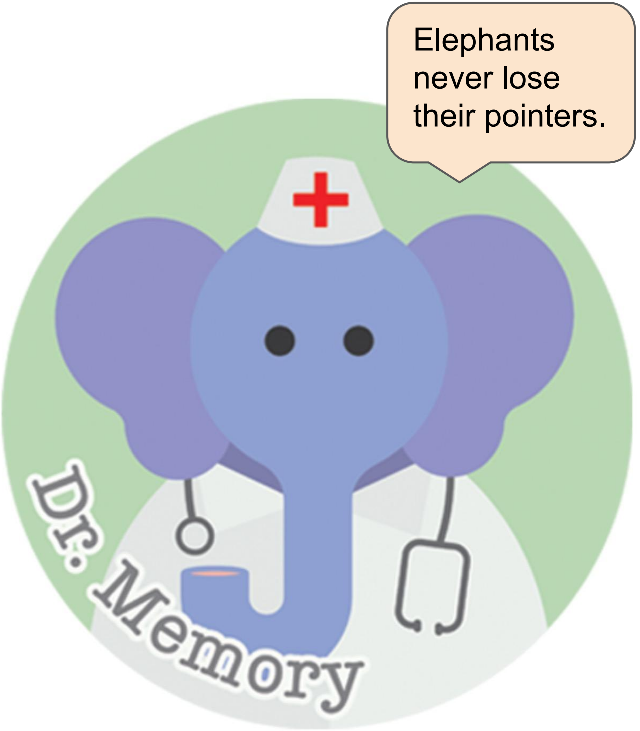


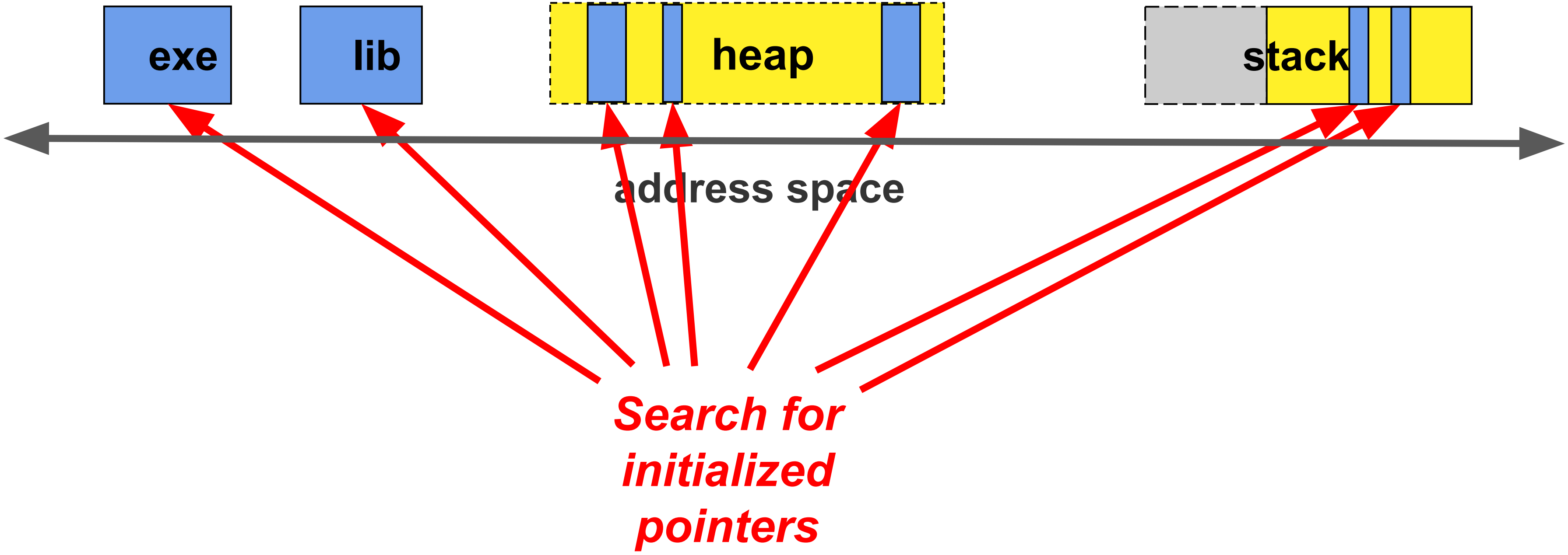
Memory Leaks Are Lost Pointers

Reachability-based leak detection: a *leak* is memory that is no longer reachable by the application

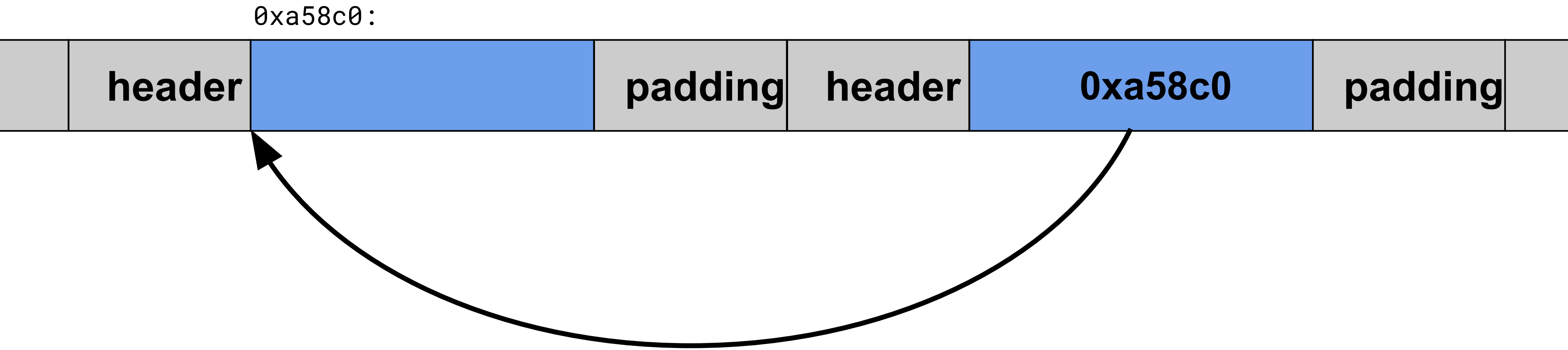
Global memory that is never freed is *not* considered a leak

