Lecture 5:
Reasoning About Code

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Announcements

- Homework 0 due today, Homework 1 due next Friday.
- Midterm 1 date is finalized: Wednesday 2/19 at 8pm.

Approaches for Ensuring Memory Safety

- Use a memory-safe language (“safe by design”)
- Use a non-memory-safe language, and check bounds in your code
- Use a non-memory-safe language, and harden the code against common exploits

Reasoning About Memory Safety

- How can we have ***confidence*** that our code executes in a memory-safe (and correct, ideally) fashion?
- Approach: build up confidence on a function-by-function / module-by-module basis
- Modularity provides boundaries for our reasoning:
  - ***Preconditions***: what must hold for function to operate correctly
  - ***Postconditions***: what holds after function completes
- These basically describe a contract for using the module
- Notions also apply to individual statements (what must hold for correctness; what holds after execution)
  - Stmt #1's postcondition should logically imply Stmt #2's precondition
  - Invariants: conditions that always hold at a given point in a function (this particularly matters for loops)

```
int deref(int *p) {
    return *p;
}
```

Precondition?

```c
/* requires: p != NULL
               (and p a valid pointer) */
int deref(int *p) {
    return *p;
}
```

Precondition: what needs to hold for function to operate correctly.

Needs to be expressed in a way that a *person* writing code to call the function knows how to evaluate.

```
void *mymalloc(size_t n) {
    void *p = malloc(n);
    if (!p) { perror("malloc"); exit(1); }
    return p;
}
```

Postcondition?

```c
/* ensures: retval != NULL (and a valid pointer) */
void *mymalloc(size_t n) {
    void *p = malloc(n);
    if (!p) { perror("malloc"); exit(1); }
    return p;
}
```

Postcondition: what the function promises will hold upon its return.

Likewise, expressed in a way that a person using the call in their code knows how to make use of.

```c
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    total += a[i];
  return total;
}
```

Precondition?

```c
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    total += a[i];
  return total;
}
```

General correctness proof strategy for memory safety:

(1) Identify each point of memory access
(2) Write down precondition it requires
(3) Propagate requirement up to beginning of function

```
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
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```
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* ?? */
    total += a[i];
  return total;
}
```

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```
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* requires: a != NULL &&
                 0 <= i && i < size(a) */
    total += a[i];
  return total;
}
```

size(X) = number of *elements* allocated for region pointed to by X
size(NULL) = 0

This is an <u>abstract</u> notion, *not* something built into C (like **`sizeof`**).

Gene

(1) Id

(2) Write down precondition it requires

(3) Propagate requirement up to beginning of function

```
int sum(int a[], size_t n) {
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                 0 <= i && i < size(a) */
    total += a[i];
  return total;
}
```

Let’s simplify, given that `a` never changes.

```c
/* requires: a != NULL */
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* requires: 0 <= i && i < size(a) */
    total += a[i];
  return total;
}
```

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/* requires: a != NULL */
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/* requires: a != NULL */
int sum(int a[], size_t n) {     ✓
  int total = 0;
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/* requires: a != NULL */
int sum(int a[], size_t n) {      ✓
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* requires: 0 <= i && i < size(a) */
    total += a[i];
  return total;
}
```

The `0 <= i` part is clear, so let's focus for now on the rest.

```c
/* requires: a != NULL */
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* requires: i < size(a) */
    total += a[i];
  return total;
}
```

```c
/* requires: a != NULL */
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* requires: i < size(a) */
    total += a[i];
  return total;
}
```

?

General correctness proof strategy for memory safety:

(1) Identify each point of memory access
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(3) Propagate requirement up to beginning of function?

```
/* requires: a != NULL */
int sum(int a[], size_t n) {          ?
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* invariant?: i < n && n <= size(a) */
    /* requires: i < size(a) */
    total += a[i];
  return total;
}
```

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  int total = 0;
  for (size_t i=0; i<n; i++)
    /* invariant?: i < n && n <= size(a) */
    /* requires: i < size(a) */
    total += a[i];
  return total;
}
```

?

How to prove our candidate invariant?

`n <= size(a)` **is straightforward because** `n` **never changes.**

```
/* requires: a != NULL && n <= size(a) */
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* invariant?: i < n && n <= size(a) */
    /* requires: i < size(a) */
    total += a[i];
  return total;
}
```

```
/* requires: a != NULL && n <= size(a) */
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* invariant?: i < n && n <= size(a) */    ?
    /* requires: i < size(a) */
    total += a[i];
  return total;
}
```

What about `i < n` ?

```
/* requires: a != NULL && n <= size(a) */
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* invariant?: i < n && n <= size(a) */        ?
    /* requires: i < size(a) */
    total += a[i];
  return total;
}
```

What about `i < n`? That follows from the loop condition.

