Baggy bounds checking

Periklis Akritidis, Manuel Costa,
Miguel Castro, Steven Hand

C/C++ programs are vulnerable

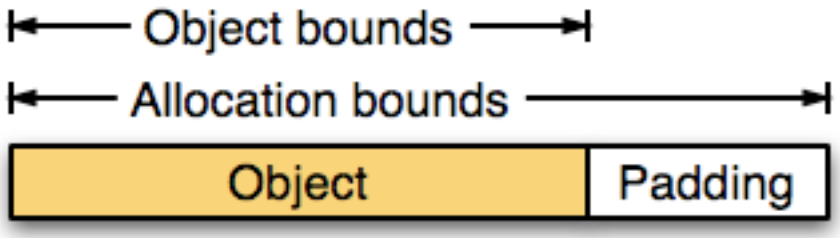
- Lots of existing code in C and C++
- More being written every day
- C/C++ programs are prone to bounds errors
- Bounds errors can be exploited by attackers

Previous solutions are not enough

- Finding all bugs is unfeasible
- Using safe languages requires porting
- Existing solutions using fat pointers (Ccured, Cyclone) break binary compatibility
- Backwards compatible solutions are slow
- And <u>performance</u> is critical for adoption

Baggy bounds checking (BBC)

- Enforce allocation instead of object bounds

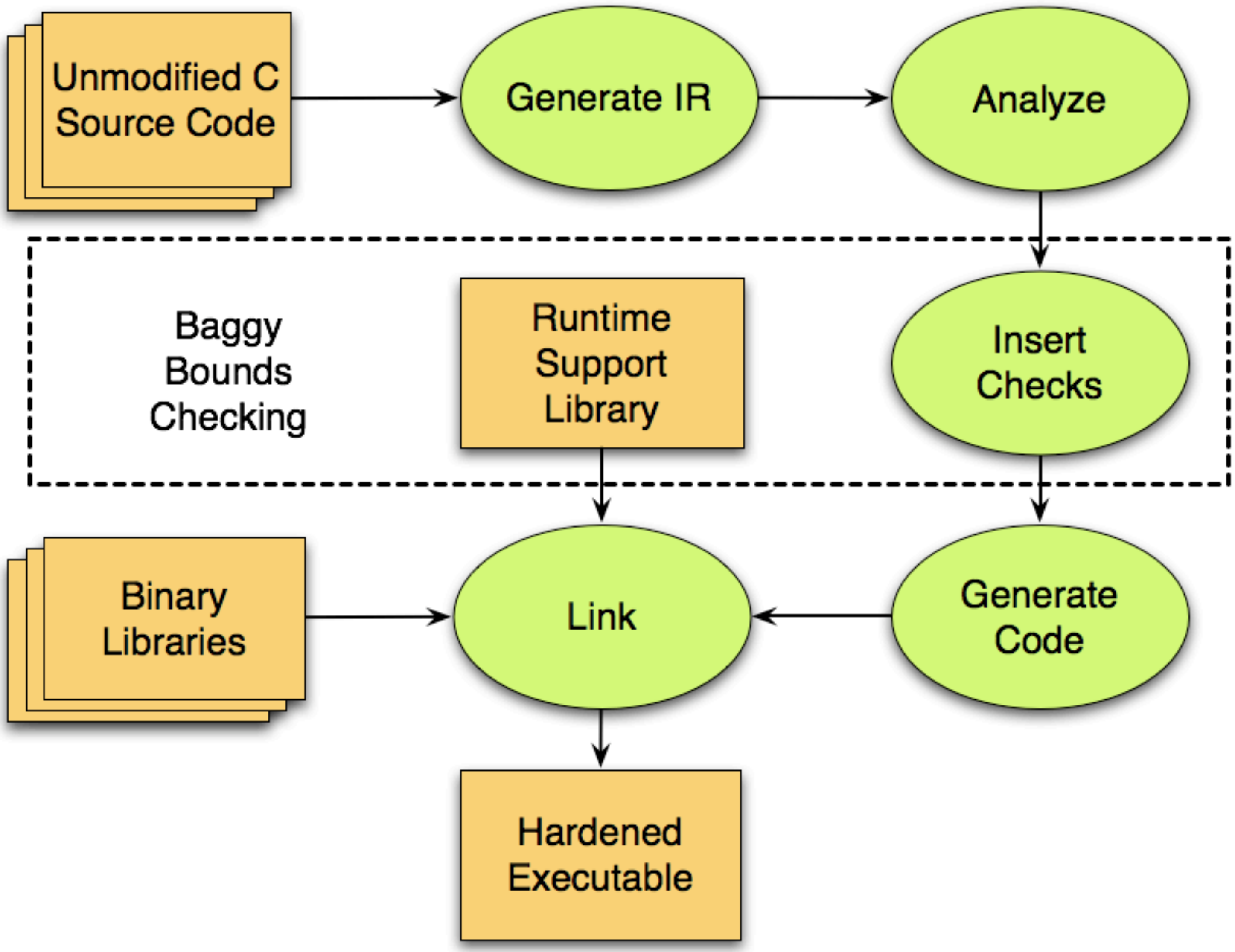


- Constrain allocation sizes and alignment to powers of two
  - Fit size in one byte
  - No need to store base address
- Fast lookup using linear table