- Acceptable to not free memory whose lifetime matches process lifetime

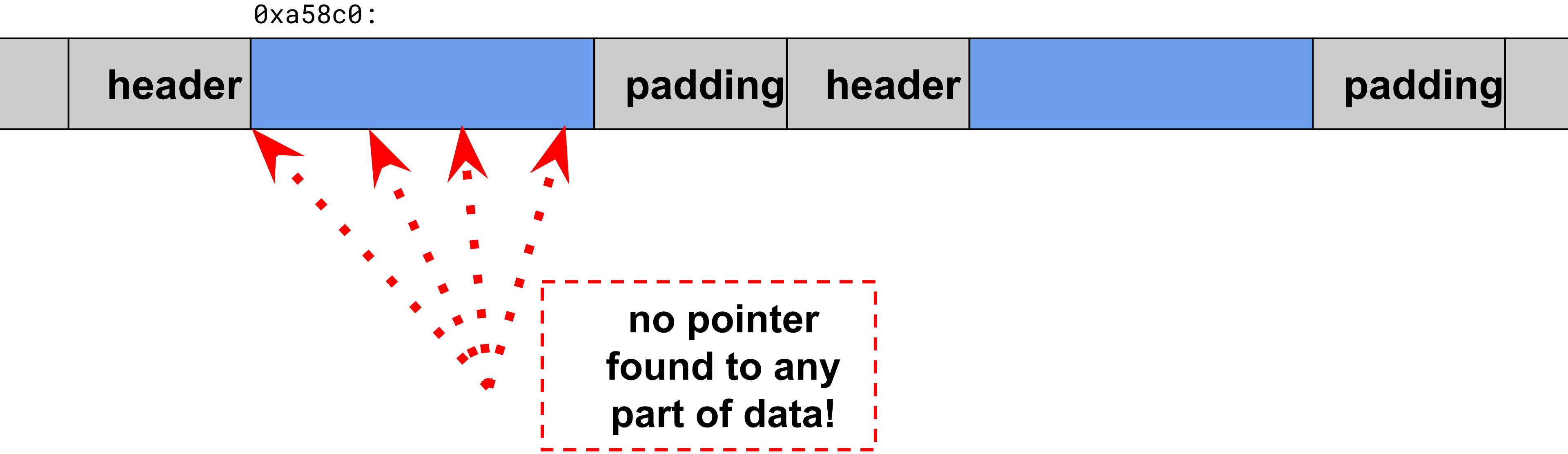
Scanning Memory



Reachable == Not A Leak

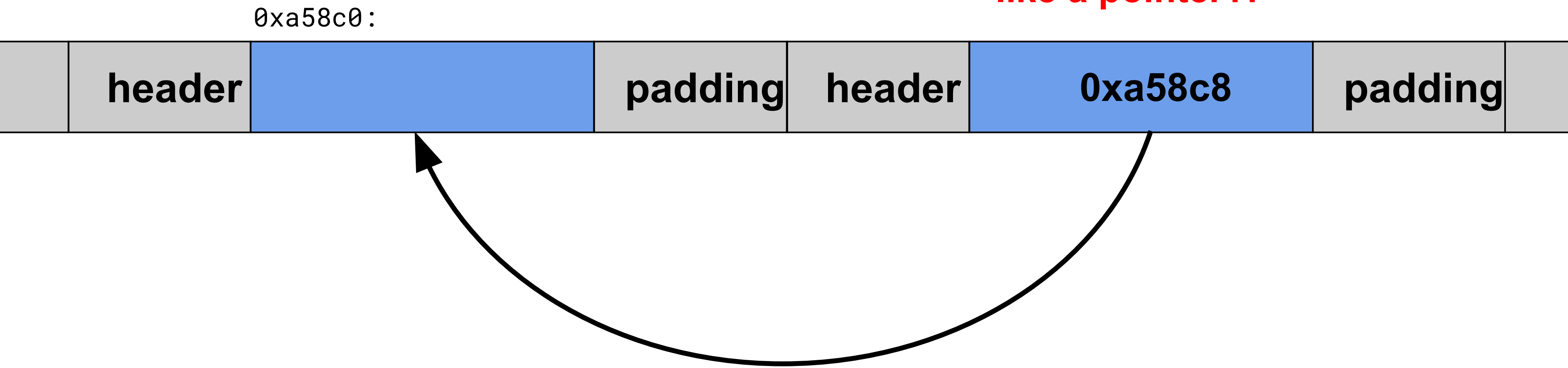


Unreachable == A Leak



no pointer found to any part of data!

Possibly Reachable Memory

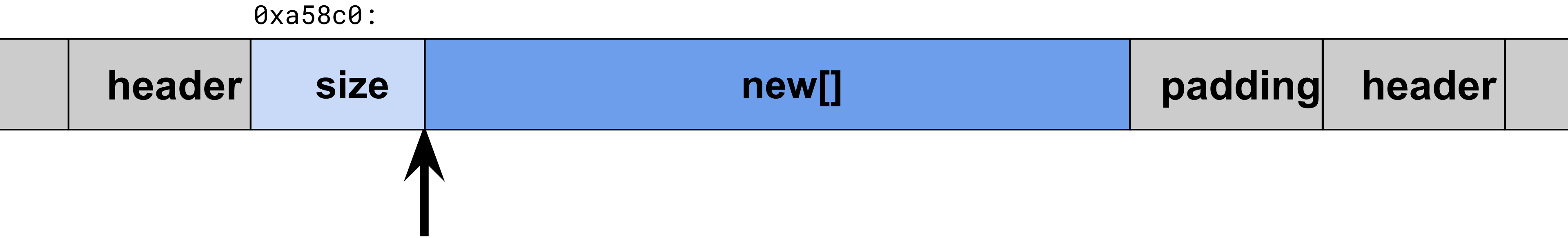


Suspicious!
Large integer that just looks like a pointer?!

