-fbounds-safety

Enforcing bounds safety for production C code

Yeoul Na (Apple), May 11th, 2023

Agenda

Motivation

Design goals and highlights

Programming model of -fbounds-safety

Optimization

Performance impact

Memory unsafety is the leading source of security vulnerabilities

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- Memory safety bugs account for 60-70% of software vulnerabilities
- High-profile attacks have exploited memory safety bugs leading to financial and physical threats

Memory safety properties

- Bounds safety (or spatial safety)
- Temporal safety (or lifetime safety)
- Type safety
- Definite initialization
- Thread safety

C does not guarantee memory safety

- ❌ Bounds safety (or spatial safety)
- ❌ Temporal safety (or lifetime safety)
- ❌ Type safety
- ❌ Definite initialization
- ❌ Thread safety

Memory-safe languages provide enhanced safety guarantees

✅ Bounds safety (or spatial safety)

✅ Temporal safety (or lifetime safety)

✅ Type safety

✅ Definite initialization

✅ Thread safety

Memory-safe languages are increasingly the best choice

- Memory-safe languages have emerged as a promising option for systems programming
- Increasingly available for more programming environments
- Incredible initiatives taking place in this domain

Transitioning from C to safe languages takes time

- Billions of lines of C code remain in production
- Efforts to rewrite existing C code using safe languages (e.g., Linux kernel)
- Rewriting requires significant engineering effort and time
- Expect continued maintenance of C code for several more decades

We need a solution to rapidly harden existing C code

Bounds unsafety is the biggest cause of dangerous vulnerabilities

2022 CWE Top 25 Most Dangerous Software Weaknesses

Rank	Name
1	Out-of-bounds Write
4	Improper Input Validation
5	Out-of-bounds Read
13	Integer Overflow or Wraparound
19	Improper Restriction of Operations within the Bounds of a Memory Buffer

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-fbounds-safety

C extension for bounds safety

-fbounds-safety only provides bounds safety

But it offers quicker way to make remaining C code safer

	C	-fbounds-safety	Memory safe languages (Swift, Rust, etc.)
Bounds safety (or spatial safety)	❌	✅	✅
Temporal safety	❌	❌	✅
Type safety	❌	❌	✅
Definite initialization	❌	❌	✅
Thread safety	❌	❌	✅

Design goals and highlights

Automatically insert bounds checks as a safety net

- Programmers manually add bounds checks, but sometimes make mistakes
- -fbounds-safety automatically adds bounds checks as a safety net

```c
void fill_array_with_indices(int *buf, size_t count) {
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```

C pointers do not have bounds information

Potential solution: Use wide pointers

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```c
typedef struct {
  int *pointer;
  int *upper_bound;
  int *lower_bound;
} wide_ptr;
```

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- a.k.a “fat” pointers

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Potential solution: Use wide pointers

- Analogous to struct with upper/lower bounds alongside the pointer value
- a.k.a “fat” pointers
- Allows compiler to automatically insert bounds check

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Problem: Wide pointers break Application Binary Interface (ABI)