BBC Benefits

- Works on unmodified source code
- Broad coverage of attacks
- Interoperability with uninstrumented binaries
- Good performance
  - 30% average CPU overhead
    - 6-fold improvement over previous approaches on SPEC
  - 7.5% average memory overhead
  - 8% throughput degradation for Apache

System overview



Attack Example

- Pointers start off valid

```
p = malloc(200);
```

- May become invalid

```
q = p + 300;
```

- And then can be used to hijack the program

```
*q = 0x00000BAD
```

Traditional Bounds Checking [Jones and Kelly]

- Use table to map allocated range to bounds

  p = malloc(200);

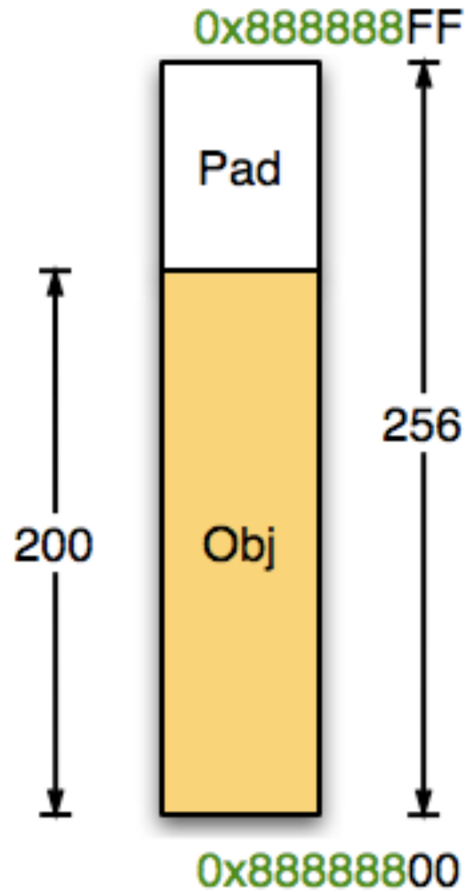
- Lookup bounds using source p

  q = p + 300;

- Check result q using bounds
- Note that source pointer p assumed valid
  - points to allocation or result of checked arithmetic
  - maintain this invariant throughout execution
- But keeping bounds information is expensive…

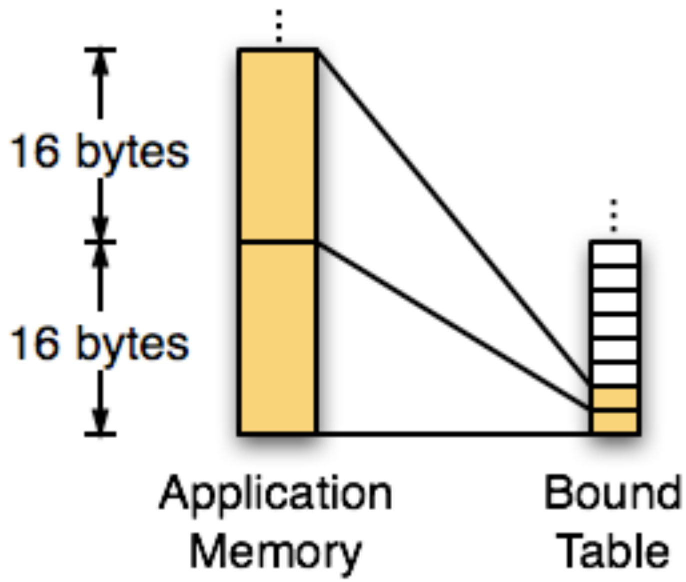
Baggy Bounds

- Pad allocations to power of 2
  - malloc(200) -> malloc(256)
- Align to allocation size
  - Upper bound: <u>**0x888888**</u>FF
  - Lower bound: <u>**0x888888**</u>00
- Can recover bounds using
  - The valid source pointer
  - The binary logarithm of the allocation size



Bound table implementation

- Previous solutions need e.g. splay tree to lookup bounds for a given source pointer
- If force allocations to be a multiple of 16 byte *slots*, can use an array with 1 byte per slot



Efficient table lookup

```
mov eax, p              ; Copy pointer
shr eax, 4              ; Right-shift by 4
mov al, [TABLE+eax]     ; One memory read
```

- Loads allocation size logarithm in register %al
- However:
    - No need to recover explicit bounds
    - Use valid pointer and allocation size directly

Efficient Checks

q = p + 300;

mov ebx, p	; copy source	0x88888800
xor ebx, q	; xor with result	0x8888892C
		0x0000012C
shr ebx, al	; right shift	>> 8
	; by table entry	0x00000001
jnz error	; check for zero	!!!

