CS107, Lecture 6
C Strings

Reading: K&R (1.9, 5.5, Appendix B3) or Essential C section 3

CS107 Topic 2: How can a computer represent and manipulate more complex data like text?

CS107 Topic 2

How can a computer represent and manipulate more complex data like text?

Why is answering this question important?

- Shows us how strings are represented in C and other languages (this time)
- Helps us better understand buffer overflows, a common bug (this time)
- Introduces us to pointers, because strings can be pointers (next time)

assign2: implement 2 functions a 1 program using those functions to find the location of different built-in commands in the filesystem. You'll write functions to extract a list of possible locations and tokenize that list of locations.

Learning Goals

- Learn how strings are represented in C; as an array of null-terminated characters.
- Understand how to use the built-in string functions for common string tasks
- Learn about buffer overflow and what might cause it

Goal: String Diamond

Write a function **`diamond`** that accepts a string parameter and prints its letters in a "diamond" format as shown below.

- For example, `diamond("BAILEY")` should print:

```
B
BA
BAI
BAIL
BAILE
BAILEY
 AILEY
  ILEY
   LEY
    EY
     Y
```

Lecture Plan

- Characters
- Strings
- Common String Operations
  - Comparing
  - Copying
  - Concatenating
  - Substrings

```
cp -r /afs/ir/class/cs107/lecture-code/lect6 .
```

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```

Char

A **`char`** is a variable type that represents a single character or "glyph".

```
char letterA = 'A';
char plus = '+';
char zero = '0';
char space = ' ';
char newLine = '\n';
char tab = '\t';
char singleQuote = '\'';
char backSlash = '\\';
```

ASCII

Under the hood, C represents each **`char`** as an *integer* (its "ASCII value").

- Uppercase letters are sequentially numbered
- Lowercase letters are sequentially numbered
- Digits are sequentially numbered
- Lowercase letters are 32 more than their uppercase equivalents (bit flip!)

```
char uppercaseA = 'A';          // Actually 65
char lowercaseA = 'a';          // Actually 97
char zeroDigit = '0’;          // Actually 48
```

ASCII

We can take advantage of C representing each **`char`** as an *integer:*

```
bool areEqual = 'A' == 'A';          // true
bool earlierLetter = 'f' < 'c';      // false
char uppercaseB = 'A' + 1;
int diff = 'c' - 'a';                // 2
int numLettersInAlphabet = 'z' – 'a' + 1;
// or
int numLettersInAlphabet = 'Z' – 'A' + 1;
```

ASCII

We can take advantage of C representing each **`char`** as an *integer:*

```
// prints out every lowercase character
for (char ch = 'a'; ch <= 'z'; ch++) {
    printf("%c", ch);
}
```

Common `ctype.h` Functions

Function	Description
`isalpha(`***ch***`)`	true if *ch* is `'a'` through `'z'` `or` `'A'` through `'Z'`
`islower(`***ch***`)`	true if *ch* is `'a'` through `'z'`
`isupper(`***ch***`)`	true if *ch* is `'A'` through `'Z'`
`isspace(`***ch***`)`	true if *ch* is a space, tab, new line, etc.
`isdigit(`***ch***`)`	true if *ch* is `'0'` through `'9'`
`toupper(`***ch***`)`	returns uppercase equivalent of a letter
`tolower(`***ch***`)`	returns lowercase equivalent of a letter

Remember: these **return** a char; they cannot modify an existing char!

More documentation with `man isalpha`, `man tolower`

Common `ctype.h` Functions

```
bool isLetter = isalpha('A');        // true
bool capital = isupper('f');         // false
char uppercaseB = toupper('b');
bool isADigit = isdigit('4');        // true
```

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```
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```

C Strings

C has no dedicated variable type for strings. Instead, a string is represented as an **array of characters** with a special ending sentinel value.

`"Hello"`

index	*0*	*1*	*2*	*3*	*4*	*5*
char	`'H'`	`'e'`	`'l'`	`'l'`	`'o'`	`'\0'`

`'\0'` is the **null-terminating character**; you always need to allocate one extra space in an array for it. `'\0'` is the character with numerical value 0.

C Strings

```
char myString[6];
myString[0] = 'H';
myString[1] = 'e';
myString[2] = 'l';
…
myString[5] = '\0';
```

String Length

Strings are **<u>not</u>** objects. They do not embed additional information (e.g., string length). We must calculate this!

index	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
value	`'H'`	`'e'`	`'l'`	`'l'`	`'o'`	`','`	`' '`	`'w'`	`'o'`	`'r'`	`'l'`	`'d'`	`'!'`	`'\0'`

We can use the provided **`strlen`** function to calculate string length. The null-terminating character does *not* count towards the length.

```
int length = strlen(myStr);      // e.g. 13
```

Caution: `strlen` is `O(N)` because it must scan the entire string! We should save the value if we plan to refer to the length later.