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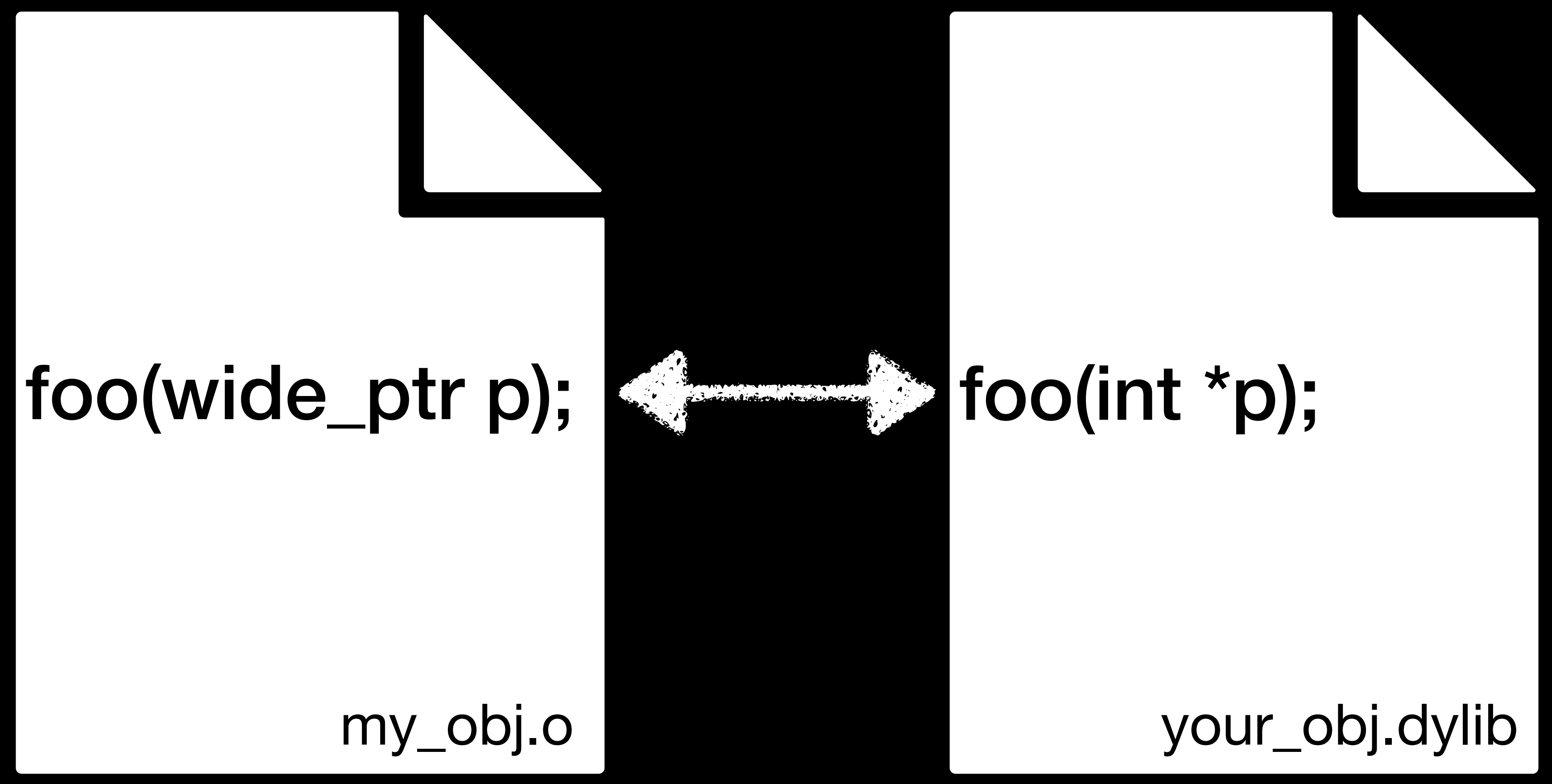