(Legal) Out-of-bounds pointers

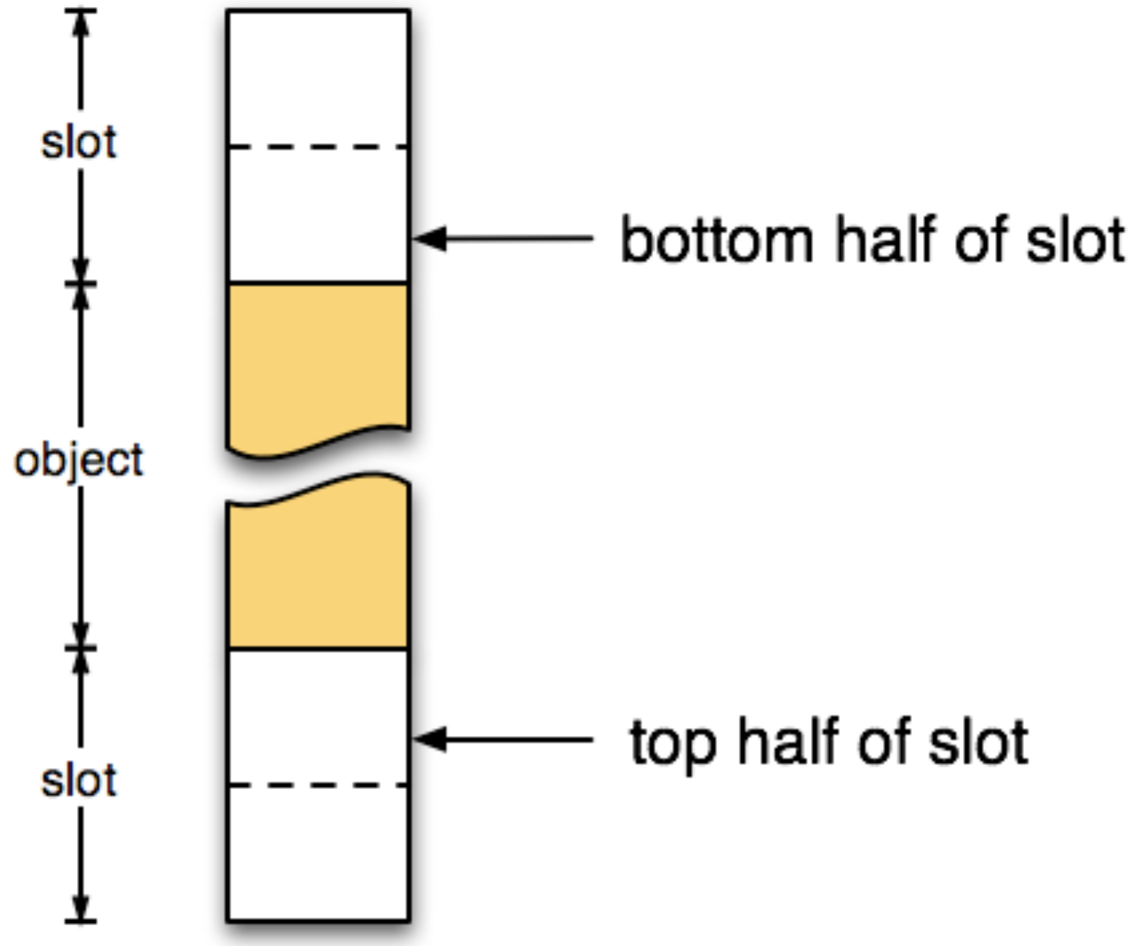
- C programs can use out-of-bounds pointers
- Cannot dereference
- Can use in pointer arithmetic
- C standard allows only one byte beyond object
  - Some programs go beyond, or below object e.g.

```
char *array = malloc(100) – 1;
                    // now can use array[1..100]
```