Eliminating False Positives: new[]

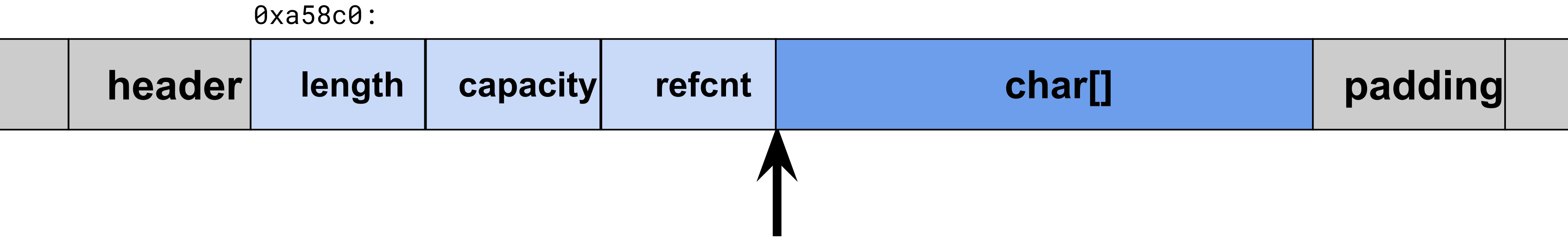
C++ arrays allocated via new[] whose elements have destructors

- new[] adds header and returns to caller address past header



Eliminating False Positives: std::string

std::string points to char[] in middle of allocation



`0xa58c0:`

header

length

capacity

refcnt

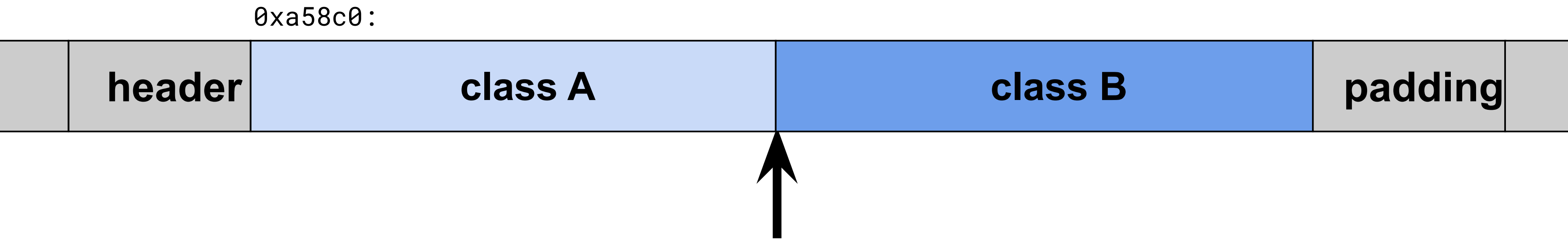
char[]

padding

Eliminating False Positives: Multiple Inheritance

A pointer to a class with multiple inheritance that is cast to one of the parents

- Points to the sub-object representation in the middle of the allocation



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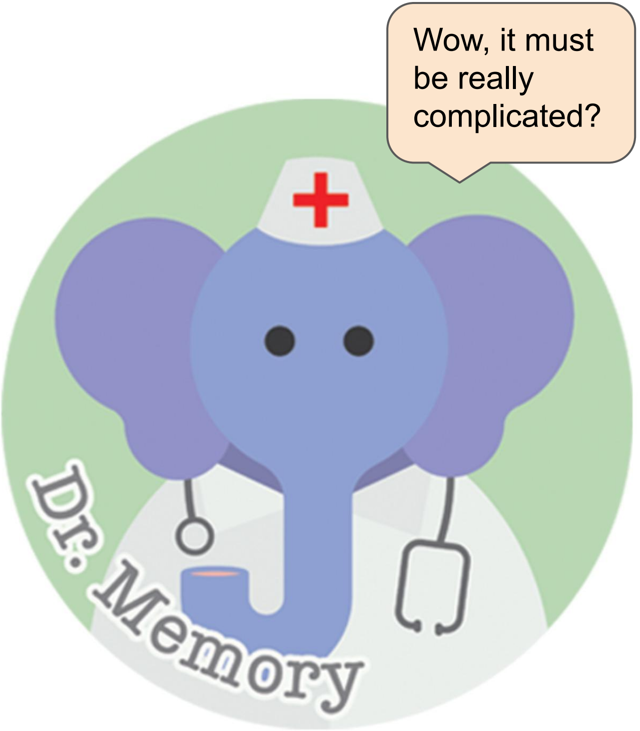


Implementation

Monitor every action taken by the application

- Not just memory reads or write: delayed uninitialized read reporting requires monitoring every instruction