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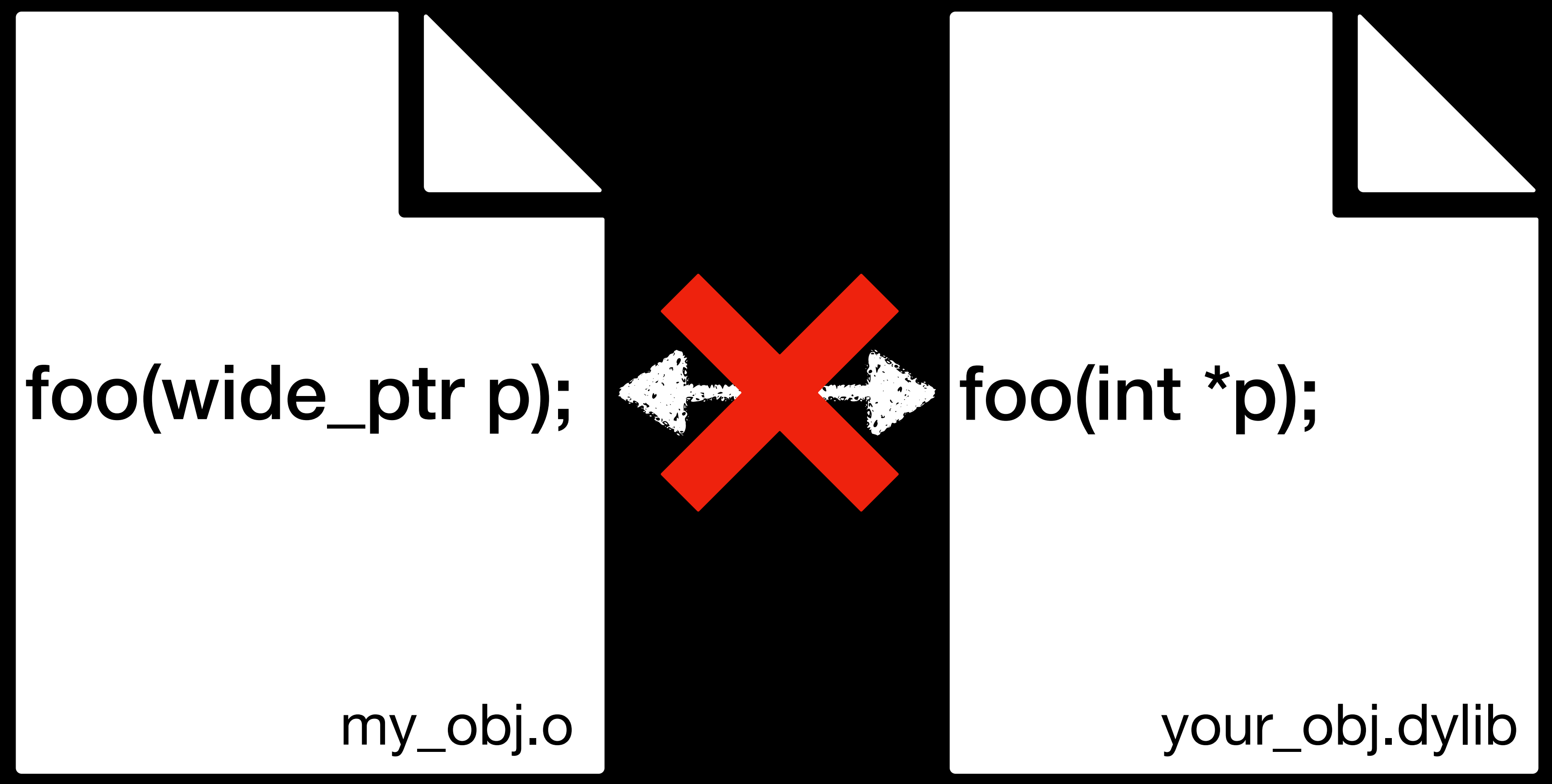
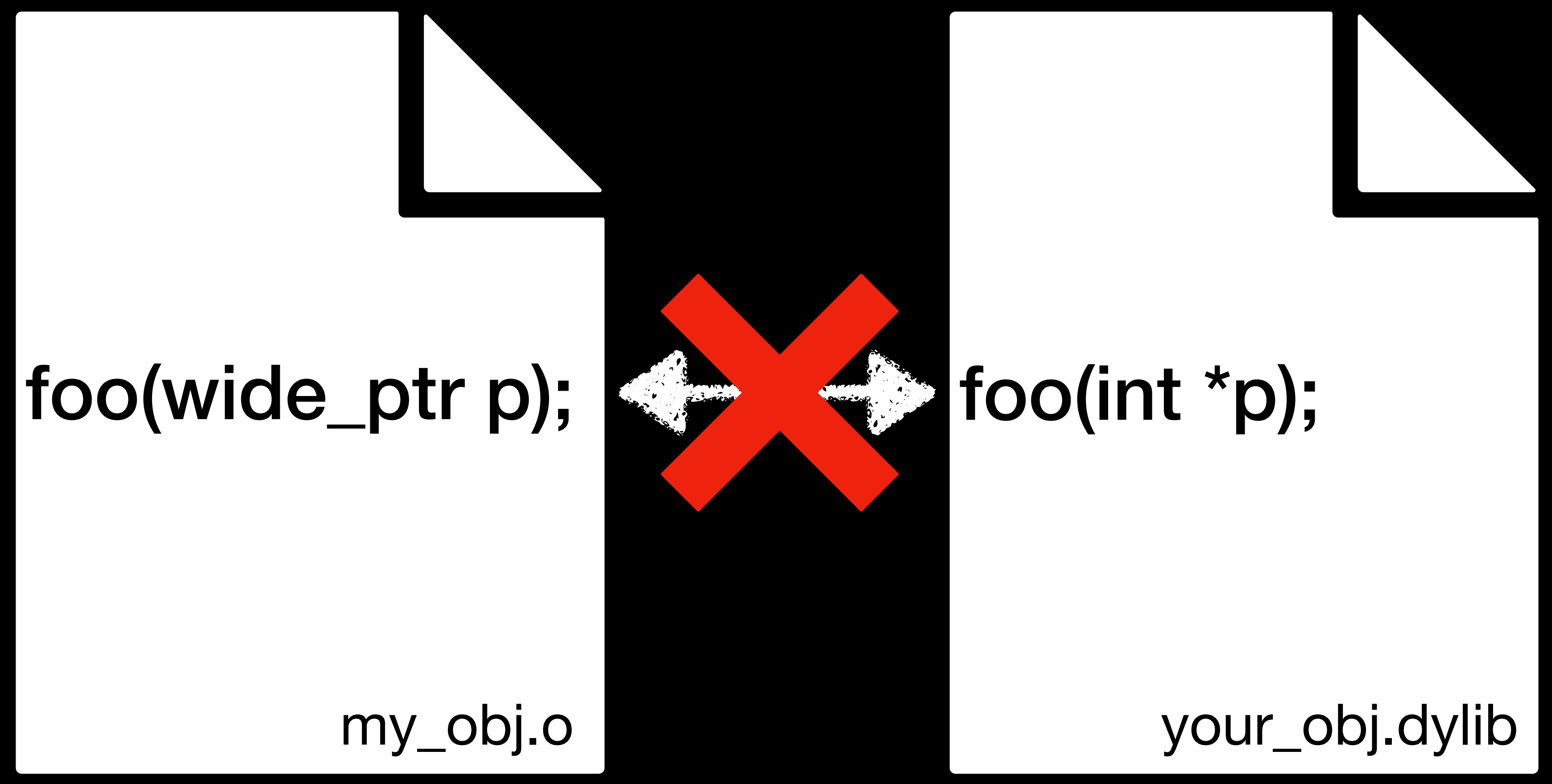