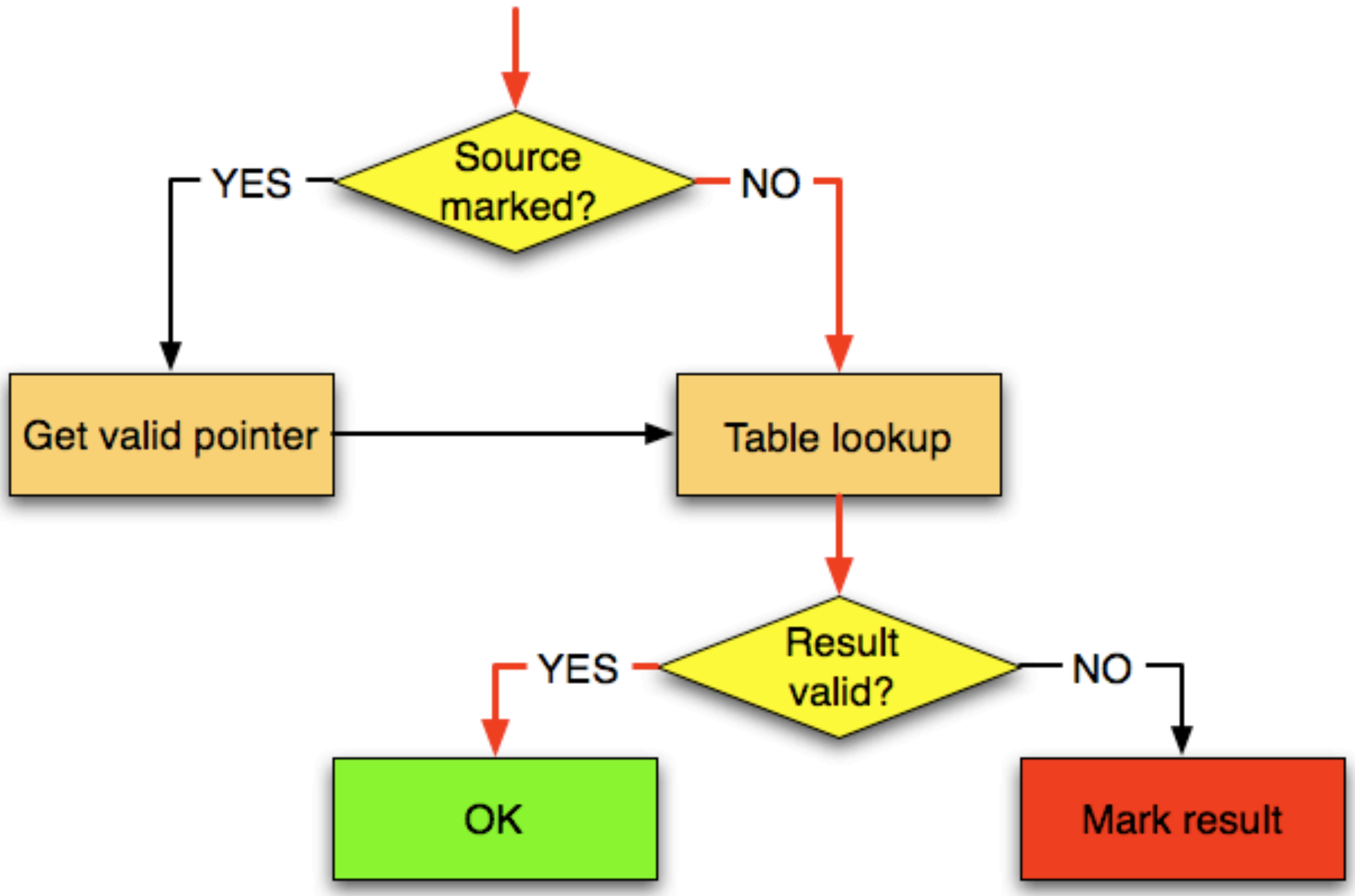
Dealing with OOB pointers

- 1. Mark to avoid dereference
  - Set pointer top bit [Dhurjati et al.]
  - Protect top half of address space
- 2. Recover valid pointer if marked
  - Can use extra data structure [Ruwase and Lam]
  - BBC: support most cases without a data structure
  - (can support more in 64-bit mode – see later)