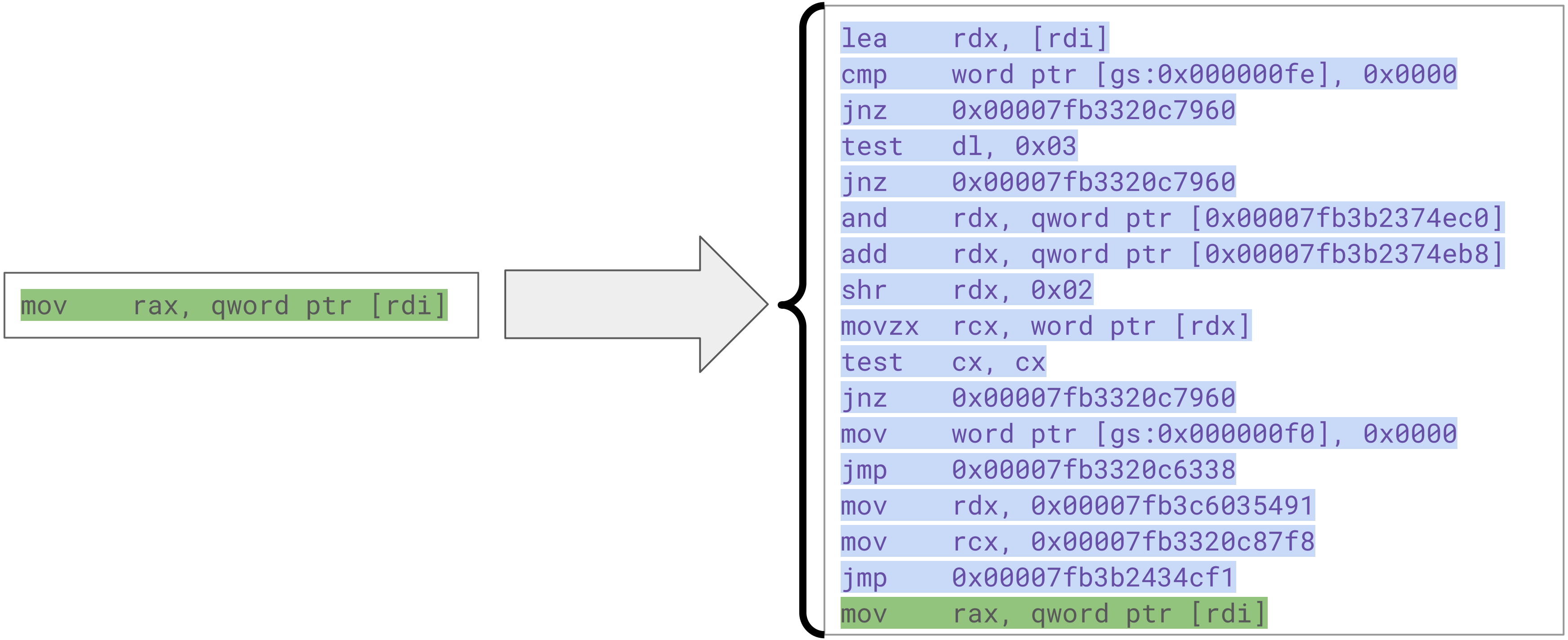
Replace heap allocator

- Insert redzones and delay frees

Dr. Memory Actions

Category	Application Action	Corresponding Tool Action
library call	new, new[], malloc, HeapAlloc	add redzones, mark between as uninitialized
library call	realloc, HeapReAlloc	add redzones, copy old shadow, mark rest as uninitialized
library call	calloc, HeapAlloc(HEAP_ZERO_MEMORY)	add redzones, mark between as defined
library call	delete, delete[], free, HeapFree	mark unaddressable and delay any re-use by malloc
system call	file or anonymous memory map	mark as defined
system call	memory unmap	mark as unaddressable
system call	pass input parameter to system call	report error if any part of parameter is not defined
system call	pass output parameter to system call	report error if any part of parameter is unaddressable; if call succeeds, mark memory written by kernel as defined
instruction	decrease stack pointer register	mark new portion of stack as uninitialized
instruction	increase stack pointer register	mark de-allocated portion of stack as unaddressable
instruction	copy from immediate	mark target as defined
instruction	copy from register or memory	copy source shadow to target shadow
instruction	combine 2 sources (arithmetic, logical, etc. operation)	combine source shadows, mirroring application operation, and copy result to target shadow
instruction	access memory via base and/or index register	report error if addressing register is uninitialized
instruction	access memory	report error if memory is unaddressable
instruction	comparison instruction	report error if any source is uninitialized