C Strings As Parameters

When we pass a string as a parameter, it is passed as a **char ***. C passes the location of the first character rather than a copy of the whole array.

```
int doSomething(char *str) {
    ...
}

char myString[6];
...
doSomething(myString);
```

C Strings As Parameters

When we pass a string as a parameter, it is passed as a **char ***. C passes the location of the first character rather than a copy of the whole array.

```
int doSomething(char *str) {
    ...
    str[0] = 'c'; // modifies original string!
    printf("%s\n", str);   // prints cello
}

char myString[6];
... // e.g. this string is “Hello”
doSomething(myString);
```

We can still use a char * the same way as a char[].

Lecture Plan

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```
cp -r /afs/ir/class/cs107/lecture-code/lect6 .
```

Common `string.h` Functions

Function	Description
`strlen(`***`str`***`)`	returns the # of chars in a C string (before null-terminating character).
`strcmp(`***`str1, str2`***`)`, `strncmp(`***`str1, str2, n`***`)`	compares two strings; returns 0 if identical, <0 if ***str1*** comes before ***str2*** in alphabet, >0 if ***str1*** comes after ***str2*** in alphabet. ***strncmp*** stops comparing after at most ***n*** characters.
`strchr(`***`str, ch`***`)` `strrchr(`***`str, ch`***`)`	character search: returns a pointer to the first occurrence of ***ch*** in ***str***, or ***NULL*** if ***ch*** was not found in ***str***. `strrchr` find the last occurrence.
`strstr(`***`haystack, needle`***`)`	string search: returns a pointer to the start of the first occurrence of ***needle*** in ***haystack***, or ***NULL*** if ***needle*** was not found in ***haystack***.
`strcpy(`***`dst, src`***`)`, `strncpy(`***`dst, src, n`***`)`	copies characters in ***src*** to ***dst***, including null-terminating character. Assumes enough space in ***dst***. Strings must not overlap. **`strncpy`** stops after at most ***n*** chars, and <u>does not</u> add null-terminating char.
`strcat(`***`dst, src`***`)`, `strncat(`***`dst, src, n`***`)`	concatenate ***src*** onto the end of ***dst***. **`strncat`** stops concatenating after at most ***n*** characters. <u>Always</u> adds a null-terminating character.
`strspn(`***`str, accept`***`)`, `strcspn(`***`str, reject`***`)`	**`strspn`** returns the length of the initial part of ***str*** which contains <u>only</u> characters in ***accept***. **`strcspn`** returns the length of the initial part of ***str*** which does <u>not</u> contain any characters in ***reject***.

Common `string.h` Functions

Function	Description
strlen(***str***)	returns the # of chars in a C string (before null-terminating character).
strcmp(***str1, str2***), strncmp(***str1, str2, n***)	compares two strings; returns 0 if identical, <0 if ***str1*** comes before ***str2*** in alphabet, >0 if ***str1*** comes after ***str2*** in alphabet. ***strncmp*** stops comparing after at most ***n*** characters.
strchr(***str, ch***) strrchr(***str, ch***)	character search: returns a pointer to the first occurrence of ***ch*** in ***str***, or ***NULL*** if ***ch*** was not found in ***str***. strrchr find the last occurrence.
strstr(***haystack, n***	first occurrence of ot found in ***haystack***.
strcpy(***dst, src***), strncpy(***dst, src, n***)	rminating character. Assumes enough space in ***dst***. Strings must not overlap. **strncpy** stops after at most ***n*** chars, and does not add null-terminating char.
strcat(***dst, src***), strncat(***dst, src, n***)	concatenate ***src*** onto the end of ***dst***. **strncat** stops concatenating after at most ***n*** characters. Always adds a null-terminating character.
strspn(***str, accept***), strcspn(***str, reject***)	**strspn** returns the length of the initial part of ***str*** which contains only characters in ***accept***. **strcspn** returns the length of the initial part of ***str*** which does not contain any characters in ***reject***.

Many string functions assume **valid string** input; i.e., ends in a null terminator.

Comparing Strings

We <u>cannot</u> compare C strings using comparison operators like ==, < or >. This compares addresses!