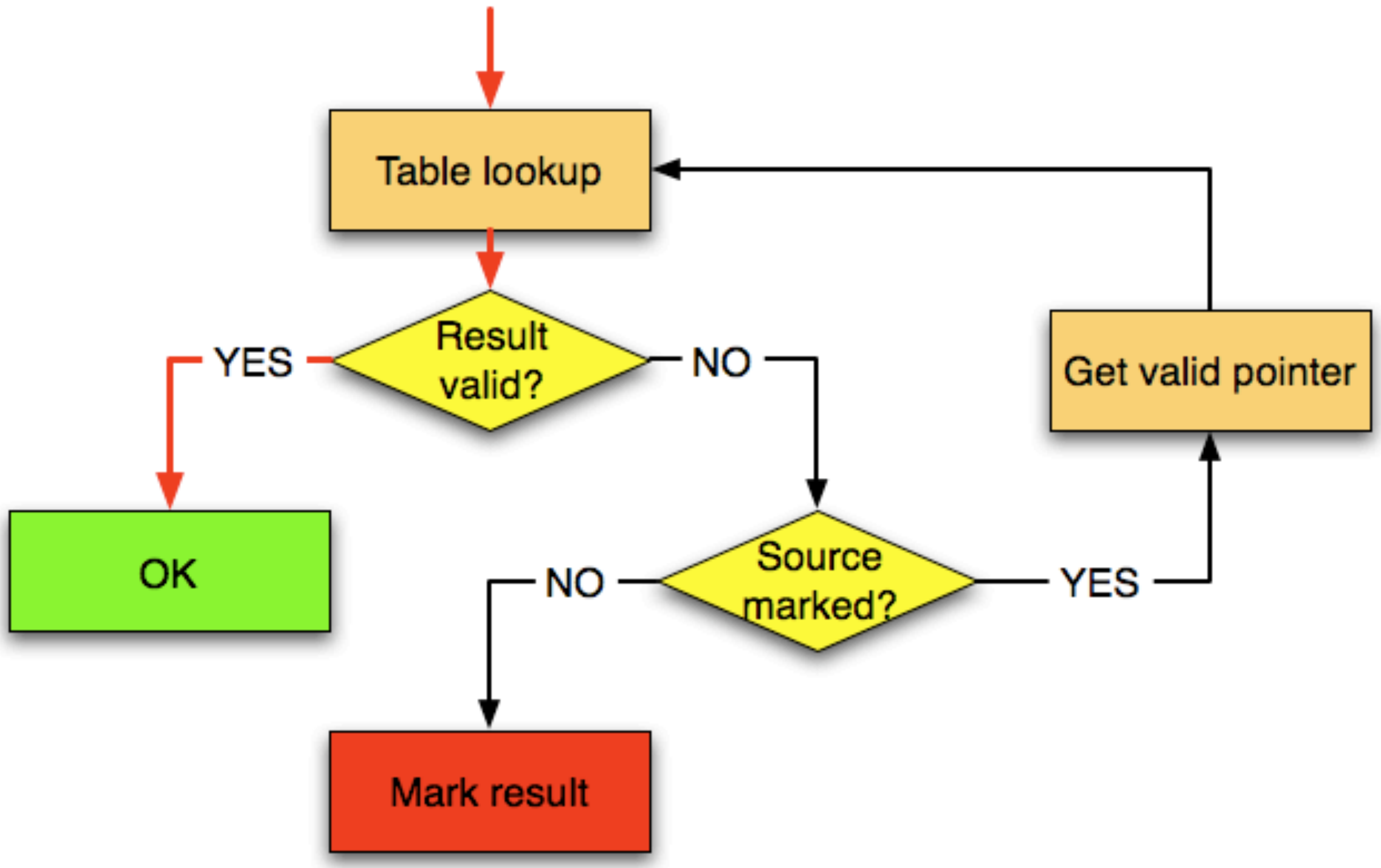
Common out-of-bounds pointers



Extra check in fast path



Optimized fast path



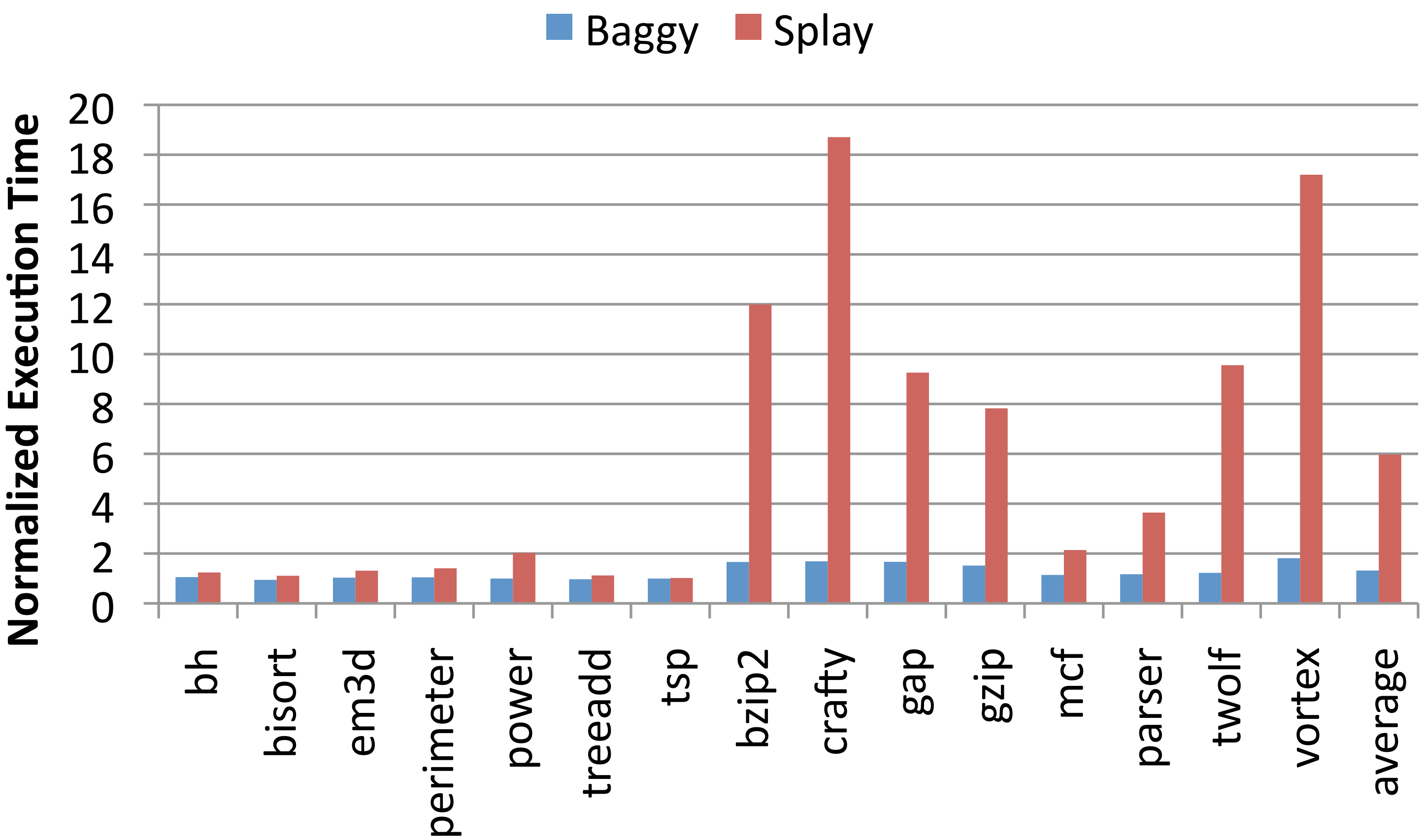
Memory Allocations

- Heap using binary buddy system
  - Perfect fit for baggy bounds
- Align stack frames at runtime
  - Only if contains array or address taken variable
- Pad and align globals at compile time
- Memory allocated by uninstrumented code has default table entry
  - Default value 31: maximal bounds

