Systems and Internet Infrastructure Security

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CMPSC 447
Spatial Errors

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Spatial Errors

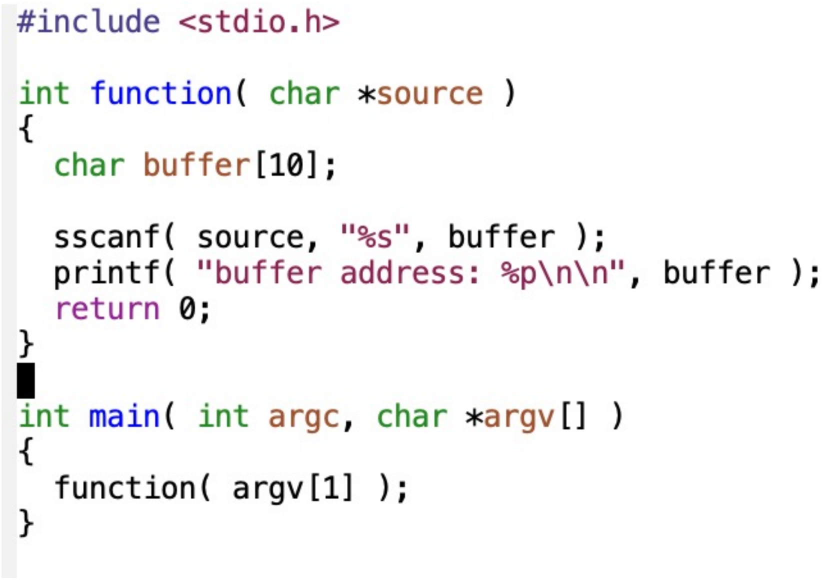
- Most common errors permit access to memory outside of the expected region
  - These are called spatial errors
  - Access outside the expected "space"
- Most of these errors are permitted by simple programming flaws
  - Of the sort that you are not taught to avoid
  - Let's see how such errors can be avoided
- Some of the changes are rather simple

Spatial Errors

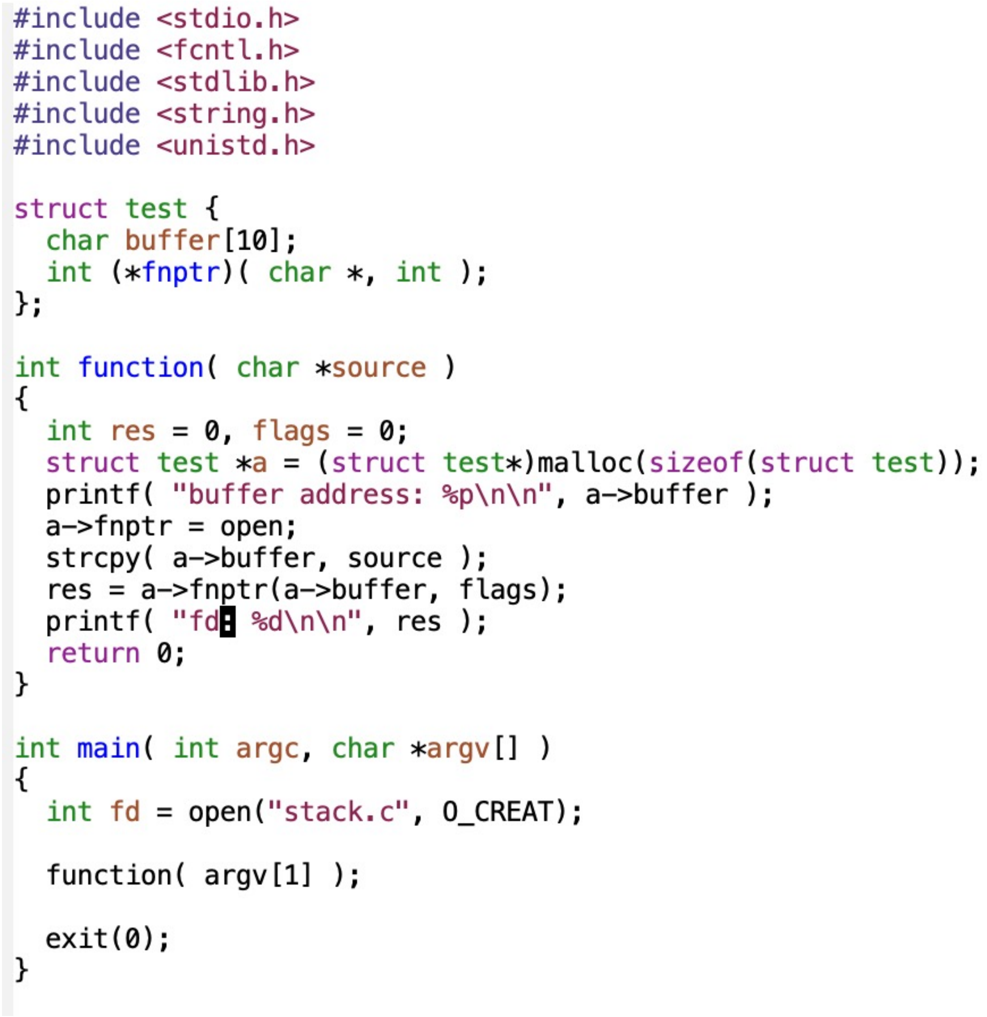
- Many of the exploits that we have discussed are the result of spatial errors

