CSC209 Summer 2015 — Software Tools and Systems Programming

www.cdf.toronto.edu/~csc209h/summer/

Week 6 — June 18, 2015

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Some materials courtesy of Karen Reid

Announcements

- **Midterm:**
  - Tuesday, June 23 from 7-8pm in UC 266

Announcements

- **Extra Office Hours:**
  - Friday, June 19, 1-3pm in BA3289
  - Monday, June 22, 1-3pm in BA3201

Announcements

- **Assignment 2:**
  - Has been released
  - Due on July 1, 2015 (*less than 2 weeks*)
  - No lecture after this one, before due date

Announcements

- **Labs:**
  - Consolidating down to **BA2210** and **BA2220** only
  - Everyone attending should muster there (there will *not* be TA’s in the other two rooms)

Agenda

- Standard library string functions
- Using the C Preprocessor for Sharing Definitions
- Makefiles
- Midterm

```
void *
```

```
sizeof (void) == 1
```

… even though `void` is an *incomplete* type,
has no values and you cannot instantiate
any variable to be of type `void` …

```
void *p = (void *) 0x1000;

// p + 1 == (void *) 0x1001
// p + 2 == (void *) 0x1002
// p + 3 == (void *) 0x1003
// p + 4 == (void *) 0x1004
// …
```

Strings in C

`char`

`char`

- The `char` datatype represents an 8-bit integer (is *signed* by default, alternatively can be declared as ***`unsigned`***)
- Small integers can fit in a `char` sized value holder:
  - `char x = 100;`
- Oversized values will be truncated and wrap around:
  - `1 == (unsigned char) 257`
- One ASCII character enclosed in *single quotes* is a `char` literal value:
  - `'A' == 65` since the ASCII code for `A` is decimal 65
  - `'0' == 48` since the ASCII code for `0` is decimal 48
  - `'\0' == 0` uses an escape code
  - `'\n' == 10` (linefeed aka newline)

Strings in C

- A **`NULL`** (zero) terminated array/sequence of **`char`** *(byte)* values
    - Typically passed around as a pointer *(**`char *`**)* to the first character
    - No extra information about length or maximum size
    - Modified *in place* (not necessarily copied)
- *String literals* will include an implicit NULL byte
    - **`char s[] = “CSC”; s[3] == 0`**

strrepr.c:

```
char course1[] = { 67,  83,  67,  50,  48,  57,    0  };
char course2[] = { 'C', 'S', 'C', '2', '0', '9', '\0' };
char course3[] = "CSC209";
```

$$\forall\ 0 \le \texttt{i} \le 6:$$

`course1[i] == course2[i] == course3[i]`

C Standard Library String Functions

- A small but useful set of functions that help you to manipulate C-style strings
  - They require care and attention to detail when using
  - Many traps for young players; source of *many* bugs
- Don’t forget to `#include <string.h>` to get the function prototypes

strlen

`strlen` - calculate the length of a string

```
size_t strlen(const char *s)
```

From the manpage: *"The **`strlen()`** function calculates the length of the string* **`s`**, *excluding the terminating null byte ('\0')..."*

String *Length*

vs

Storage *Size*

strlen.c:

```
char hello[] = { 'C', 'S', 'C', '2', '0', '9', '\0' };

printf("hello            = \"%s\"\n", hello);
printf(“sizeof (hello) = %zu\n", sizeof (hello));
printf(“strlen(hello)  = %zu\n", strlen(hello));
```

```
hello          = "CSC209"
sizeof (hello) = 7
strlen(hello)  = 6
```

length + 1 ≤ size

strcmp

```
strcmp(“CSC209”, “CSC209”) == 0
```

```
strcmp(“CSCB09”, “CSC209”) > 0
```

since `‘B’ > ‘2’` (ASCII 66 *vs* 50)

```
strcmp(“CSC209”, “CSC309”) < 0
```

since `‘2’ < ‘3’` (ASCII 50 *vs* 51)

strchr *and* **str*r*chr**

`strchr` & **`str`*`r`*`chr`** — locate first/last occurrence of a character within a string

```
char *strchr (const char *s, int c)
char *strrchr(const char *s, int c)
```

From the manpage: *“The **strchr()**/ **strrchr()** function returns a pointer to the first/last occurrence of the character **c** in the string **s**.”*

strchr.c

strcat

`strcat` - append (concatenate) one string onto another

```
char *strcat(char *dest, const char *src)
```

From the manpage: *“The **`strcat()`** function appends the **`src`** string to the **`dest`** string, overwriting the terminating null byte ('\0') at the end of **`dest`**, and then adds a terminating null byte. … returns **`dest`**.”*

strcat.c:

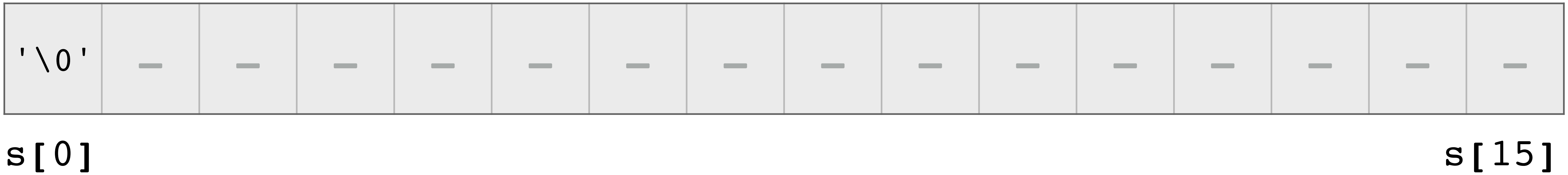
```c
#include <stdio.h>
#include <string.h>

int main(int argc, char *argv[])
{
    char s[16];
    int i;

    s[0] = '\0';

    // Concatenate each `argv[i]` onto `s`
    for (i = 1; i < argc; i++) {
        strcat(s, argv[i]);
        strcat(s, "!");
    }

    printf("%s\n", s);
    return 0;
}
```

```
argv[1] = “hello”
argv[2] = “csc209”
argv[3] = “fun”
```