Performance Evaluation

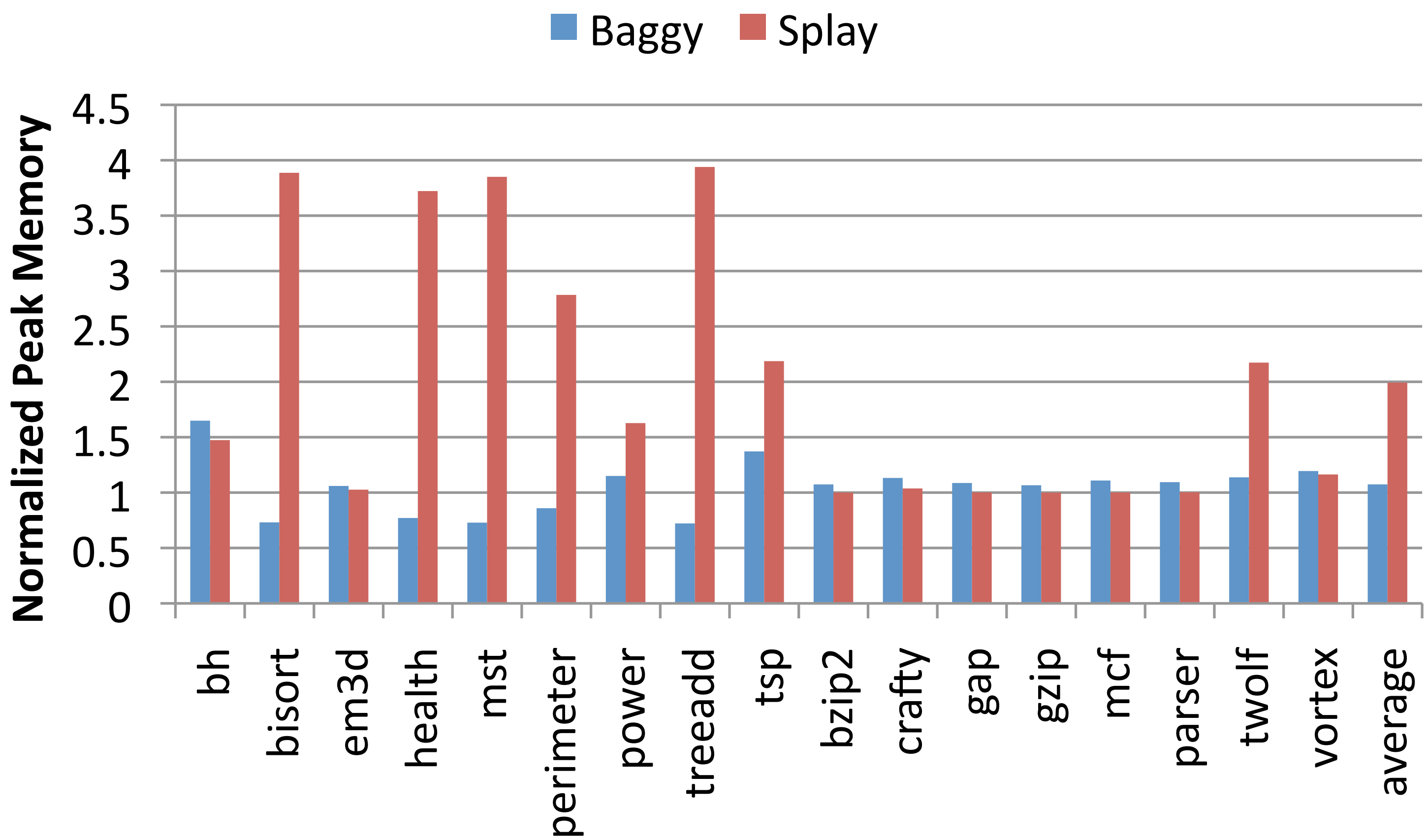
- Measured CPU and memory overhead
  - Olden and SPEC benchmarks
- Baggy
  - Baggy bounds checking as described
- Splay
  - Splay tree from previous solutions
  - Standard allocator
  - Same checks

Execution Time vs. Splay Tree



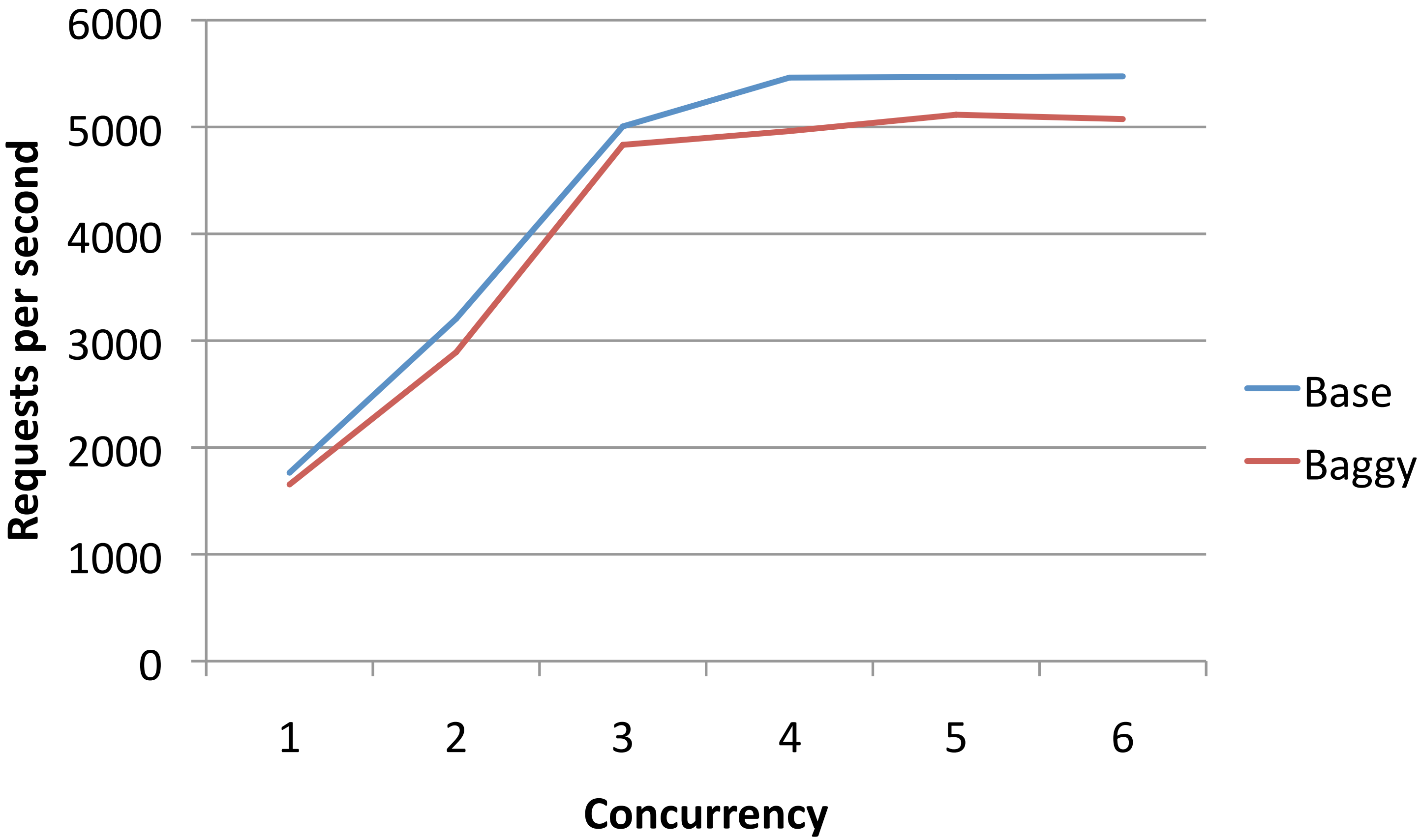
- 30% for baggy vs. 6x for splay tree on average