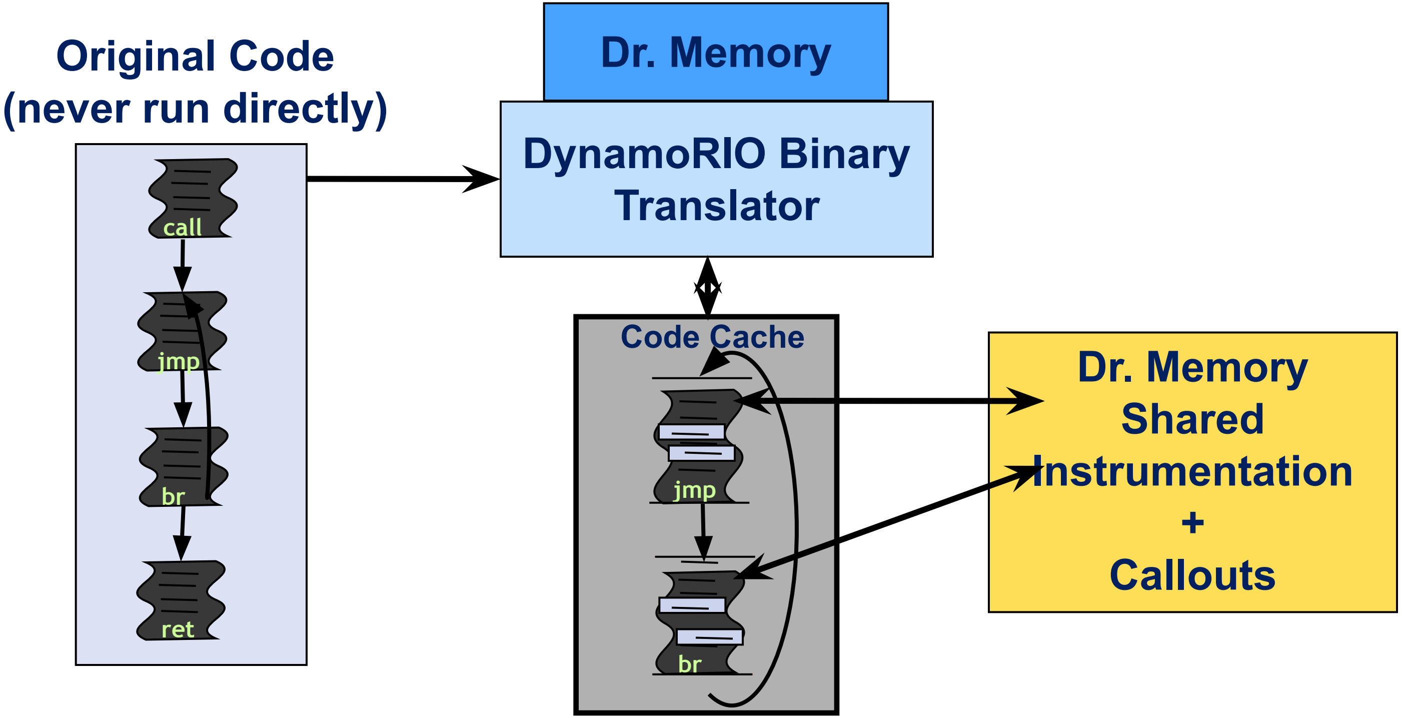
Instrumentation Overhead



```
mov     rax, qword ptr [rdi]
```

```
lea     rdx, [rdi]
cmp     word ptr [gs:0x000000fe], 0x0000
jnz     0x00007fb3320c7960
test    dl, 0x03
jnz     0x00007fb3320c7960
and     rdx, qword ptr [0x00007fb3b2374ec0]
add     rdx, qword ptr [0x00007fb3b2374eb8]
shr     rdx, 0x02
movzx   rcx, word ptr [rdx]
test    cx, cx
jnz     0x00007fb3320c7960
mov     word ptr [gs:0x000000f0], 0x0000
jmp     0x00007fb3320c6338
mov     rdx, 0x00007fb3c6035491
mov     rcx, 0x00007fb3320c87f8
jmp     0x00007fb3b2434cf1
mov     rax, qword ptr [rdi]
```

Instrumentation Platform: DynamoRIO



Original Code
(never run directly)

Dr. Memory

DynamoRIO Binary Translator

Code Cache

Dr. Memory Shared Instrumentation + Callouts

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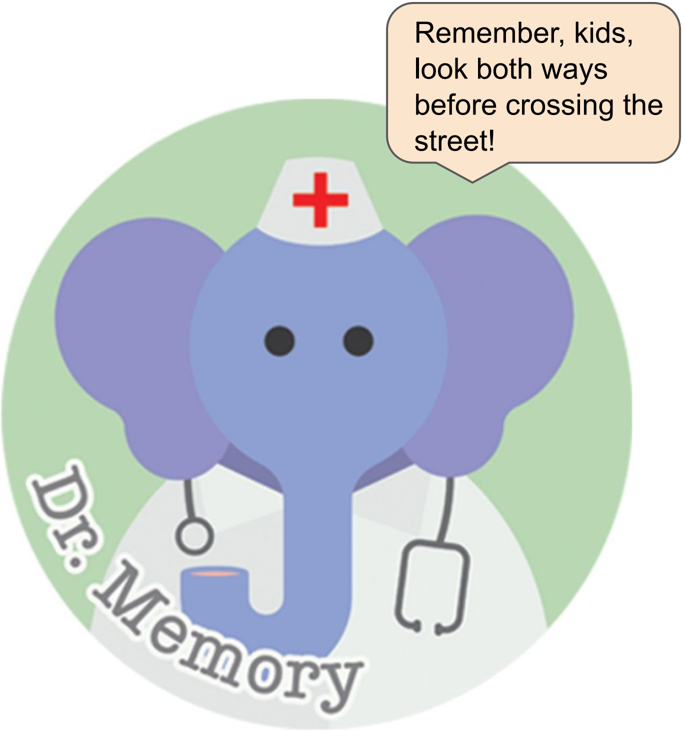


Valgrind Memcheck

Similar system in errors found and deployment

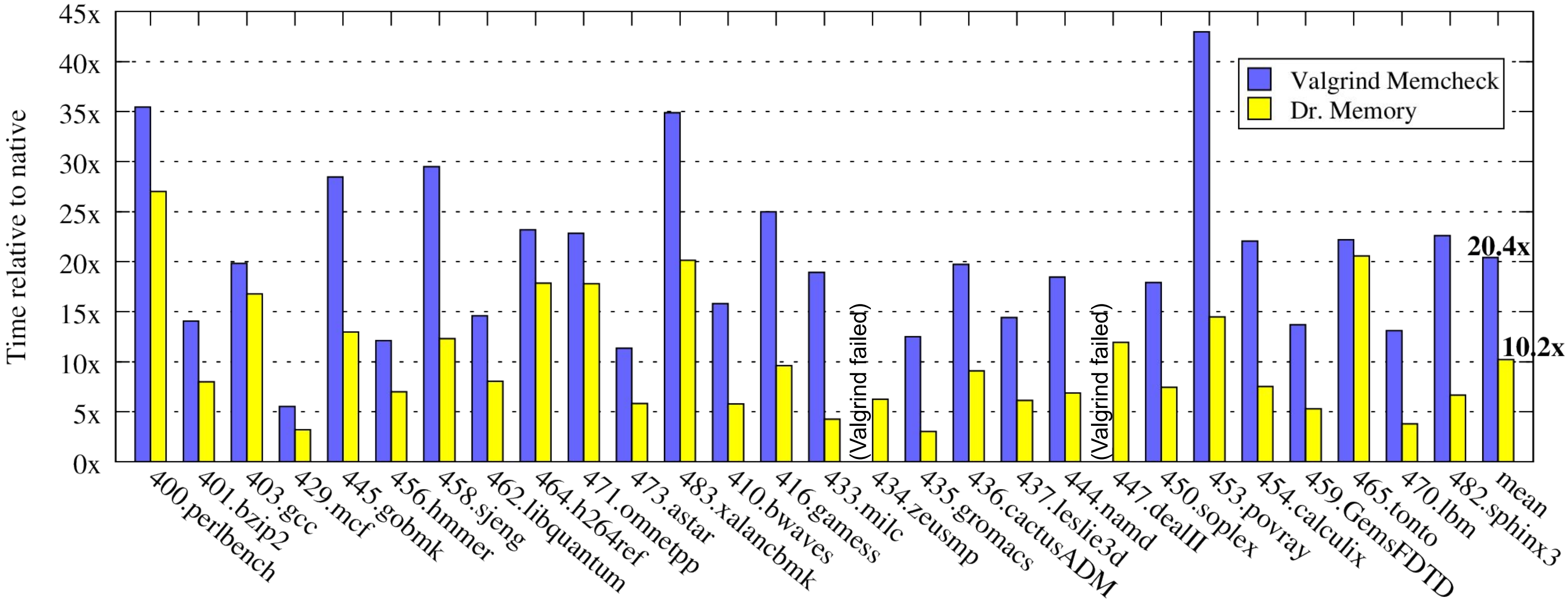
Dr. Memory runs the application natively, with instrumentation inserted as inlined fastpaths and callouts to slowpaths