```
// e.g. str1 = 0x7f42, str2 = 0x654d
void doSomething(char *str1, char *str2) {
    if (str1 > str2) { …   // compares 0x7f42 > 0x654d!
```

Instead, use **`strcmp`**.

The string library: `strcmp`

`strcmp(str1, str2)`: compares two strings.

- returns 0 if identical
- <0 if ***str1*** comes before ***str2*** in alphabet
- >0 if ***str1*** comes after ***str2*** in alphabet.

```
int compResult = strcmp(str1, str2);
if (compResult == 0) {
     // equal
} else if (compResult < 0) {
     // str1 comes before str2
} else {
     // str1 comes after str2
}
```

Copying Strings

We <u>cannot</u> copy C strings using =. This copies addresses!

```
// e.g. param1 = 0x7f42, param2 = 0x654d
void doSomething(char *param1, char *param2) {
      param1 = param2;   // copies 0x654d.  Points to same string!
      param2[0] = 'H';   // modifies the one original string!
```

Instead, use **strcpy**.

The string library: `strcpy`

`strcpy(dst, src)`: copies the contents of **src** into the string **dst**, including the null terminator.

```
char str1[6];
strcpy(str1, "hello");

char str2[6];
strcpy(str2, str1);
str2[0] = 'c';

printf("%s", str1);        // hello
printf("%s", str2);        // cello
```

Copying Strings - `strcpy`

We must make sure there is enough space in the destination to hold the entire copy, *including the null-terminating character*.

```
char str2[6];                       // not enough space!
strcpy(str2, "hello, world!");   // overwrites other memory!
```

Writing past memory bounds is called a “buffer overflow”. It can allow for security vulnerabilities!

Copying Strings – Buffer Overflows