Spatial Errors

- What were the fundamental causes from these two example?



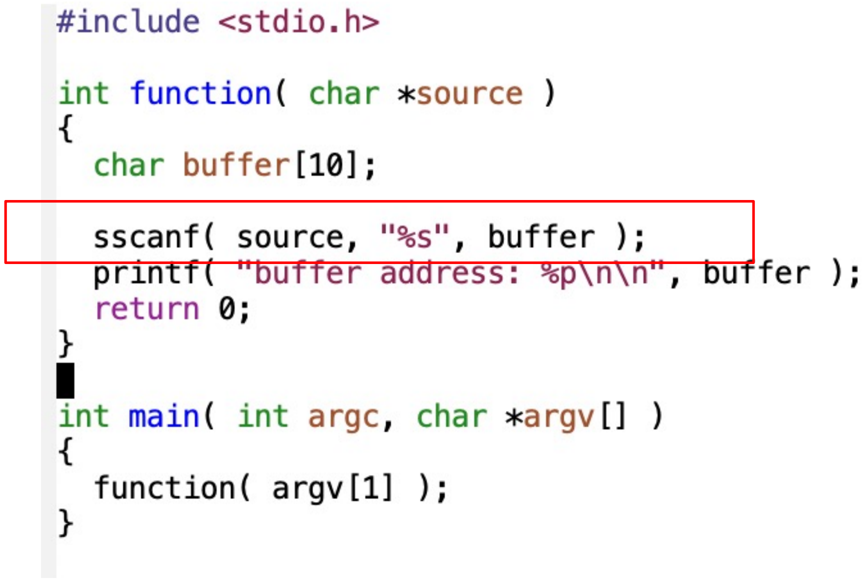
```c
#include <stdio.h>

int function( char *source )
{
  char buffer[10];

  sscanf( source, "%s", buffer );
  printf( "buffer address: %p\n\n", buffer );
  return 0;
}

int main( int argc, char *argv[] )
{
  function( argv[1] );
}
```



```c
#include <stdio.h>
#include <fcntl.h>
#include <stdlib.h>
#include <string.h>
#include <unistd.h>

struct test {
  char buffer[10];
  int (*fnptr)( char *, int );
};

int function( char *source )
{
  int res = 0, flags = 0;
  struct test *a = (struct test*)malloc(sizeof(struct test));
  printf( "buffer address: %p\n\n", a->buffer );
  a->fnptr = open;
  strcpy( a->buffer, source );
  res = a->fnptr(a->buffer, flags);
  printf( "fd: %d\n\n", res );
  return 0;
}

int main( int argc, char *argv[] )
{
  int fd = open("stack.c", O_CREAT);

  function( argv[1] );

  exit(0);
}
```