Valgrind runs instrumentation natively, and emulates the application

Dr. Memory is 2x faster

Dr. Memory supports Windows

Performance Comparison With Valgrind



AddressSanitizer

Implements unaddressable checking and leak checking in the compiler

- No uninitialized read detection
  - MemorySanitizer
- Only detects bugs in recompiled code
  - Also intercepts common libc and libc++ function calls
- Binary pays cost of checks on every run, so a separate dedicated build is required

AddressSanitizer Performance

Faster (2x vs native) than Dr. Memory (10x) or Valgrind (20x)

- Not propagating values for uninitialized reads
- Ignores compiler “glue code”
- Register allocation and optimizations integrated with application

Bug Coverage Comparison

Tool	Bugs in entire program and libraries	Use-after-free	Heap over/under flow	Stack var over/under flow	Global var over/under flow	Uninitialized reads	Leaks with no stale pointers	Leaks with stale pointers
Dr. Memory	✓	✓	✓	✗	✗	✓	✓	✓
Valgrind	✓	✓	✓	✗	✗	✓	✓	✓
Address Sanitizer	✗	✓	✓	✓	✓	✗	✓	✗

Example Bad Pointer Missed by AddressSanitizer

```
#include <pthread.h>
#include <iostream>
void *func(void *) { return nullptr; }
int main() {
  pthread_t *p = new pthread_t;
  delete p;
  pthread_create(p, nullptr, func,
                 nullptr);
  std::cout << "All good\n";
  return 0;
}
```

```
$ clang++ -fsanitize=address -g noasan2.cpp -lpthread && ./a.out
All good
```

```
$ clang++ -g noasan2.cpp -lpthread &&
~/DrMemory-Linux-2.3.0-1/bin64/drmemory -- ./a.out
~~Dr.M~~ Dr. Memory version 2.3.0
~~Dr.M~~
~~Dr.M~~ Error #1: UNADDRESSABLE ACCESS of freed memory: writing
0x41eb30-0x41eb38 8 byte(s)
~~Dr.M~~ # 0 libpthread.so.0!__pthread_create_2_1
~~Dr.M~~ # 1 main                                    [.../noasan2.cpp:6]
~~Dr.M~~ Note: @0:00:01.054 in thread 1759547
~~Dr.M~~ Note: next higher malloc: 0x41eb90-0x41ecb0
~~Dr.M~~ Note: 0x41eb30-0x41eb38 overlaps memory 0x41eb30-0x41eb70 that was
freed here:
~~Dr.M~~ Note: # 0 replace_operator_delete_array [.../alloc_replace.c:2999]
~~Dr.M~~ Note: # 1 main                          [.../noasan2.cpp:5]
~~Dr.M~~ Note: instruction: mov    %rbx -> (%rax)
All good
```

Example Leak Missed by AddressSanitizer

```cpp
#include <iostream>
void func1() {
  char buf1[1024];
  int *ptr = new int[4];
  std::cout<<"ptr="<<std::hex<<ptr<<"\n";
  char buf2[1024];
  buf1[0] = 'a';
  buf2[0] = 'b';
}
void func2() {
  char buf1[1024 + sizeof(int*)];
  char buf2[1024];
  exit(0);
}
int main() {
  func1();
  func2();
  return 0;
}
```

```
$ clang++ -fsanitize=address -g noasan.cpp &&
ASAN_OPTIONS="detect_leaks=1" ./a.out
ptr=0x602000000010

$ clang++ -fsanitize=address -g noasan.cpp &&
ASAN_OPTIONS="detect_leaks=1:detect_stack_use_after_return=1" ./a.out
ptr=0x602000000010
```

```
$ clang++ -g noasan.cpp && ~/DrMemory-Linux-2.3.0-1/bin64/drmemory -- ./a.out
~~Dr.M~~ Dr. Memory version 2.3.0
ptr=0x41e2e0
~~Dr.M~~
~~Dr.M~~ Error #1: LEAK 16 direct bytes 0x41e2e0-0x41e2f0 + 0 indirect bytes
~~Dr.M~~ # 0 replace_operator_new_array [.../alloc_replace.c:2929]
~~Dr.M~~ # 1 func1                      [.../noasan.cpp:4]
~~Dr.M~~ # 2 main                       [.../noasan.cpp:16]
```