```
char str1[14];
strcpy(str1, "hello, world!");
char str2[6];
strcpy(str2, str1);   // not enough space - overwrites other memory!
```

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	5	
str2	?	?	?	?	?	?	- other program memory -

Copying Strings – Buffer Overflows

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str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	5	
str2	'h'	?	?	?	?	?	- other program memory -

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	0	1	2	3	4	5	
str2	'h'	'e'	?	?	?	?	- other program memory -

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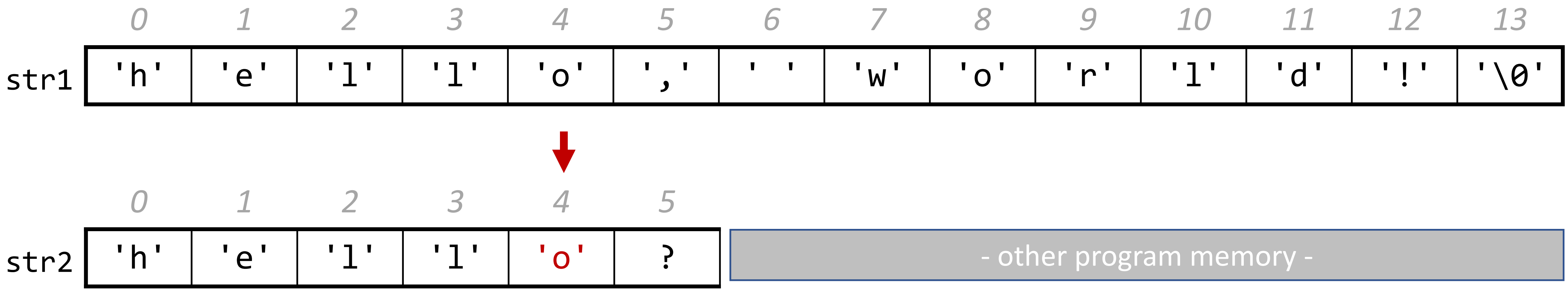

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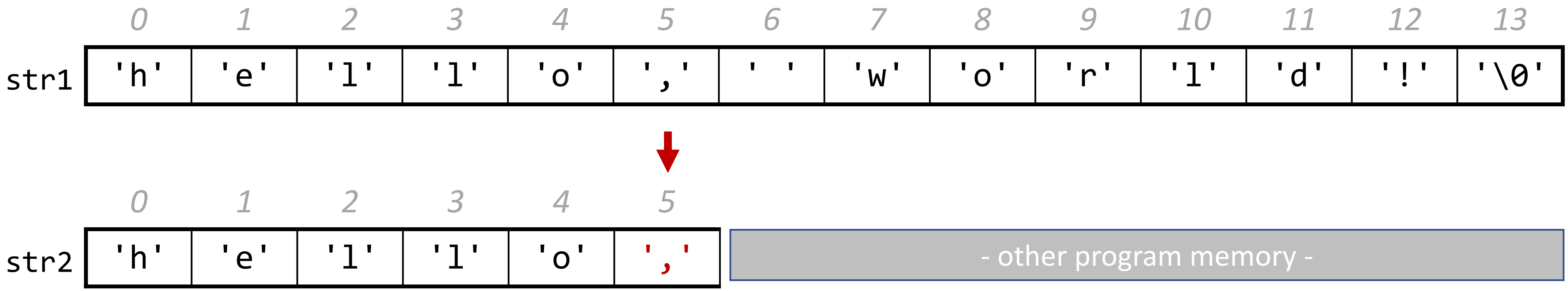

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str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	5	
str2	'h'	'e'	'l'	'l'	'o'	','	' ' - other program memory -

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str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	5			
str2	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	- other program memory -

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str2	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	- other program memory -

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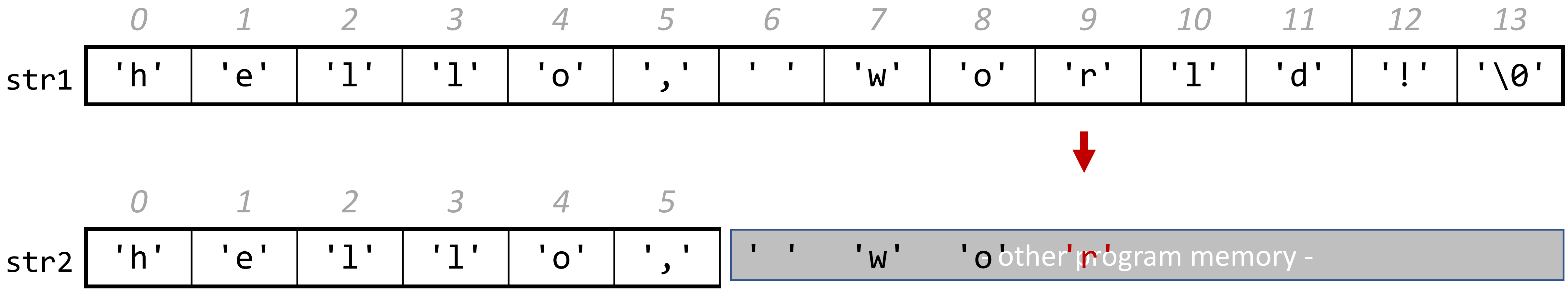

Copying Strings – Buffer Overflows

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str2	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'

- other program memory -

Copying Strings – Buffer Overflows

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char str1[14];
strcpy(str1, "hello, world!");
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str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	5	
str2	'h'	'e'	'l'	'l'	'o'	','	' ' 'w' 'o' 'r' 'l' 'd' - other program memory -

Copying Strings – Buffer Overflows

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- other program memory -

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	0	1	2	3	4	5	- other program memory -							
str2	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

Copying Strings – Buffer Overflows

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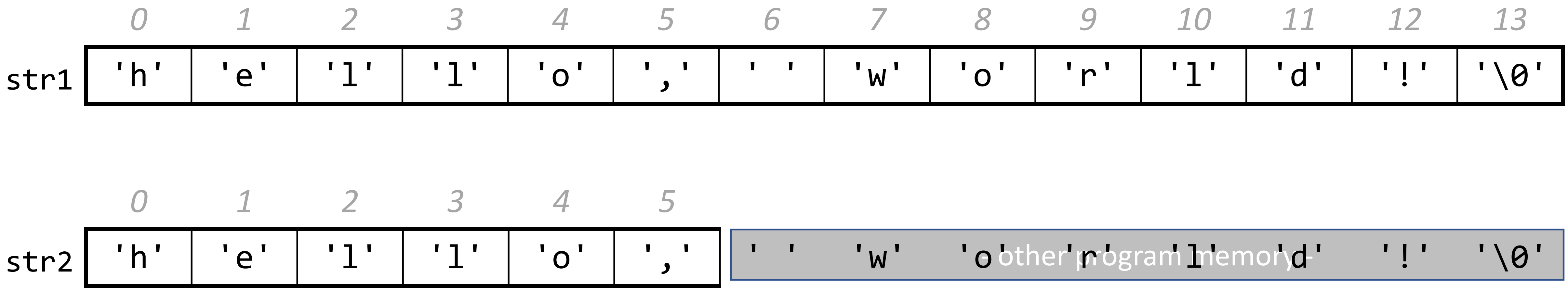

Copying Strings - `strncpy`

`strncpy(dst, src, n)`: copies at most the first n bytes from **src** into the string **dst**. If there is no null-terminating character in these bytes, then **`dst`** will *not be null terminated*!