'\0'	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

s[0] s[15]

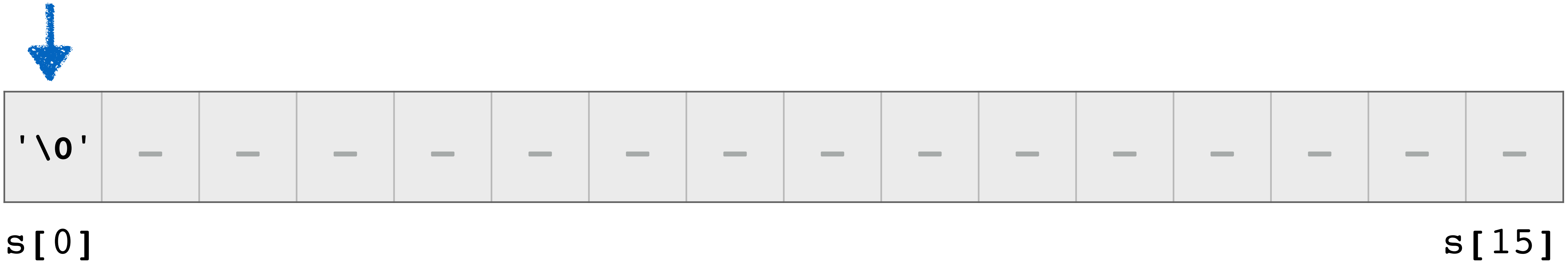
```
strcat(s, argv[1]);
strcat(s, “!”);

strcat(s, argv[2]);
strcat(s, “!”);

strcat(s, argv[3]);
strcat(s, “!”);
```



'\0'	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_

s[0] s[15]

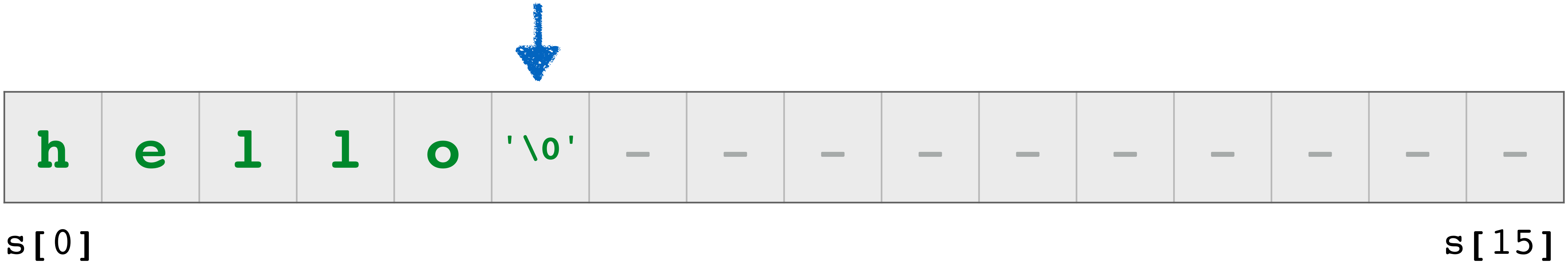
```
strcat(s, "hello");
strcat(s, "!");

strcat(s, "CSC209");
strcat(s, "!");

strcat(s, "fun");
strcat(s, "!");
```



'\0'	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_

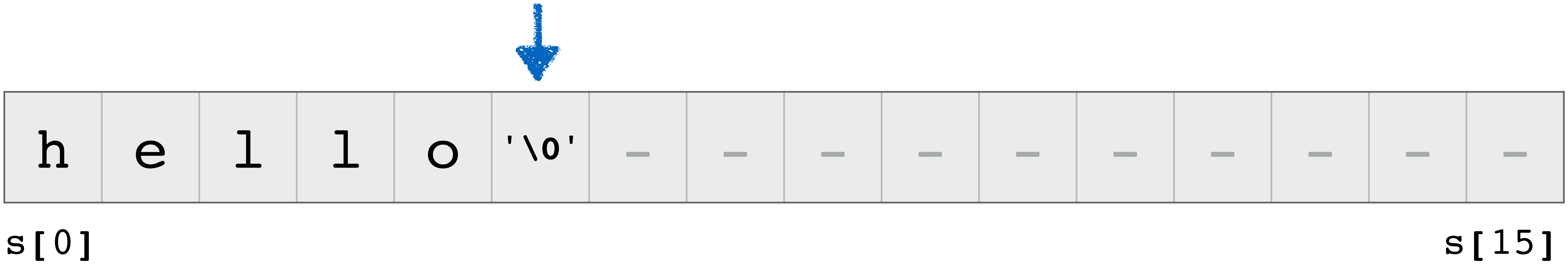
s[0] s[15]

```
strcat(s, “hello”);
strcat(s, “!”);
strcat(s, “CSC209”);
strcat(s, “!”);
strcat(s, “fun”);
strcat(s, “!”);
```