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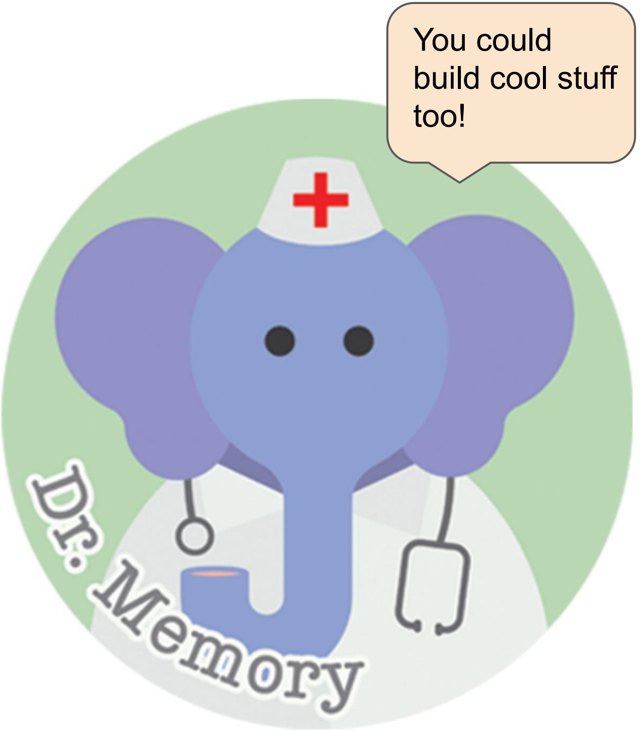
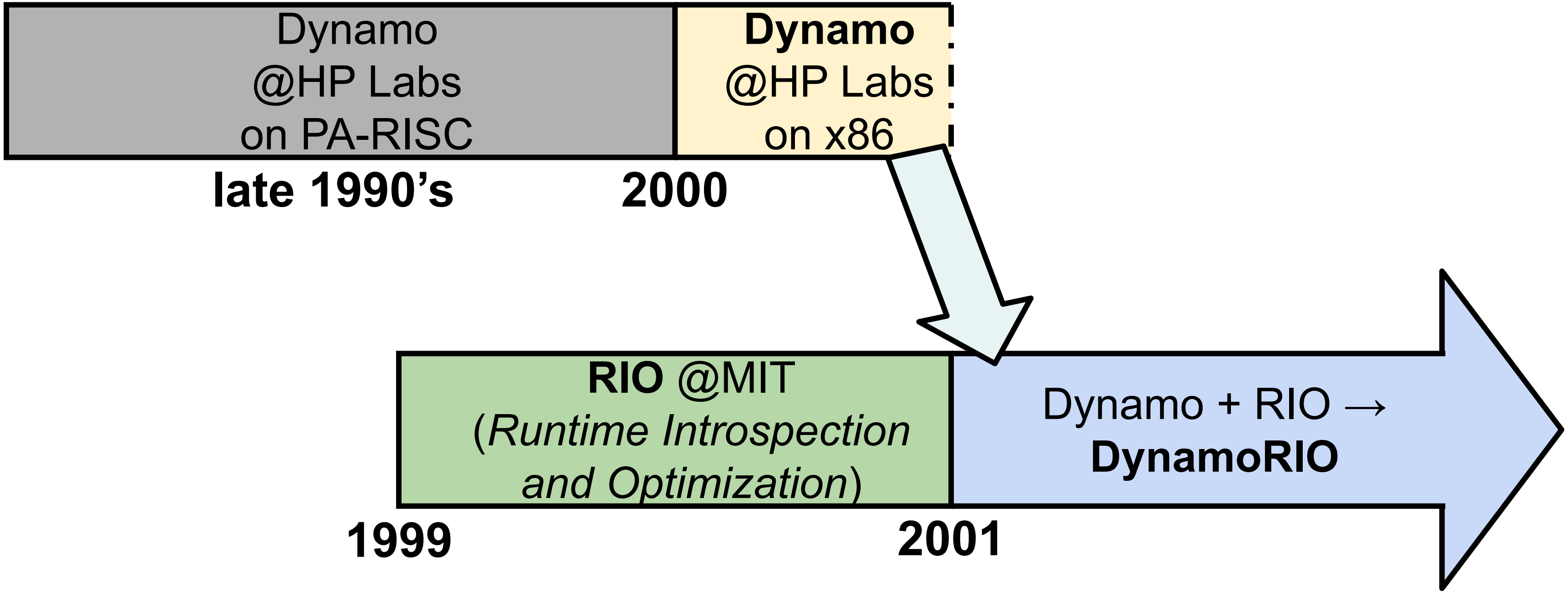