```
// copying "hello"
char str2[5];
strncpy(str2, "hello, world!", 5);     // doesn't copy '\0'!
```

If there is no null-terminating character, we may not be able to tell where the end of the string is anymore. E.g. `strlen` may continue reading into some other memory in search of `'\0'`!

Copying Strings - strncpy

```
char str2[5];
strncpy(str2, "hello, world!", 5);
int length = strlen(str2);
```

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	
str2	?	?	?	?	?	- other program memory -

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	0	1	2	3	4	
str2	'h'	'e'	'l'	'l'	'o'	- other program memory -

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	0	1	2	3	4	
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	0	1	2	3	4	
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Copying Strings - strncpy

```c
char str2[5];
strncpy(str2, "hello, world!", 5);
int length = strlen(str2);
```

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	
str2	'h'	'e'	'l'	'l'	'o'	- other program memory -

Copying Strings - strncpy

```
char str2[5];
strncpy(str2, "hello, world!", 5);
int length = strlen(str2);
```

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	
str2	'h'	'e'	'l'	'l'	'o'	- other program memory -

Copying Strings - strncpy

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char str2[5];
strncpy(str2, "hello, world!", 5);
int length = strlen(str2);
```

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	
str2	'h'	'e'	'l'	'l'	'o'	- other program memory -

Copying Strings - strncpy

```c
char str2[5];
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	0	1	2	3	4	5	6	7	8	9	10	11	12	13
str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	
str2	'h'	'e'	'l'	'l'	'o'	- other program memory -

Copying Strings - strncpy

```
char str2[5];
strncpy(str2, "hello, world!", 5);
int length = strlen(str2);
```

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
str1	'h'	'e'	'l'	'l'	'o'	','	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	
str2	'h'	'e'	'l'	'l'	'o'	- other program memory -

Copying Strings - `strncpy`

If necessary, we can add a null-terminating character ourselves.

```
// copying "hello"
char str2[6];                               // room for string and '\0'
strncpy(str2, "hello, world!", 5);     // doesn’t copy '\0'!
str2[5] = '\0';                             // add null-terminating char
```

C Doesn’t Automatically Initialize

Important note: C doesn’t automatically initialize variables or values to a default value.

```
int x;    // contains garbage value
char str[6];  // contains garbage characters
```

Copying Strings - strncpy

```
char str1[14];
strncpy(str1, "hello there", 5);
```

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
str1	?	?	?	?	?	?	?	?	?	?	?	?	?	?

Copying Strings - strncpy

```
char str1[14];
strncpy(str1, "hello there", 5);
```

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
str1	'h'	'e'	'l'	'l'	'o'	?	?	?	?	?	?	?	?	?

Copying Strings - strncpy

```
char str1[14];
strncpy(str1, "hello there", 5);
printf("%s\n", str1);
```

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
str1	'h'	'e'	'l'	'l'	'o'	?	?	?	?	?	?	?	?	?

```
hello??J???
```

String Exercise

What is printed out by the following program?

```c
int main(int argc, char *argv[]) {
    char str[9];
    strcpy(str, "Hi earth");
    str[2] = '\0';
    printf("str = %s, len = %zu\n",
           str, strlen(str));
    return 0;
}
```

A. `str = Hi, len = 8`
B. `str = Hi, len = 2`
C. `str = Hi earth, len = 8`
D. `str = Hi earth, len = 2`
E. None/other

Respond with your thoughts on PollEv:
pollev.com/cs107 or text CS107 to 22333 once to join.

What is printed out by the example string program?

str = Hi, len = 8

str = Hi, len = 2

str = Hi earth, len = 8

str = Hi earth, len = 2

None/other

Concatenating Strings

We cannot concatenate C strings using +. This adds addresses!

```
// e.g. param1 = 0x7f, param2 = 0x65
void doSomething(char *param1, char *param2) {
    printf("%s", param1 + param2);   // adds 0x7f and 0x65!
```

Instead, use **strcat**.

The string library: `str(n)cat`

`strcat(dst, src)`: concatenates the contents of **src** into the string **dst**.

`strncat(dst, src, n)`: same, but concats at most n bytes from **src**.

```
char str1[13];          // enough space for strings + '\0'
strcpy(str1, "hello ");
strcat(str1, "world!");    // removes old '\0', adds new '\0' at end
printf("%s", str1);        // hello world!
```

Both **`strcat`** and **`strncat`** remove the old '\0' and add a new one at the end.

Concatenating Strings

```c
char str1[13];
strcpy(str1, "hello ");
char str2[7];
strcpy(str2, "world!");

strcat(str1, str2);
```

	0	1	2	3	4	5	6	7	8	9	10	11	12
str1	'h'	'e'	'l'	'l'	'o'	' '	'\0'	?	?	?	?	?	?

	0	1	2	3	4	5	6
str2	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

Concatenating Strings

```c
char str1[13];
strcpy(str1, "hello ");
char str2[7];
strcpy(str2, "world!");

strcat(str1, str2);
```

	0	1	2	3	4	5	6	7	8	9	10	11	12
str1	'h'	'e'	'l'	'l'	'o'	' '	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

	0	1	2	3	4	5	6
str2	'w'	'o'	'r'	'l'	'd'	'!'	'\0'

Substrings

To omit characters at the end, make a new string that is a partial copy of the original.