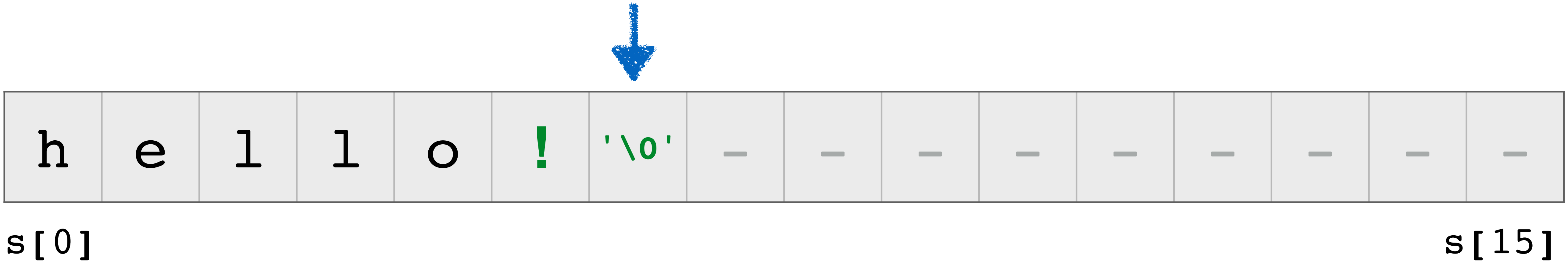
h	e	l	l	o	'\0'	–	–	–	–	–	–	–	–	–	–

```
strcat(s, “hello”);
strcat(s, “!”);
strcat(s, “CSC209”);
strcat(s, “!”);
strcat(s, “fun”);
strcat(s, “!”);
```



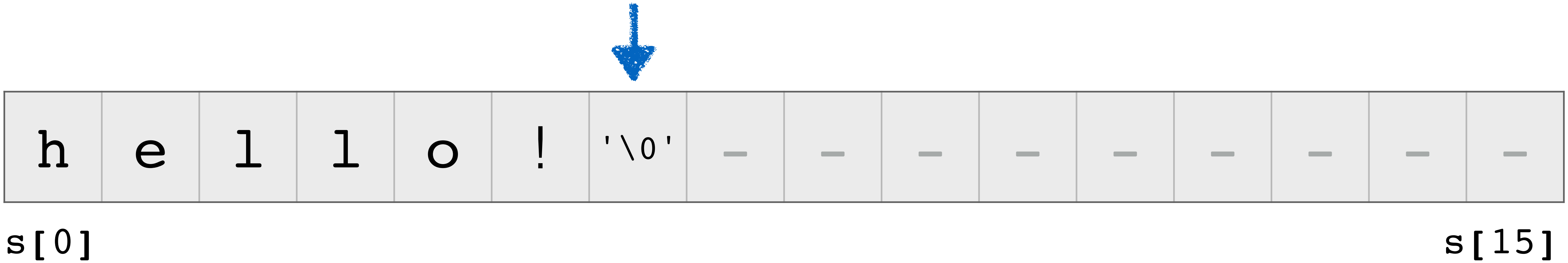
h	e	l	l	o	'\0'	–	–	–	–	–	–	–	–	–	–

```
strcat(s, “hello”);
strcat(s, “!”);
strcat(s, “CSC209”);
strcat(s, “!”);
strcat(s, “fun”);
strcat(s, “!”);
```



h	e	l	l	o	!	'\0'	–	–	–	–	–	–	–	–	–
s[0]															s[15]

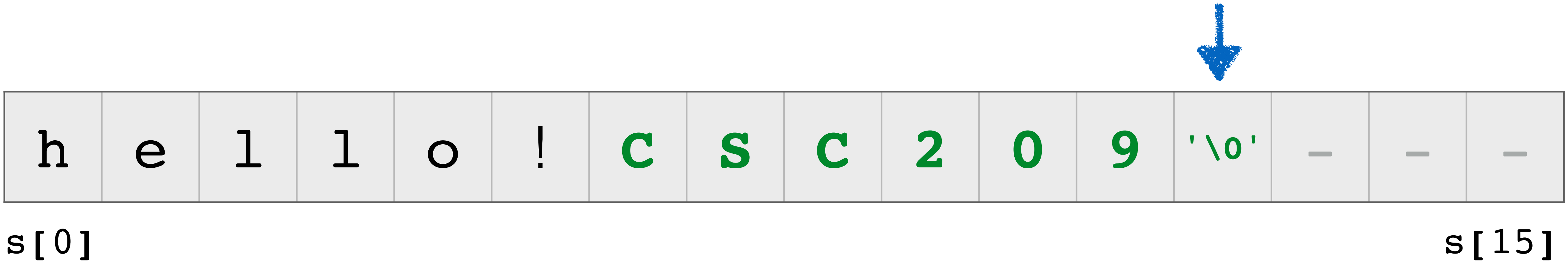
```
strcat(s, “hello”);
strcat(s, “!”);
strcat(s, “CSC209”);
strcat(s, “!”);
strcat(s, “fun”);
strcat(s, “!”);
```



h	e	l	l	o	!	'\0'	_	_	_	_	_	_	_	_	_

s[0] s[15]

```
strcat(s, “hello”);
strcat(s, “!”);
strcat(s, “CSC209”);
strcat(s, “!”);
strcat(s, “fun”);
strcat(s, “!”);
```

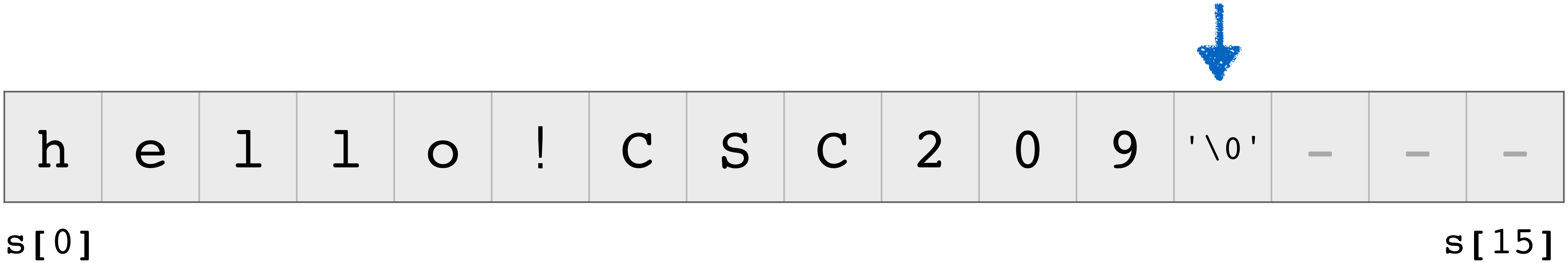


h	e	l	l	o	!	C	S	C	2	0	9	'\0'	_	_	_

s[0]