Problem: Wide pointers break Application Binary Interface (ABI)

- Problem interacting with external libraries
- Difficult to incrementally adopt the technique



Incremental adoption is crucial

- Adoption often requires significant engineering effort
- Adopting on a large project all at once is likely infeasible

Potential solution: Use bounds annotations

- Require programmers to provide bounds annotation on their code
  - e.g., `void foo(int *__counted_by(n) buf, int n);`
- No need to change pointer representation
- Preserves ABI
- Enables incremental adoption

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Problem: Annotation burden

- Adding annotations on every pointer requires significant programmer effort
- Prevents wide adoption in practice

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- Bounds annotations on ABI surface
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-fbounds-safety:

Automatic bounds checking with bounds annotations

- Programmers adopt bounds annotations on:
  - Function prototypes, struct fields, globals
- Compiler adds guaranteed bounds checks

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void fill_array_with_indices(int *buf, size_t count) {
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Array subscript on single pointer ‘buf’ must use a constant index of 0 to be in bounds

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-fbounds-safety doesn’t require bounds annotations all the time

Local variables are wide by default

Solution to keep bounds annotation burden low

- Compiler implicitly carries bounds for local variables
  - No manual annotation is required
- No ABI implications

```
void foo(int i) {
  char *buf = (char *)malloc(10);
  if (buf + i < buf || buf + i >= buf + 10) trap(); // automatically inserted
  buf[i] = 0xff;
  // more code ...
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All pointers except locals are single by default

- Most pointers are pointing to a single object
  - No need for pointer arithmetic
  - No need for bounds information
- Annotation __single is default for all pointers except locals

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void fill_struct(struct s_t *p);

// example usage
struct s_t s;
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- **Requirement: Must not introduce new syntax that C compilers don't understand**

Bounds annotations are macro-defined C attributes

- Bounds annotations are syntactically C type attributes
  - Do not introduce new syntax
- Bounds annotations are macro-defined
  - When defined to empty they are still valid C

-fbounds-safety solves real-world challenges

- ABI compatibility ✅
- Incremental adoption ✅
- Low adoption burden ✅
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- Allows strategy of incremental adoption

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- Found to be effective for real-world applications

Programming model

Enforcing bounds safety at language level

Bounds annotations

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- Prevents out-of-bounds memory accesses via bounds checking
- Prevents pointer operations that cannot be proven safe (or with insufficient bounds information)
- Maintains correctness of bounds annotations

-fbounds-safety prevents unsafe behaviors by …

- Compile-time warning / error when the compiler knows an operation will be unsafe
- Run-time checks and traps when behavior cannot be proven safe/unsafe at compile time
- Compiler uses its best effort to report errors at compile time

Bounds annotations

External bounds annotations

Describe relationship between pointer and bounds information

`count` is the element count of `buf`

```
void fill_array_with_indices(int *__counted_by(count) buf, size_t count) {
  for (size_t i = 0; i <= count; ++i) {
    buf[i] = i;
  }
}
```

Bounds annotation: __counted_by(N)

- `buf` has `count` elements with the valid range [0, count)
- Can be indexed in a positive direction ➡️
- Can be used inside array bracket,.e.g, int arr[__counted_by(count)]

```
void fill_array_int(int *__counted_by(count) buf, size_t count);

// example usage
fill_array_int(array, 10);
```

Bounds annotation: __sized_by(N)

- `buf` has `byte_count` with the valid range [0, byte_count)
- Can be indexed in a positive direction ➡️

```
void fill_array_byte(void *__sized_by(byte_count) buf, size_t byte_count);

// example usage
fill_array_byte(array, 10 * sizeof(array[0]));
```

Bounds annotation: __ended_by(P)

- `end` is the upper bound of `buf` with the valid range [0, end - buf)
- `buf` indexed in a positive direction ➡️; `end` in a negative direction ⬅️

```
void fill_array_to_end(int *__ended_by(end) buf, int *end);

// example usage
fill_array_to_end(array, &array[10]);
```

Maintaining correctness of __counted_by

Updating pointer may invalidate bounds information

```c
void foo(int *__counted_by(count) buf, size_t count) {
  buf = (int *)malloc(4);
}
// usage
foo(buf , 10);
```

Updating pointer may invalidate bounds information

- Updating `buf` to point to an object of byte size 4

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Assignment to 'int * __counted_by(count)' 'buf' requires corresponding assignment to 'count'

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void foo(int *__counted_by(count) buf, size_t count) {
  if (4 * sizeof(int) > 4) trap();
  buf = (int *)malloc(4);
  count = 4;
}
// usage
foo(buf , 10);
```

Annotation for C strings: __null_terminated

```c
size_t my_strlen(const char *__null_terminated str);

// example usage
size_t ak_len = my_strlen(“abcdefghijk”);
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Annotation for C strings: __null_terminated

- Indicates `str` has the null terminator

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Annotation for C strings: __null_terminated

- Indicates `str` has the null terminator
- Ensures that `str` is not accessed beyond the null terminator

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size_t ak_len = my_strlen("abcdefghijk");
```

__single: pointers to single object

- `p` is pointing to a single valid object (this is the case for most pointers)
- Can NOT be indexed in any direction 🚫

```
void fill_struct(struct s_t *__single p);

// example usage
struct s_t s = {};
fill_struct(&s);
```

Help us support more use cases with your feedback!