```
// Want just "race"
char str1[8];
strcpy(str1, "racecar");

char str2[5];
strncpy(str2, str1, 4);
str2[4] = '\0';
printf("%s\n", str1);          // racecar
printf("%s\n", str2);          // race
```

Goal: String Diamond

Write a function **`diamond`** that accepts a string parameter and prints its letters in a "diamond" format as shown below.

- For example, `diamond("BAILEY")` should print:

```
B
BA
BAI
BAIL
BAILE
BAILEY
 AILEY
  ILEY
   LEY
    EY
     Y
```

To start: let's print the top half of the diamond.

Demo: Diamond, Part 1

`diamond.c`

Substrings and char *

You can also create a char * variable yourself that points to an address within in an existing string.

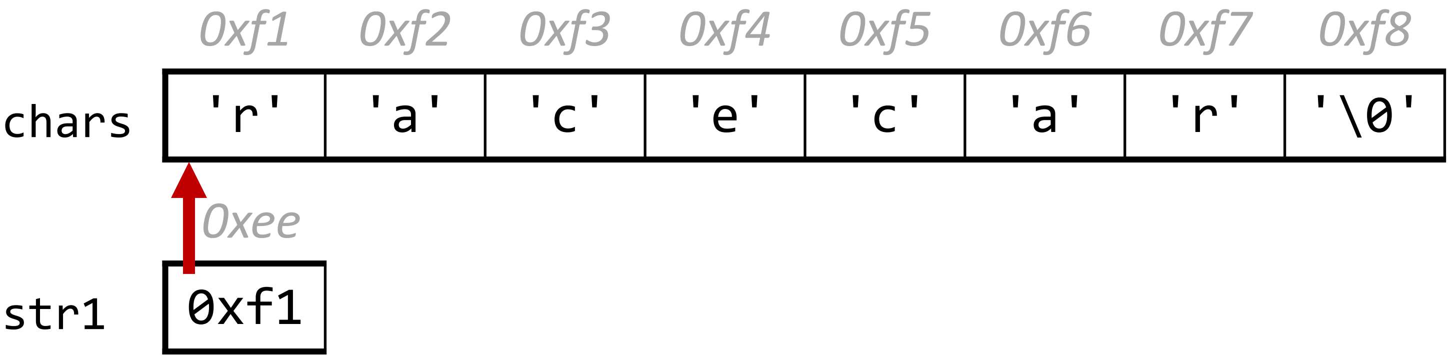
```
char myString[3];
myString[0] = 'H';
myString[1] = 'i';
myString[2] = '\0';