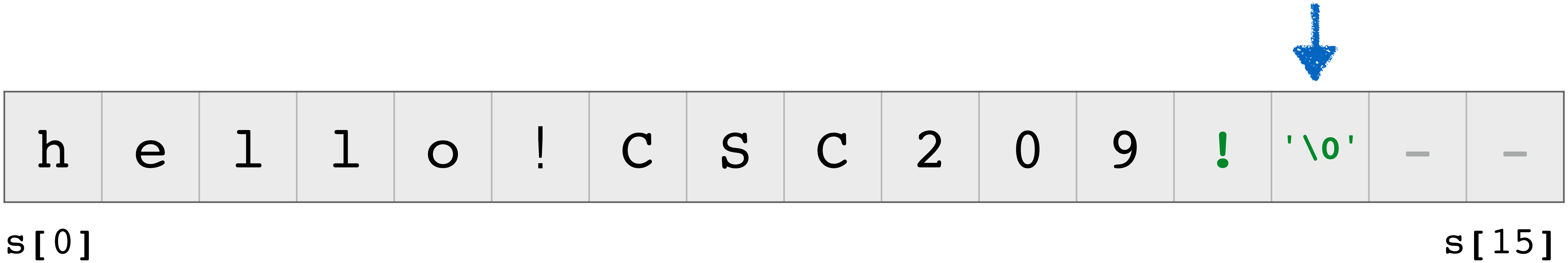
s[15]

```
strcat(s, "hello");
strcat(s, "!");
strcat(s, "CSC209");
strcat(s, "!");
strcat(s, "fun");
strcat(s, "!");
```



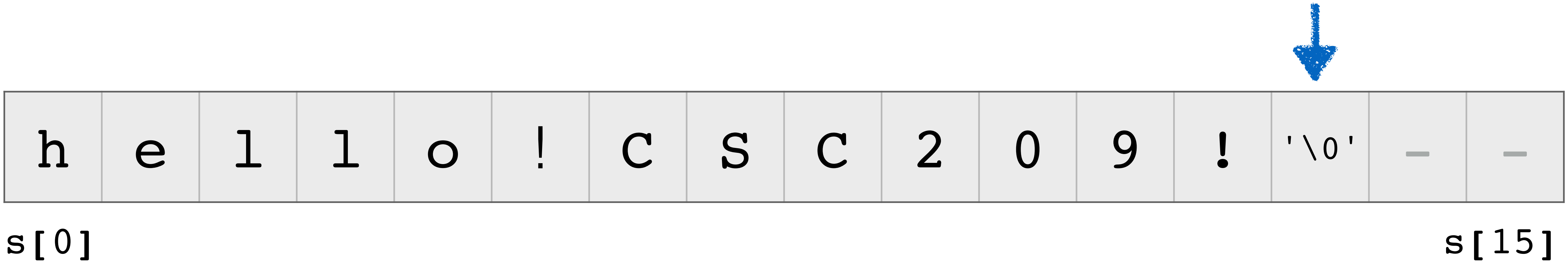
h	e	l	l	o	!	C	S	C	2	0	9	'\0'	–	–	–
s[0]															s[15]

```
strcat(s, “hello”);
strcat(s, “!”);

strcat(s, “CSC209”);
strcat(s, “!”);

strcat(s, “fun”);
strcat(s, “!”);
```



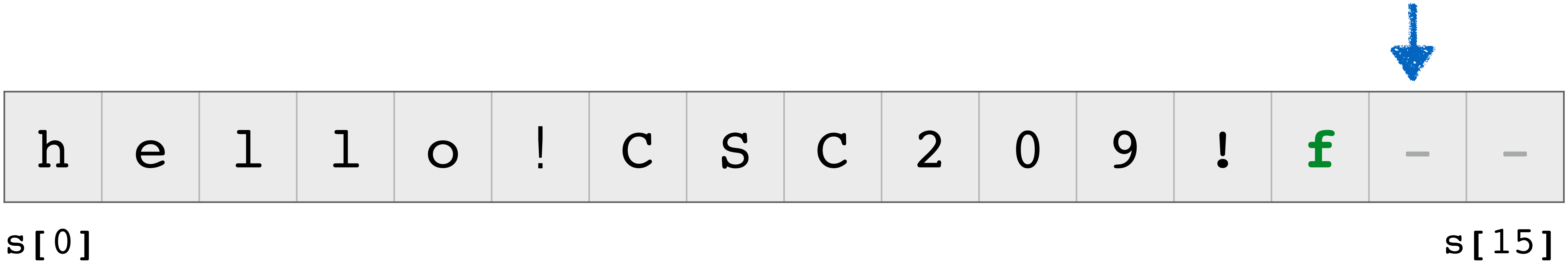
h	e	l	l	o	!	C	S	C	2	0	9	!	'\0'	–	–

```
  strcat(s, “hello”);
  strcat(s, “!”);

  strcat(s, “CSC209”);
→ strcat(s, “!”);

  strcat(s, “fun”);
  strcat(s, “!”);
```