Internal bounds annotations

Escape hatches that allow to explicitly use wide pointers

Internal bounds annotation: __bidi_indexable

```c
void fill_array_internal_bounds(int *__bidi_indexable buf);

// example usage
int array[10] = {0};
fill_array_internal_bounds(array);
```

Internal bounds annotation: __bidi_indexable

- __bidi_indexable turns `buf` into a wide pointer with upper and lower bounds

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- ⚠️ Avoid using it on the ABI surface

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Internal bounds annotation: __indexable

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- Can be indexed in a positive direction ➡️

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```

Default pointer annotations

Key for ABI compatibility & less manual annotation

- ABI visible pointers : __single by default
- Non-ABI visible pointers : __bidi_indexable by default
- const char * : __null_terminated by default

- Secures all pointers by default
- Preserves ABI compatibility by default
- Doesn’t need manual annotation all the time

Interoperability w/ bounds-unsafe code enables incremental adoption

__unsafe_indexable: pointers from bounds-unsafe code

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- Just like normal C pointers
  - Can be indexed in both directions ↔️
  - No checks are added ❌

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// my_system.h
void *__unsafe_indexable system_function(void *__unsafe_indexable buf);
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- Default for system headers

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- The model doesn't allow initializing any safe pointer with an unsafe pointer

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int *safe_buf = unsafe_func(); // error
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- Use __unsafe_forge_bidi_indexable (T,P,S) to create a __bidi_indexable pointer from an __unsafe_indexable pointer

```
int *safe_buf =
  __unsafe_forge_bidi_indexable(int *, unsafe_func(), byte_size_of_buf); // ok
```

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- The model doesn't allow initializing any safe pointer with an unsafe pointer

```
int *safe_buf = unsafe_func(); // error
```

- Use __unsafe_forge_bidi_indexable (T,P,S) to create a __bidi_indexable pointer from an __unsafe_indexable pointer

```
int *safe_buf =
  __unsafe_forge_bidi_indexable(int *, unsafe_func(), byte_size_of_buf); // ok
```

Avoid using this intrinsic for any other purposes!

Bounds annotation summary

	ABI Compatibility	Index directions	Bounds checks	Default for
__counted_by(N)	✅	➡️	✅	
__sized_by(N)	✅	➡️	✅	
__ended_by(N)	✅	➡️	✅	
__null_terminated	✅	1️⃣➡️	✅	const char *
__single	✅	❌	✅	Function prototypes / struct fields / globals
__indexable	❌ (2x bigger)	➡️	✅	
__bidi_indexable	❌ (3x bigger)	↔️	✅	Locals
__unsafe_indexable	✅	↔️	❌	Pointers in system headers

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- Automatic bounds checks may introduce redundant checks
- LLVM optimizer remove redundant checks
- Primary motivation for the constraint-elimination pass we implement in LLVM

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Constraint elimination to remove redundant checks

- Collect known conditions through CFG
- Remove redundant checks based on the known conditions

```
for (size_t i = 0; i < count; ++i) {
   // known fact: 0 <= i < count
   if (i < 0 || i >= count) trap(); // <- always `false`
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- Fewer checks will be inserted if the code already has most of the necessary bounds checks

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Performance impact

Benchmark results
w/ Ptrdist and Olden benchmark suites

- Pointer-intensive benchmark suites used by other related approaches
- Did not adopt two benchmarks, one in Ptrdist and one in Olden

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  - Can be improved with optimization improvements

System-level performance impact

- Measurement on iOS
- 0-8% binary size increase per project
- No measurable performance or power impact on boot, app launch
- Minor overall performance impact on audio decoding/encoding (1%)

- **System-level performance cost is remarkably low and worth paying for the security benefit**

Acknowledgments

- Félix Cloutier
- Patryk Stefanski
- Dan Liew
- Henrik Olsson
- Florian Hahn
- Devin Coughlin
- Filip Pizlo

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- Planning to upstream and standardize the language model
- RFC is coming soon — we are very excited to get your feedback!