Memory Usage vs. Splay Tree



- 7.5% for baggy vs. 100% for splay on average

Apache Throughput



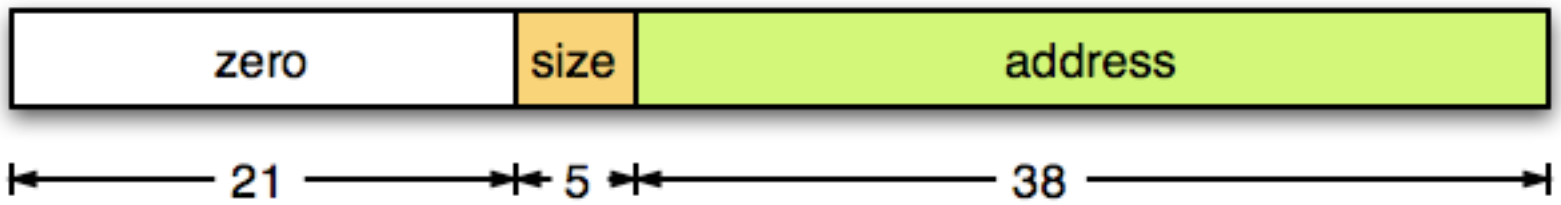
- 8% throughput decrease with saturated CPU

Effectiveness

- Evaluated using buffer overflow suite [Wilander and Kamkar]
- Blocked 17 out of 18 attacks
- Missed overflow between structure fields

Baggy bounds on x64

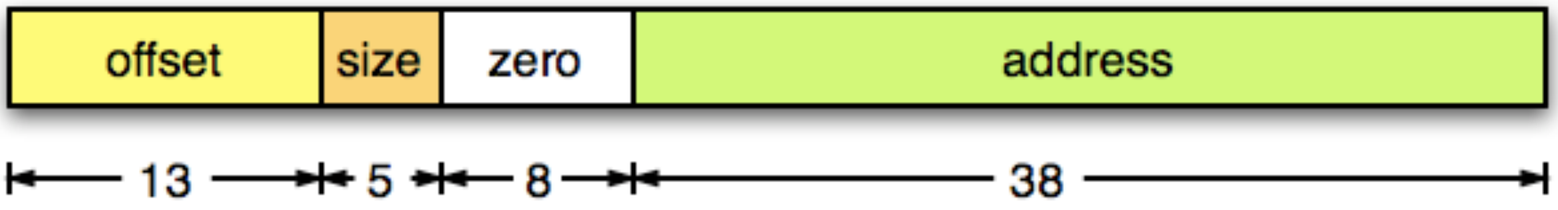
- Baggy bounds can fit inside pointers



Avoid memory lookup entirely:

```
mov rax, p      ; copy pointer
shr rax, 38     ; shift tag to %al
```

x64 Out-of-bounds pointers



- Adjust pointer by offset in spare bits
- Greatly increases out-of-bounds range

Conclusions

- Baggy Bounds Checking provides practical protection from bounds errors in C\C++
- Works on unmodified programs
- Preserves binary compatibility
- Good performance
  - Low CPU overhead (30% average)
  - Low memory overhead (7.5% average)
- Can protect systems in production runs