h	e	l	l	o	!	C	S	C	2	0	9	!	'\0'	_	_

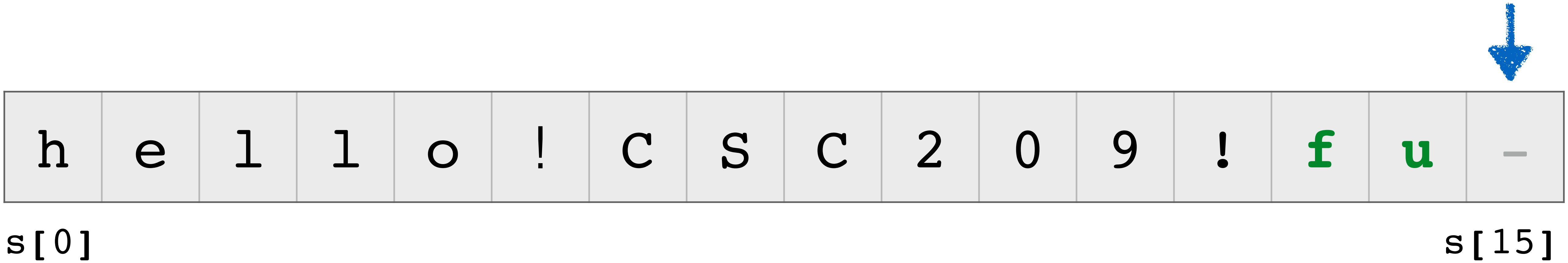
```
strcat(s, “hello”);
strcat(s, “!”);

strcat(s, “CSC209”);
strcat(s, “!”);

strcat(s, “fun”);
strcat(s, “!”);
```



h	e	l	l	o	!	C	S	C	2	0	9	!	f	–	–

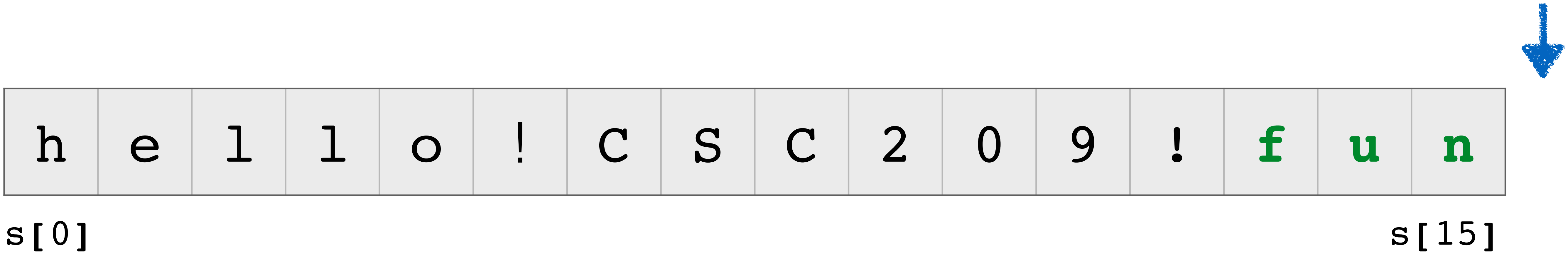
s[0] s[15]

```
strcat(s, “hello”);
strcat(s, “!”);

strcat(s, “CSC209”);
strcat(s, “!”);

strcat(s, “fun”);
strcat(s, “!”);
```



h	e	l	l	o	!	C	S	C	2	0	9	!	**f**	**u**	–
s[0]															s[15]

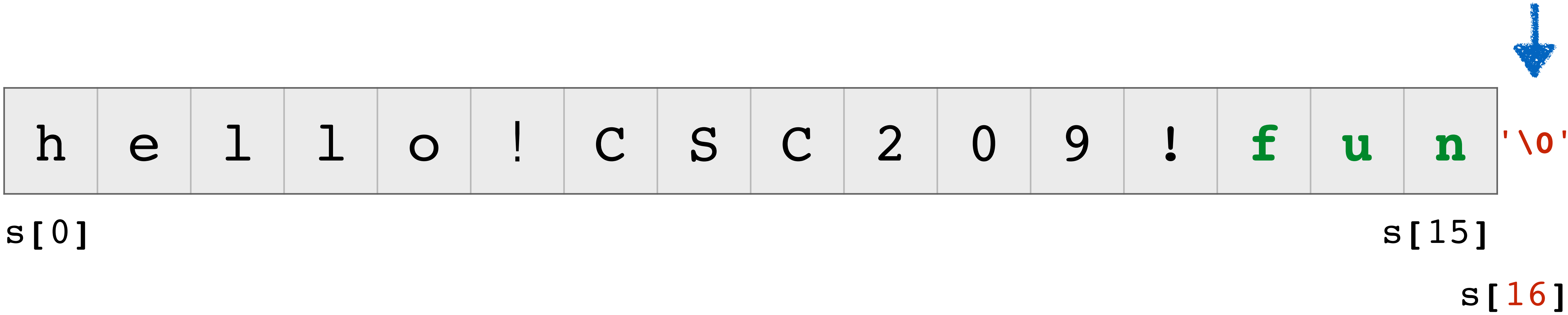
```
   strcat(s, “hello”);
   strcat(s, “!”);

   strcat(s, “CSC209”);
   strcat(s, “!”);

→  strcat(s, “fun”);
   strcat(s, “!”);
```



h	e	l	l	o	!	C	S	C	2	0	9	!	**f**	**u**	**n**

s[0] s[15]

```
strcat(s, “hello”);
strcat(s, “!”);
strcat(s, “CSC209”);
strcat(s, “!”);
strcat(s, “fun”);
strcat(s, “!”);
```



h	e	l	l	o	!	C	S	C	2	0	9	!	**f**	**u**	**n**	'\0'

s[0]

s[15]