DynamoRIO



Dynamo
@HP Labs
on PA-RISC

Dynamo
@HP Labs
on x86

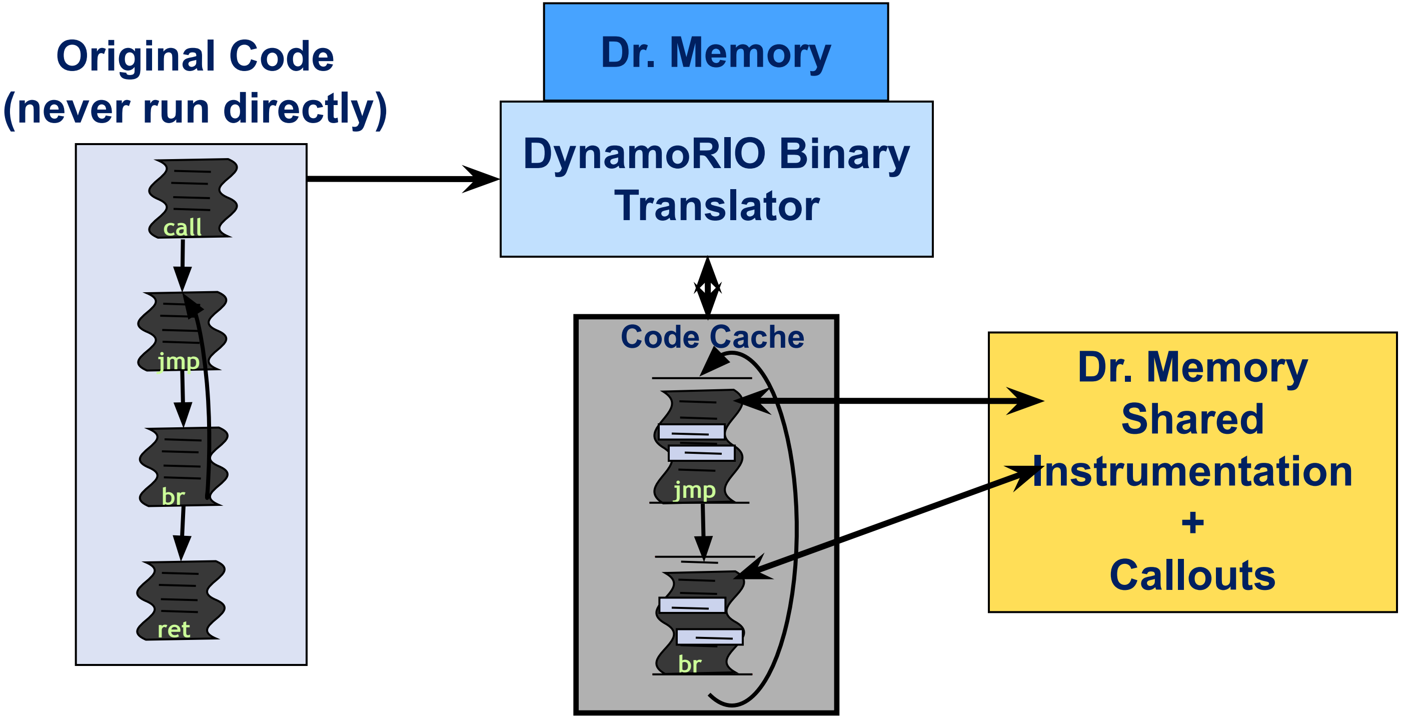
late 1990's **2000**

RIO @MIT
(*Runtime Introspection and Optimization*)

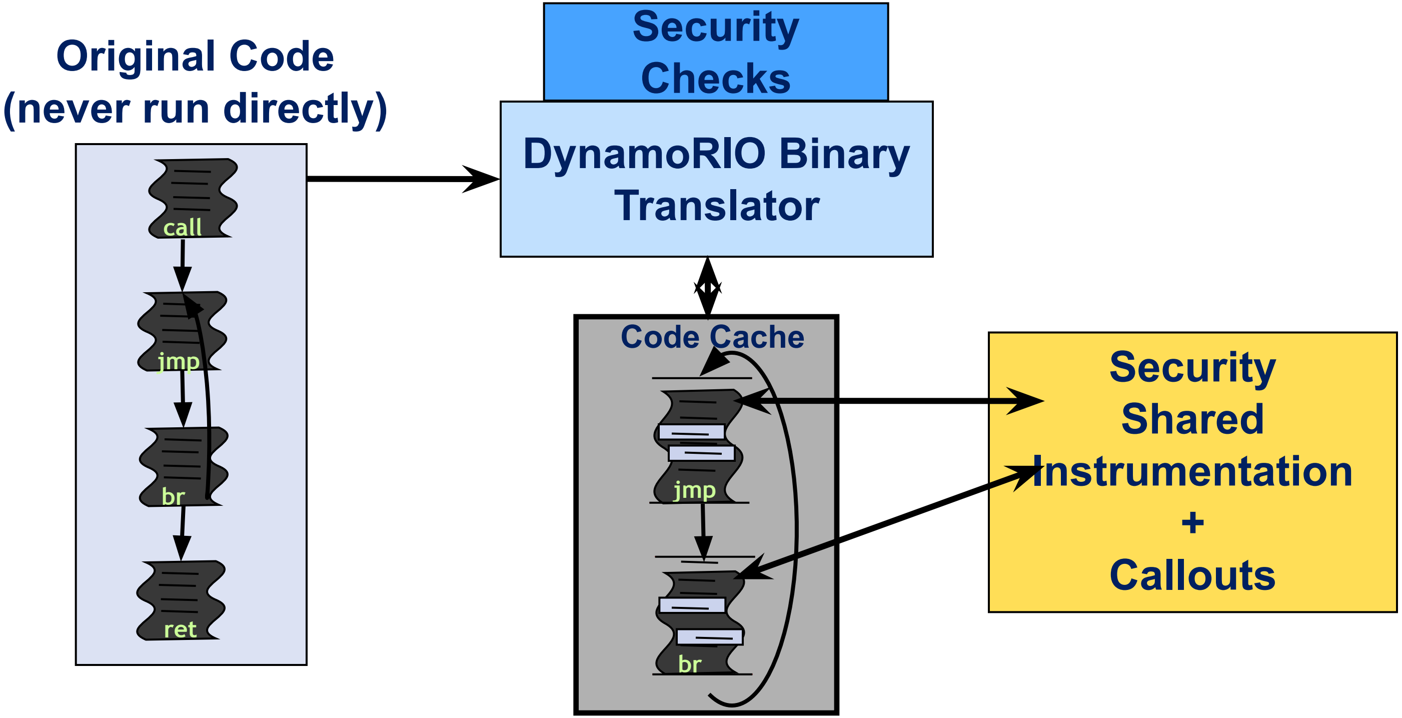
Dynamo + RIO →
DynamoRIO

1999 **2001**

Graduate School + Industry History



Security Startup



Original Code (never run directly)

Security Checks

DynamoRIO Binary Translator

Code Cache

Security Shared Instrumentation + Callouts

Dr. Memory in the Real World

Used by the Chrome developers for several years

- Found several hundred bugs in Chrome

Open-source

- Contributions welcome
- Google Summer of Code participant in the past
- RCOS project possibilities

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