Spatial Errors

- Operations that may handle string buffers unsafely



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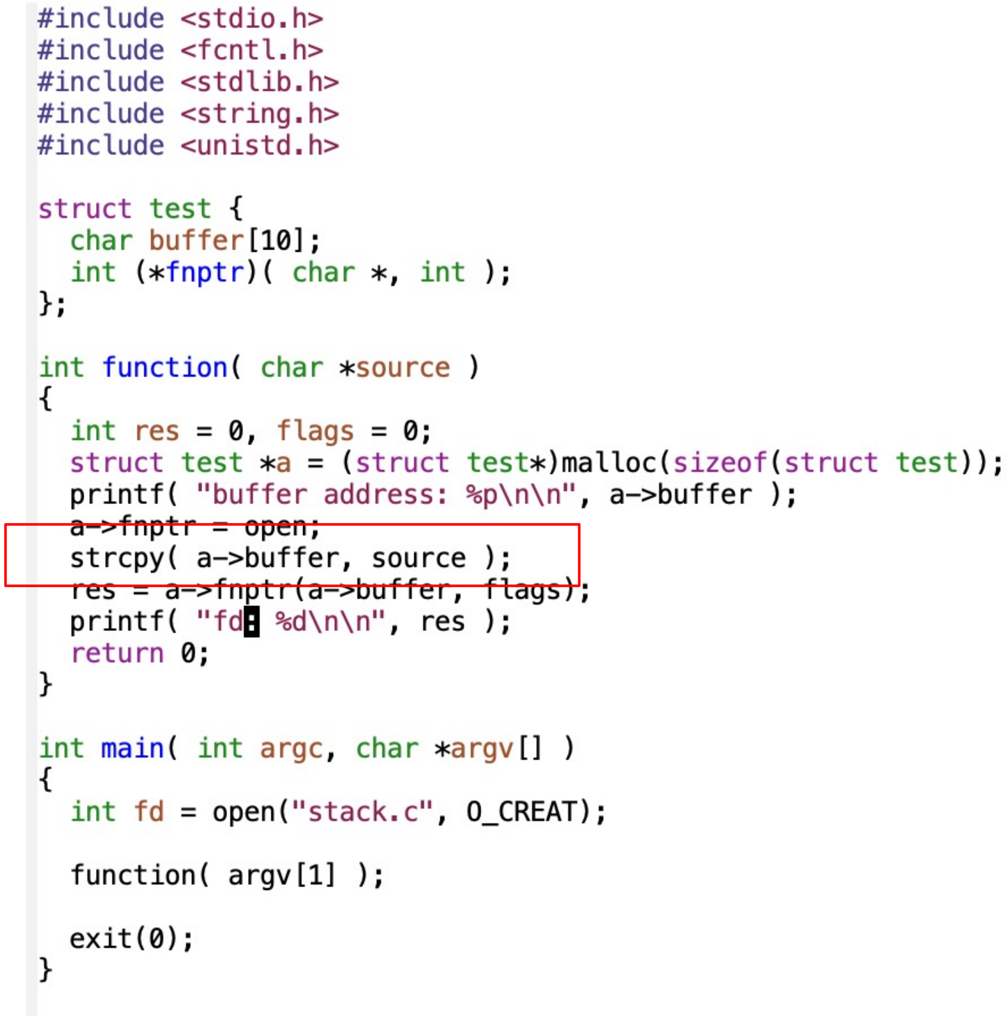

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What Is Going Wrong?

- Both of these functions process "strings"?
  - What is a string?

What Is Going Wrong?