s[16]

```
strcat(s, “hello”);
strcat(s, “!”);
strcat(s, “CSC209”);
strcat(s, “!”);
strcat(s, “fun”);
strcat(s, “!”);
```

h	e	l	l	o	!	C	S	C	2	0	9	!	f	u	n

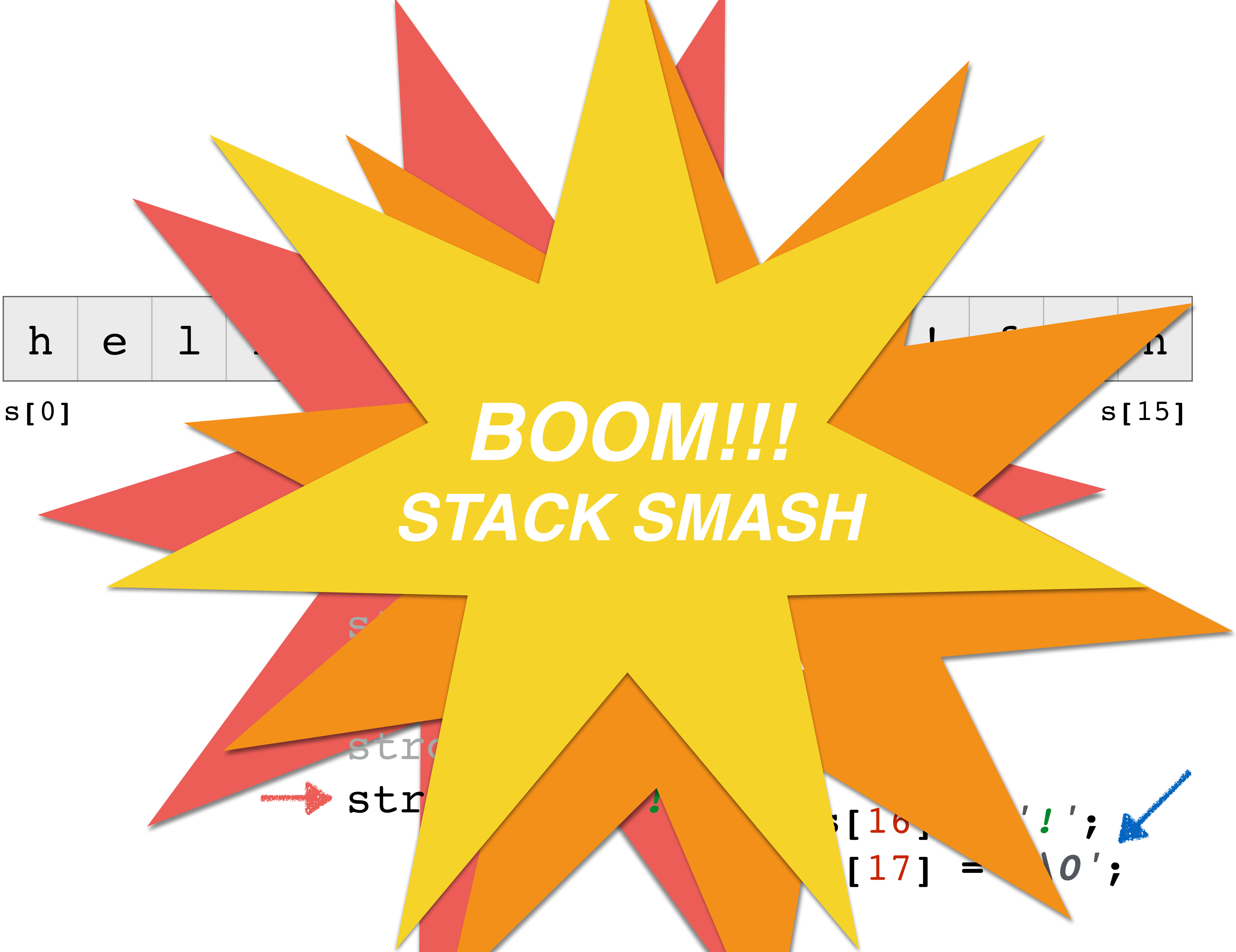
s[0] s[15]

```
strcat(s, “hello”);
strcat(s, “!”);

strcat(s, “CSC209”);
strcat(s, “!”);

strcat(s, “fun”);
strcat(s, “!”);
```

```
s[16] = '!';
s[17] = '\0';
```

h	e	l										!			h

s[0] s[15]



BOOM!!!

STACK SMASH

```
str
str
str                    s[16] = '!';
                       s[17] = '\0';
```

Caveat: This was on a Mac OS X laptop…

Try ***“`fun12345678`”*** on CDF for similar effect…

What was in memory at `s[16]` and `s[17]`, and what other purpose was it serving?

Regardless, `strcat` went further in memory than ***we*** should have allowed it.

Solution: keep track of how big `dest` will *need* to be, and correctly allocate sufficient space using `malloc`.