```
/* requires: a != NULL && n <= size(a) */
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* invariant: i < n && n <= size(a) */
    /* requires: i < size(a) */
    total += a[i];
  return total;
}
```

At this point we know the proposed invariant will always hold...

```c
/* requires: a != NULL && n <= size(a) */
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* invariant: i < n && n <= size(a) */
    /* requires: i < size(a) */
    total += a[i];
  return total;
}
```

… and we're done!

```
/* requires: a != NULL && n <= size(a) */
int sum(int a[], size_t n) {
  int total = 0;
  for (size_t i=0; i<n; i++)
    /* invariant: a != NULL &&
       0 <= i && i < n && n <= size(a) */
    total += a[i];
  return total;
}
```

A more complicated loop might need us to use *induction*:

Base case: first entrance into loop.

Induction: show that *postcondition* of last statement of loop, plus loop test condition, implies invariant.

```c
int sumderef(int *a[], size_t n) {
    int total = 0;
    for (size_t i=0; i<n; i++)
        total += *(a[i]);
    return total;
}
```

```
/* requires: a != NULL &&
      size(a) >= n &&
             ???                         */
int sumderef(int *a[], size_t n) {
    int total = 0;
    for (size_t i=0; i<n; i++)
        total += *(a[i]);
    return total;
}
```

```
/* requires: a != NULL &&
     size(a) >= n &&
     for all j in 0..n-1, a[j] != NULL */
int sumderef(int *a[], size_t n) {
    int total = 0;
    for (size_t i=0; i<n; i++)
        total += *(a[i]);
    return total;
}
```

This may still be memory ***safe***
but it can still have undefined behavior!

```c
char *tbl[N]; /* N > 0, has type int */


int hash(char *s) {
  int h = 17;
  while (*s)
    h = 257*h + (*s++) + 3;
  return h % N;
}

bool search(char *s) {
  int i = hash(s);
  return tbl[i] && (strcmp(tbl[i], s)==0);
}
```

```
char *tbl[N];

/* ensures: ??? */
int hash(char *s) {
  int h = 17;
  while (*s)
    h = 257*h + (*s++) + 3;
  return h % N;
}
```

What is the correct *postcondition* for hash()?

(a) 0 <= retval < N, (b) 0 <= retval,

(c) retval < N, (d) none of the above.

Discuss with a partner.

=0);

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Discuss with a partner.

```
=0);
```

```
char *tbl[N];

/* ensures: 0 <= retval && retval < N */
int hash(char *s) {
  int h = 17;                        /* 0 <= h */
  while (*s)
    h = 257*h + (*s++) + 3;
  return h % N;
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bool search(char *s) {
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  return tbl[i] && (strcmp(tbl[i], s)==0);
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/* ensures: 0 <= retval && retval < N */
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  int h = 17;                          /* 0 <= h */
  while (*s)                           /* 0 <= h */
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char *tbl[N];

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int hash(char *s) {
  int h = 17;                   /* 0 <= h */
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    h = 257*h + (*s++) + 3;     /* 0 <= h */
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bool search(char *s) {
  int i = hash(s);
  return tbl[i] && (strcmp(tbl[i], s)==0);
}
```

```
char *tbl[N];

/* ensures: 0 <= retval && retval < N */
int hash(char *s) {
  int h = 17;                          /* 0 <= h */
  while (*s)                           /* 0 <= h */
    h = 257*h + (*s++) + 3;            /* 0 <= h */
  return h % N; /* 0 <= retval < N */
}

bool search(char *s) {
  int i = hash(s);
  return tbl[i] && (strcmp(tbl[i], s)==0);
}
```

```c
char *tbl[N];

/* ensures: 0 <= retval && retval < N */
unsigned int hash(char *s) {
  unsigned int h = 17;            /* 0 <= h */
  while (*s)                      /* 0 <= h */
    h = 257*h + (*s++) + 3;       /* 0 <= h */
  return h % N;         /* 0 <= retval < N */
}