- Both of these functions process “strings”?
  - What is a string?
    - Sequence of bytes terminating with a null byte
- Issues with strings
  - Sequence may be longer than the memory region (bounds)
  - Sequence may not be terminated by a null byte (bounds)
  - Sequence may be terminated before expected (truncate)
- Each of these issues may lead to problems
  - If undetected

Obvious Solution in C

- "Obvious" solution when using C is to always enforce bounds

Enforcing Bounds

- Two ways to enforce bounds
  - Check memory bounds
  - Automatic memory resizing
- Checking bounds
  - Make sure that a memory operation is limited to the associated memory region
- Automatic resizing
  - Resize the memory region to accommodate the memory required to satisfy the operation safely
- Typical functions do not check bounds or auto resize

Function w/o Bounds Checks

- gets(3) – reads input without checking. Don’t use it!
- strcpy(3) – *strcpy(dest, src)* – copies from *src* to *dest*
  - If *src* longer than *dest* buffer, keeps writing!
- strcat(3) – *strcat(dest, src)* – appends *src* to *dest*
  - If src+data-in-dest longer than dest buffer, keeps writing!
- scanf() family of input functions – many options
  - *scanf*(3), *fscanf*(3), *sscanf*(3), *vscanf*(3), *vsscanf*(3), *vfscanf*(3)
  - Default options don’t control max length (e.g., bare “%s”)
- Many other dangerous functions, e.g.:
  - realpath(3), getopt(3), getpass(3)
  - streadd(3), strecpy(3), and strtrns(3)

Bounds Checking Methods

- For each byte in the operation:
- If oversized option (1) – stop processing input
  - Reject and try again, or even halt program (may make DoS)
- If oversized option (2) – truncate data
  - Common approach, but has issues:
    - Terminates text “in the middle” at place of attacker’s choosing
    - *Way* better to truncate than to allow easy buffer overflow attack
    - But, still could lead to problems?

Truncation

- Issues with truncation
  - Terminates text "in the middle" at place of attacker's choosing
  - Can strip off critical data, escapes, etc. at the end
  - Can break in the middle of multi-byte character
    - UTF-8 variable-width character encoding (> one byte sometimes)
    - UTF-16 usually 2 bytes/character, but can be 4 bytes/character
  - Some routines truncate & return indicator so you can stop processing input

Automatic Resizing

- For each byte in the operation:
- If oversized – Auto-resize – move string to a new memory region, if necessary
  - This is what most languages do automatically
    - other than C
    - Must deal with "too large" data
- By default, handling auto-resize manually in C can create issues
  - More code changes/complexity in existing C code
  - Dynamic allocation is manual in C, so adds new risks
    - Temporal errors – later

Traditional Solutions

- Depend mostly on strncpy(3), strncat(3), sprintf(3)
  - Can be hard to use correctly
- char **strncpy*(char *DST, const char *SRC, size_t LENGTH)
  - Copy bytes from SRC to DST
  - Up to LENGTH bytes; if less, NULL-fills
- If LENGTH is the size of the DST memory region
  - Can fill memory region without null-terminator
    - Thus, does not guarantee creating a C string
  - Can truncate "in the middle," leaving malformed data
    - Yet difficult to detect when it happens

Traditional Solutions

- Depend mostly on strncpy(3), strncat(3), sprintf(3)
  - Can be hard to use correctly
- char **strncat*(char *DST, const char *SRC, size_t LENGTH)
  - Find end of string in DST (\0)
  - Append up to LENGTH characters in SRC there
- If result is the size of the DST memory region
  - Can fill memory region without null-terminator
    - Thus, does not guarantee creating a C string
  - Can truncate "in the middle," leaving malformed data
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Strncpy/Strncat

- Fill buffer to length and return reference to result
  - No termination

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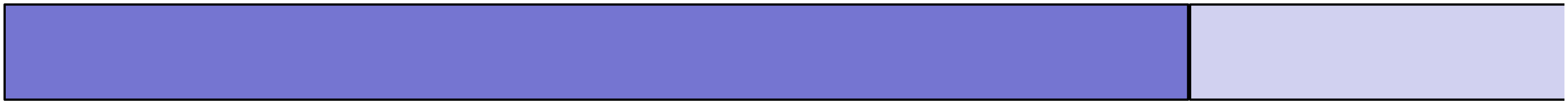
  - Truncation? How do we check?