This is error prone and
very easy to get wrong.

strcat2.c:

```
…

size_t len = 0;

// Add up all string lengths
for (i = 1; i < argc; i++) {
    len += strlen(argv[i]);
    // Add +1 for each '!'
    len++;
}

// Another +1 for the NUL terminator
char *s = (char *) malloc(len + 1);

s[0] = ‘\0’;


…
```

strcat

- Only use it once you've determined the size of **`src`** and know that **`dest`** has sufficient *free* space to accommodate

- *No way of telling* **`strcat`** *how large* **`dest`** *is (so that it won't accidentally go beyond the end)*

`strcpy`

`strcpy` - copy a string

```
char *strcpy(char *dest, const char *src)
```

From the manpage: *“The `strcpy()` function copies the string pointed to by `src`, including the terminating null byte (`'\0'`), to the buffer pointed to by `dest`. The strings may not overlap, and the destination string `dest` must be large enough to receive the copy. … returns `dest`.”*

Whereas `strcat` looks for the `NUL` terminator of `dest` and then appends the contents of `src` starting there, `strcpy` overwrites from the beginning of `dest`.

```
char s[1024];
s[0] = '\0';

strcat(s, "Hello ");
strcat(s, "CSC209!");
printf("%s\n", s);
```

```
Hello CSC209!
```

```
char s[1024];
s[0] = '\0';

strcpy(s, "Hello ");
strcpy(s, "CSC209!");
printf("%s\n", s);
```

```
CSC209!
```

Another trap: what happens if **`src`** is larger than **`dest`**?

strcpy2.c:

```c
char s[16];
s[0] = '\0';

strcpy(s, "The quick brown fox jumps over the lazy dog");
```

Introducing `strncpy`

strncpy - copy a string

```
char *strncpy(char *dest,
              const char *src,
              size_t n)
```

From the manpage: *“The **strncpy**() function is similar, except that **at most n** bytes of **src** are copied. **Warning**: If there is no zero byte among the first **n** bytes of **src**, the string placed in **dest** will* not *be zero terminated.”*

It is your responsibility to
keep track of how many bytes
are free/unused in **`dest`**.

strncpy.c

You should *always* use **`strncpy`**, and *never* use **`strcpy`** because it is so outrageously unsafe.

See also **`strncmp`** and **`strncat`** (but they still only deal with **`src`** size, not **`dest`** size.)

strdup

`strdup` - duplicate a string

```
char *strdup(const char *s)
```

From the manpage: *“The **`strdup()`** function returns a pointer to a new string which is a duplicate of the string **`s`**. Memory for the new string is obtained with **`malloc(3)`**, and can be freed with **`free(3)`**..”*

It’s not unusual for a C standard library function to modify a string argument *in-place*.

Functions that take a **`const char *`** argument are guaranteeing that they will *not* modify that argument.

strdup209.c:

```c
char *strdup209(const char *s)
{
    size_t len = strlen(s);

    char *dup = (char *) malloc(len + 1);
    if (!dup) {
        return NULL;
    }

    int i;
    for (i = 0; s[i] != '\0'; i++) {
        dup[i] = s[i];
    }
    dup[i] = '\0';

    return dup;
}
```

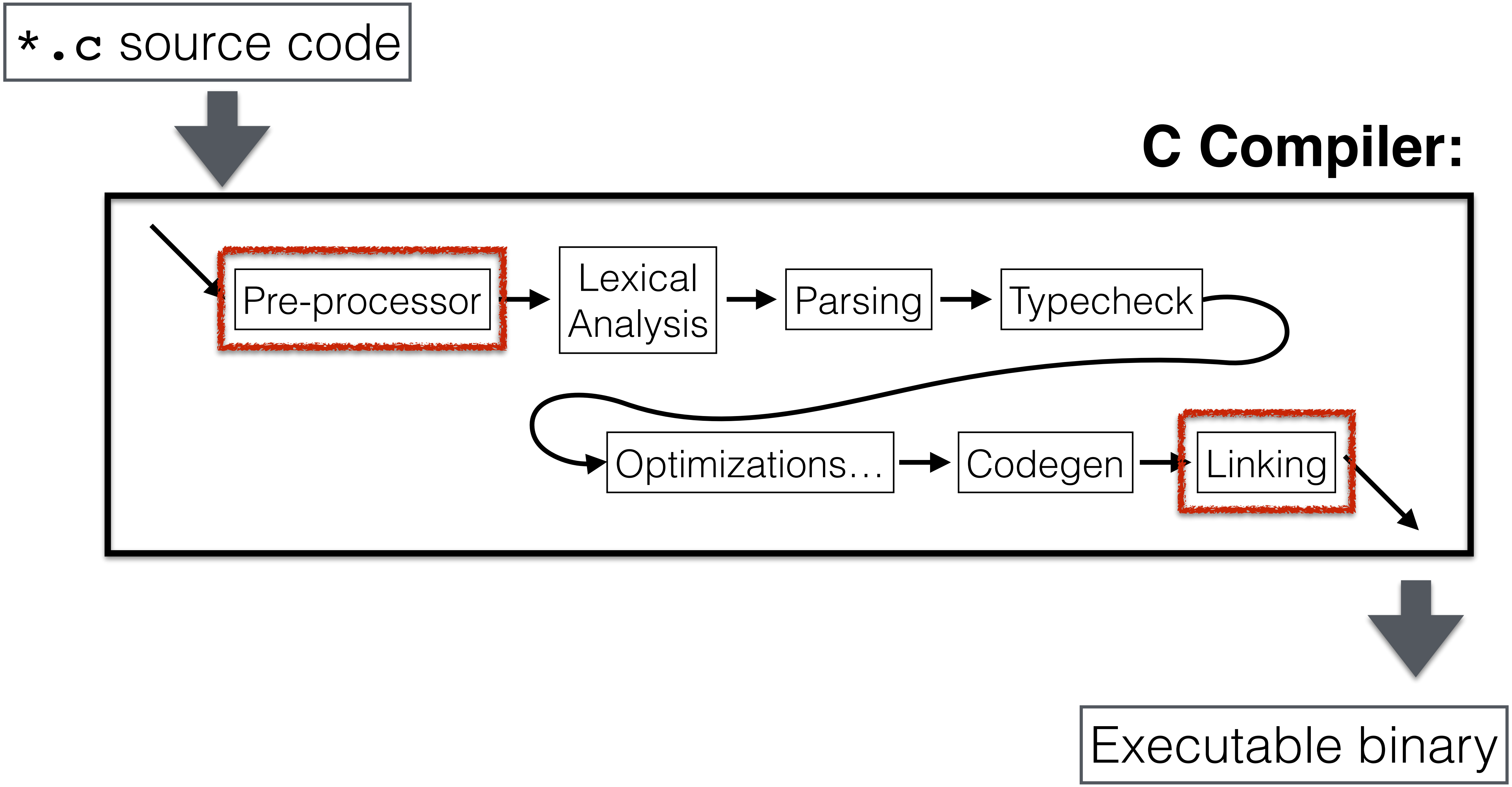
String Function Summary

- Remember that we are just changing bytes in memory
- *Always* keep in mind who is taking responsibility for the zero/`NUL` terminating byte
    - … and ultimately, it is still up to you to ensure it is where it is suppose to be!
- Prefer the `strn–` variations whenever possible