char *otherStr = myString;  // points to 'H'
```

Substrings

char ***s** (pointers to characters) *are strings*. We can use them to create substrings of larger strings.

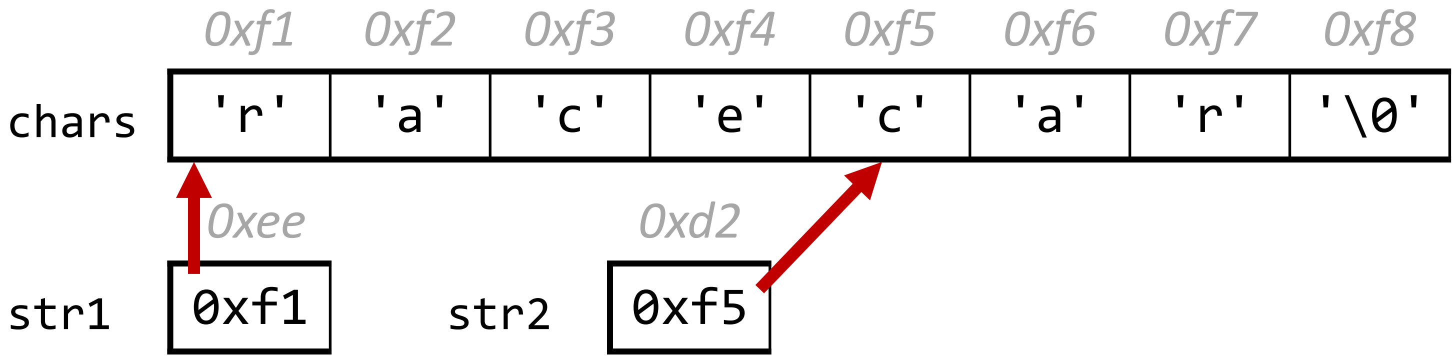
```
// Want just "car"
char chars[8];
strcpy(chars, "racecar");
char *str1 = chars;
```



Substrings

Since C strings are pointers to characters, we can adjust the pointer to omit characters at the beginning.

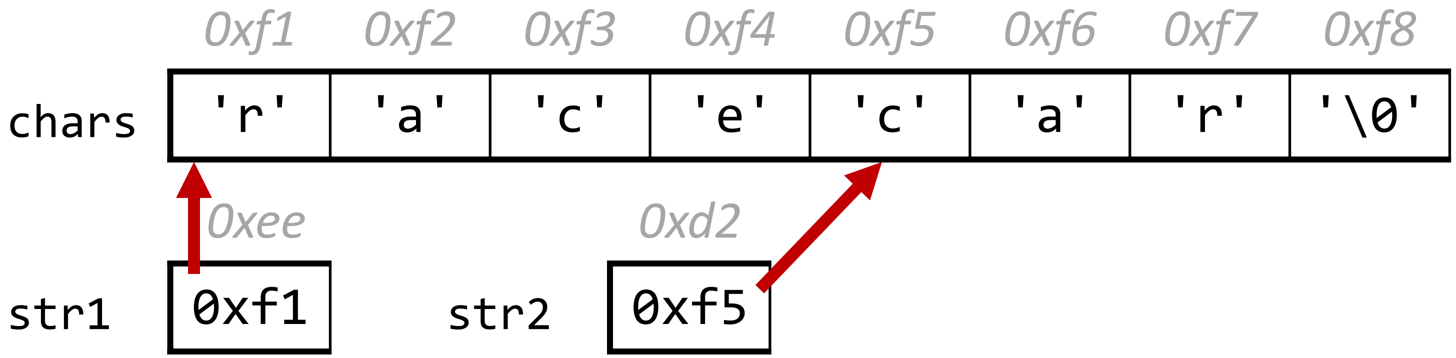
```
// Want just "car"
char chars[8];
strcpy(chars, "racecar");
char *str1 = chars;
char *str2 = chars + 4;
```



Substrings

Since C strings are pointers to characters, we can adjust the pointer to omit characters at the beginning.

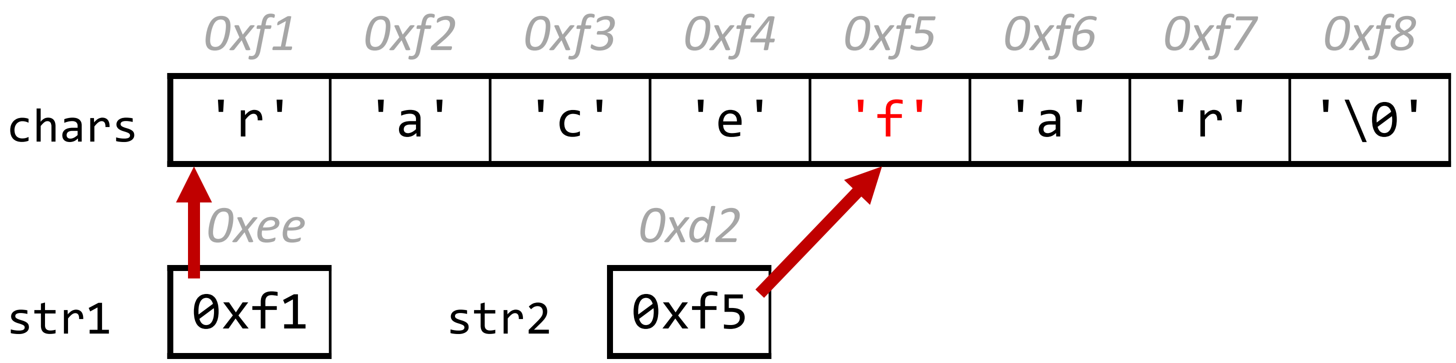
```
char chars[8];
strcpy(chars, "racecar");
char *str1 = chars;
char *str2 = chars + 4;
printf("%s\n", str1);         // racecar
printf("%s\n", str2);         // car
```



Substrings

Since C strings are pointers to characters, we can adjust the pointer to omit characters at the beginning. **NOTE:** the pointer still refers to the same characters!

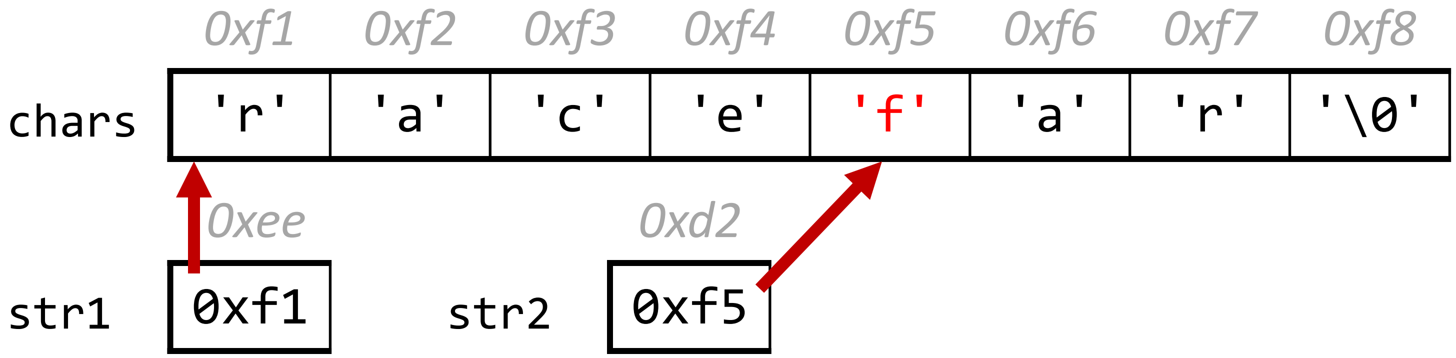
```
char chars[8];
strcpy(chars, "racecar");
char *str1 = chars;
char *str2 = chars + 4;
str2[0] = 'f';
printf("%s %s\n", chars, str1);
printf("%s\n", str2);
```



Substrings

Since C strings are pointers to characters, we can adjust the pointer to omit characters at the beginning. **NOTE:** the pointer still refers to the same characters!