  - Only returns a reference to the start of the region
    - Telling us nothing about its state

Traditional Solutions

- Depend mostly on strncpy(3), strncat(3), sprintf(3)
  - Can be hard to use correctly
- int *sprintf*(char *STR, const char *FORMAT, ...);
  - Results put into STR
  - FORMAT can include length control information
- For example, *sprintf*(DEST, "%.*s", MAXLEN, SRC);
  - Like strncpy/strncat, does not guarantee null-termination
    - Does return the number of characters “printed”
  - Don’t forget the “.” – or no bounds checking
  - Using "*", then you can pass the maximum size (MAXLEN) as a parameter

There Is Help

- There are command APIs and options for existing commands that provide
  - Bound checking and notification of truncation
  - Auto-resizing without truncation
- The ones available now are a bit complex, but others have been proposed that are not yet widely available

Traditional Solution – That Works!

- Available now: snprintf(3), vsnprintf(3)
  - Essentially the same functions, although arg format differs
- int *snprintf*(char *S, size_t N, const char *FORMAT, ...);
  - Writes output to buffer S up to N chars (bounds check)
  - Always writes '\0' at end if N>=1 (terminate)
  - Returns "length that would have been written" or negative if error (reports truncation or error)
- Thus, achieves goals of correct bounds checking
  - Enforces bounds, ensures correct C string, and reports truncation or error
    - len = snprintf(buf, buflen, "%s", original_value);
    - if (len < 0 || len >= buflen) … // handle error/truncation

Traditional Solution – That Works!

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  - Essentially the same functions, although arg format differs
- int *snprintf*(char *S, size_t N, const char *FORMAT, ...);
  - So, you should use this for safe programming today
  - Replaces strcpy and others directly
  - How do you use for strcat?

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- int *snprintf*(char *S, size_t N, const char *FORMAT, ...);
  - So, you should use this for safe programming today
  - Replaces strcpy and others directly
  - How do you use for strcat?
    - Need to find end of string to concatenate – set to S
    - Need to find the remaining size of the buffer – set to N
      - Do need to compute this correctly
    - At least this snprintf/vsnprintf will ensure null-termination at N
    - Don't forget to check whether truncation or an error occurred

Traditional Solution – That Works!

- Available now: snprintf(3), vsnprintf(3)
  - Essentially the same functions, although arg format differs
- int *snprintf*(char *S, size_t N, const char *FORMAT, ...);
  - Kind of ugly to use
  - Other options?

Emerging Solutions

- Available in limited systems: strlcpy(3), strlcat(3)
  - Similar to snprintf in semantics – from *BSD
- Int *strlcpy*(char *DST, const char *SRC, size_t SIZE);
  - Looks more like strncpy/strncat; but less error prone
  - Take SIZE of the buffer DST – rather than a length (bounds)
  - Ensure null-termination relative to SIZE (terminate)
  - Return number of bytes that would have been read (truncate)
- Relatively easy to use
  - if (strlcpy(dest, src, destsize) >= destsize) … // truncation!
  - Not universally available

Emerging Solutions

- Available in limited systems: strcpy_s, strcat_s
  - Similar to snprintf in semantics – from Microsoft
- errno_t *strcpy_s*(char *restrict DST, rsize_t SIZE, const char *restrict SRC);
  - Looks more like strncpy/strncat; but less error prone
  - Take SIZE of the buffer DST – rather than a length (bounds)
  - Checks constraints and returns if they are met (return 0)
  - Key constraint: all bytes of SRC will fit in DST with \0
- Relatively easy to use
  - if (strcpy_s(dest, src, destsize) < 0) … // truncation!
  - Not universally available – multithreading limitations