bool search(char *s) {
  unsigned int i = hash(s);
  return tbl[i] && (strcmp(tbl[i], s)==0);
}
```

Memory safe languages

- You can spare yourself this work by using a memory-safe language
  - Turns "undefined" memory references into an immediate exception or program termination
  - Now you simply don't have to worry about buffer overflows and similar vulnerabilities
- Plenty to choose from:
  - Python, Java, Go, Rust, Swift, C#, … Pretty much everything other than C/C++/Objective C

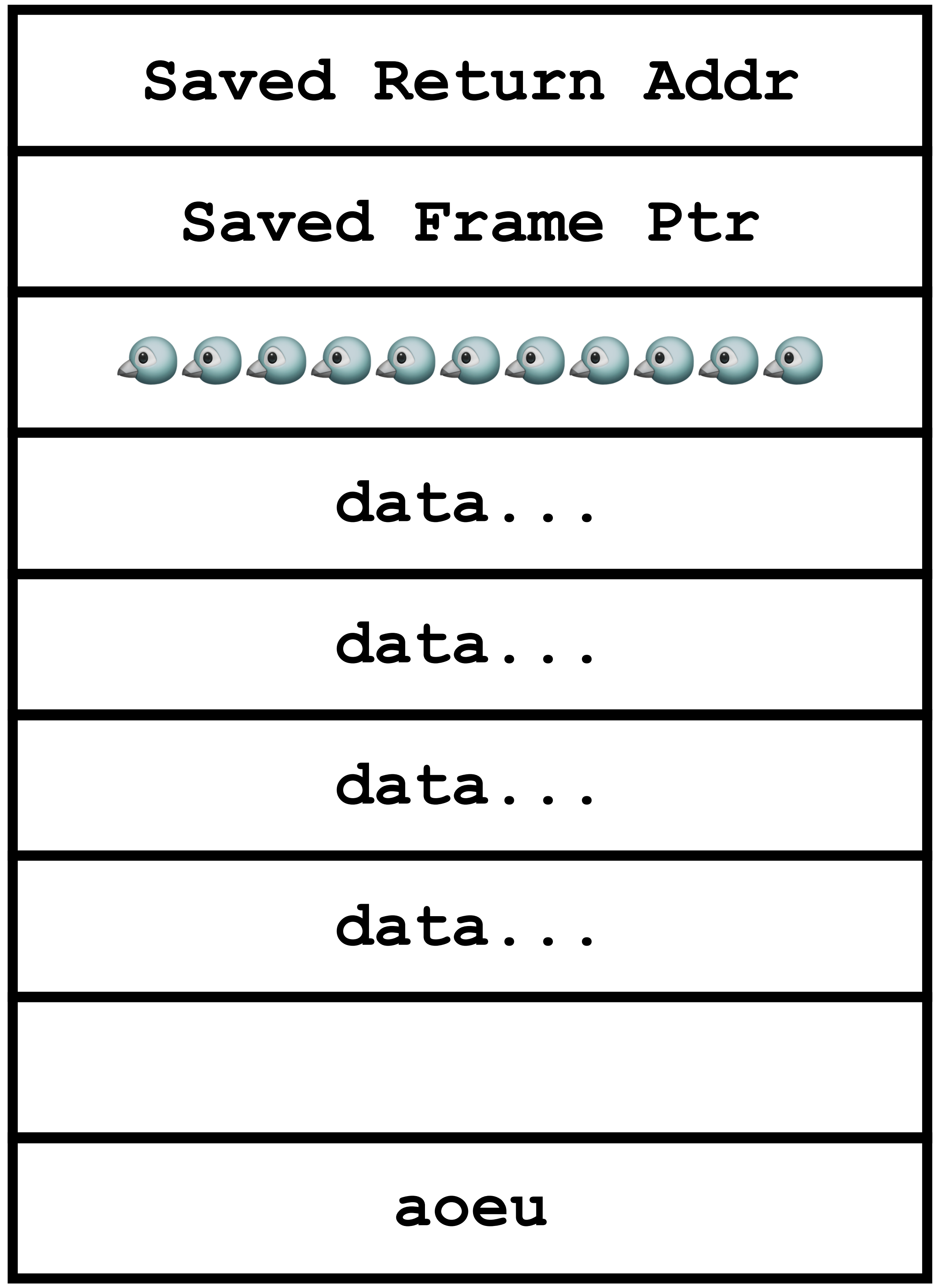
Code Hardening

Defending Legacy Code

- A large back-and-forth arms race trying to prevent memory errors from being ***exploitable for code injection***
  - An attacker can still use them to crash the program
  - An attempt at defense-in-depth
- Stack Canaries
- Non-Executable Pages (aka DEP or W^X)
- Address Space Layout Randomization (ASLR)

Stack Canaries

- Goal: protect the return pointer from being overwritten by a stack buffer…
- Store canary before saved return address
  - “Stack canary” = random value chosen when program starts
  - Function prologue pushes canary, epilogue checks canary against stored value to see if it has changed



Attacks on Stack Canaries

- Learn the value of the canary, and overwrite it with itself
  - e.g., a format string vulnerability, an information leak elsewhere that dumps it
- Random-access write past the canary
  - Canary only defends against consecutive writes
- Overflow in the heap
- Overwrite function pointer or C++ object on the stack
- Bottom line: Bypassable but raises the bar
  - A simple stack overflow doesn't work anymore:
    Need something a bit more robust
  - Minor but nearly negligible performance impact