```
char chars[8];
strcpy(chars, "racecar");
char *str1 = chars;
char *str2 = chars + 4;
str2[0] = 'f';
printf("%s %s\n", chars, str1);          // racefar racefar
printf("%s\n", str2);                    // far
```



Substrings

We can combine pointer arithmetic and copying to make any substrings we'd like.

```
// Want just "ace"
char str1[8];
strcpy(str1, "racecar");

char str2[4];
strncpy(str2, str1 + 1, 3);
str2[3] = '\0';
printf("%s\n", str1);          // racecar
printf("%s\n", str2);          // ace
```

Goal: String Diamond

Write a function **`diamond`** that accepts a string parameter and prints its letters in a "diamond" format as shown below.

- For example, `diamond("BAILEY")` should print:

```
B
BA
BAI
BAIL
BAILE
BAILEY
 AILEY
  ILEY
   LEY
    EY
     Y
```

Now let's implement the second half of the diamond!

Demo: Diamond, Part 2

`diamond.c`

char * vs. char[]

- char * is an 8-byte pointer – it stores an address of a character
- char[] is an array of characters – it stores the actual characters in a string
- When you pass a char[] as a parameter, it is automatically passed as a char * (pointer to its first character)
- Stay tuned for next lecture for more!

Recap

- Characters
- Strings
- Common String Operations
  - Comparing
  - Copying
  - Concatenating
  - Substrings

Lecture 6 takeaway: C strings are null-terminated arrays of characters. We can manipulate them using string and pointer operations.

Next time: more strings

```
cp -r /afs/ir/class/cs107/lecture-code/lect6 .
```

Extra Practice

Copycat exercise

Challenge: implement **strcat** using other string functions.

```
char src[9];
strcpy(src, "We Climb");
char dst[200];    // lots of space
strcpy(dst, "The Hill ");

strcat(dst, src);
```

How could we replace a call to **strcat** with a call to **strcpy** instead?

🤔

Copycat exercise

Challenge: implement **strcat** using other string functions.

```
char src[9];
strcpy(src, "We Climb");
char dst[200];     // lots of space
strcpy(dst, "The Hill ");
```

```
strcat(dst, src);
```

equivalent

```
strcpy(dst + strlen(dst), src);
```

Strings Practice

```c
1 char buf[9];
2 strcpy(buf, "Potatoes");
3 printf("%s\n", buf);
4 char *word = buf + 2;
5 strncpy(word, "mat", 3);
6 printf("%s\n", buf);
```

Line 6: What is printed?

A. matoes
B. mattoes
C. Pomat
D. Pomatoes
E. Something else
F. Compile error