Safe Bounds Checking

- Take the size of the buffer
  - Limit length based on buffer size with termination

  - Truncation: detect happens and how much truncation

  - Return value enables determination whether any and ho much truncation occurred to assess security

Auto Resize Solutions

- Available in limited systems: asprintf(3), vasprintf(3)
  - Auto-resize versions of sprint and vsprintf (are unsafe)
- int *asprintf*(char **S, const char *FORMAT, ...);
  - Pass a pointer to a reference to a string buffer
  - Memory for the buffer and its reference are assigned to S
  - The memory allocated is sufficient to hold a proper C string of the value resulting from the processing of FORMAT
  - Returns # of bytes "printed"; -1 if error
- Simple to use; no termination, but need to "free"
  - char *result = NULL;
  - asprintf(&result, "x=%s and y=%s\n", x, y);

Scanf and Friends

- What about other functions like scanf?
  - scanf, fscanf, sscanf, vscanf, vsscanf, vfscanf – all unsafe by default
  - Why?
    - char buffer[10];
    - scanf(buffer, “%s”);

Scanf and Friends

- What about other functions like scanf?
  - scanf, fscanf, sscanf, vscanf, vsscanf, vfscanf – all unsafe by default
  - Why?
    - char buffer[10];
    - scanf(buffer, “%s”);
  - Fortunately, these can be made safe quite easily
    - By leveraging auto-resizing option

Scanf and Friends

- What about other functions like scanf?
  - scanf, fscanf, sscanf, vscanf, vsscanf, vfscanf – all unsafe by default
  - Instead, use “%ms” to auto-resize
    - char *buffer = NULL;   // Must be set to NULL
    - scanf(buffer, “%ms”);
  - Allocates memory for the buffer dynamically to hold input safely – null-terminated, no truncation required
- Note: also, can use for other functions that process input like getline
  - Should check whether the function you use supports this option

Scanf in a Loop

- What happens when…
  - Use “%ms” to auto-resize, but the function (scanf) is in a loop?
    - char *buffer = NULL;   // Must be set to NULL
    - while (TRUE) {
    -         scanf(buffer, “%ms”);
    - }

Scanf in a Loop

- What happens when…
  - Use “%ms” to auto-resize, but the function (scanf) is in a loop?
    - char *buffer = NULL;   // Must be set to NULL
    - while (TRUE) {
    -         scanf(buffer, “%ms”);
    - }
- Good news: The library knows and will keep resizing!
  - If necessary – when the input is too big for the current buffer

Memory Object Copying

- What about just copying memory buffers?
    - That are not strings (i.e., no termination)
    - E.g., structure
- What would you normally do to copy a structure of an object of type A to a memory region of size N?

Traditional Solution

- Usual: memcpy(3)
    - Basic copying of memory values to a new region
- void **memcpy*(void *restrict DST, const void *restrict SRC, size_t N);
- Copies N bytes from memory area SRC to memory area DST
    - Provides bounds checking
    - Does not consider null-termination
        - No null-terminator in this case, so that is OK
    - Does not consider truncation
        - Need to check for that

Memory and Strings

- POSIX now includes memccpy:
- void* *memccpy*(void* restrict DST, const void* restrict SRC, int C, size_t N);
  - Copies up to N bytes from SRC to DST until C is found, which is copied (e.g., C ='\0', so can use for strings),
  - Returns a pointer to just past the copy of the specified character C
  - or NULL if C was not found in the first N characters of SRC
  - So, can detect whether truncation occurred
- Note: You still have to calculate N (# bytes to copy)
- Adopted by C standard committee in 2019

Take Away

- The original versions of C string and memory functions did not consider spatial errors
  - So, spatial errors have become common
- To ensure correct operation, we need to enforce memory region bounds
  - Check bounds or automatically resize
- There are now several function APIs that enforce bounds
  - Check bounds, ensure null-termination (if required), and report whether truncation occurred (to assess)