- Find the length of a string:
    - **`size_t strlen(const char *s)`**
- Compare two strings:
    - **`int strcmp(const char *s1, const char *s2)`**
    - **`int strncmp(const char *s1, const char *s2, size_t n)`**
- Find the first/last occurrence of a character within a string
    - **`char *strchr(const char *s, int c)`**
    - **`char *strrchr(const char *s, int c)`**
- Append one string onto another:
    - **`char *strcat(char *dest, const char *src)`**
- Copy one string to another:
    - **`char *strncpy(char *dest, const char *src)`**
    - Avoid using **`char *strcpy(char *dest, const char *src)`**
- Duplicate a string:
    - **`char *strdup(const char *s)`**

Compilation Process

Compilation Process



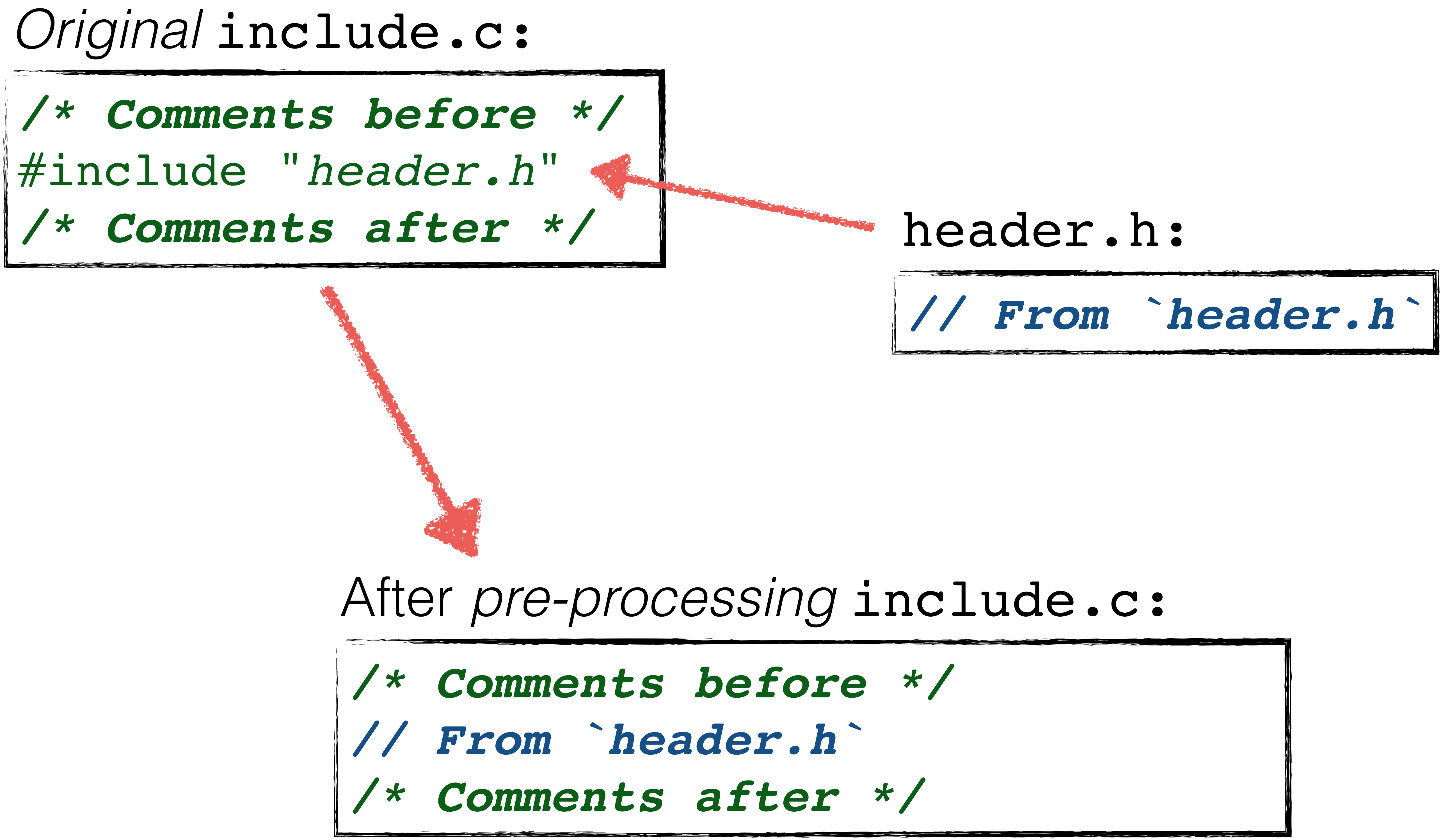
Using the C Preprocessor for Sharing Definitions

example.c:

```
//#include <stdlib.h>


…
void *ptr = malloc(…);
…
```

```
$ gcc example.c
example.c:15:5: warning: implicit declaration of function 'malloc'
```

Pre-processor Inclusion Mechanism



Original `include.c`:

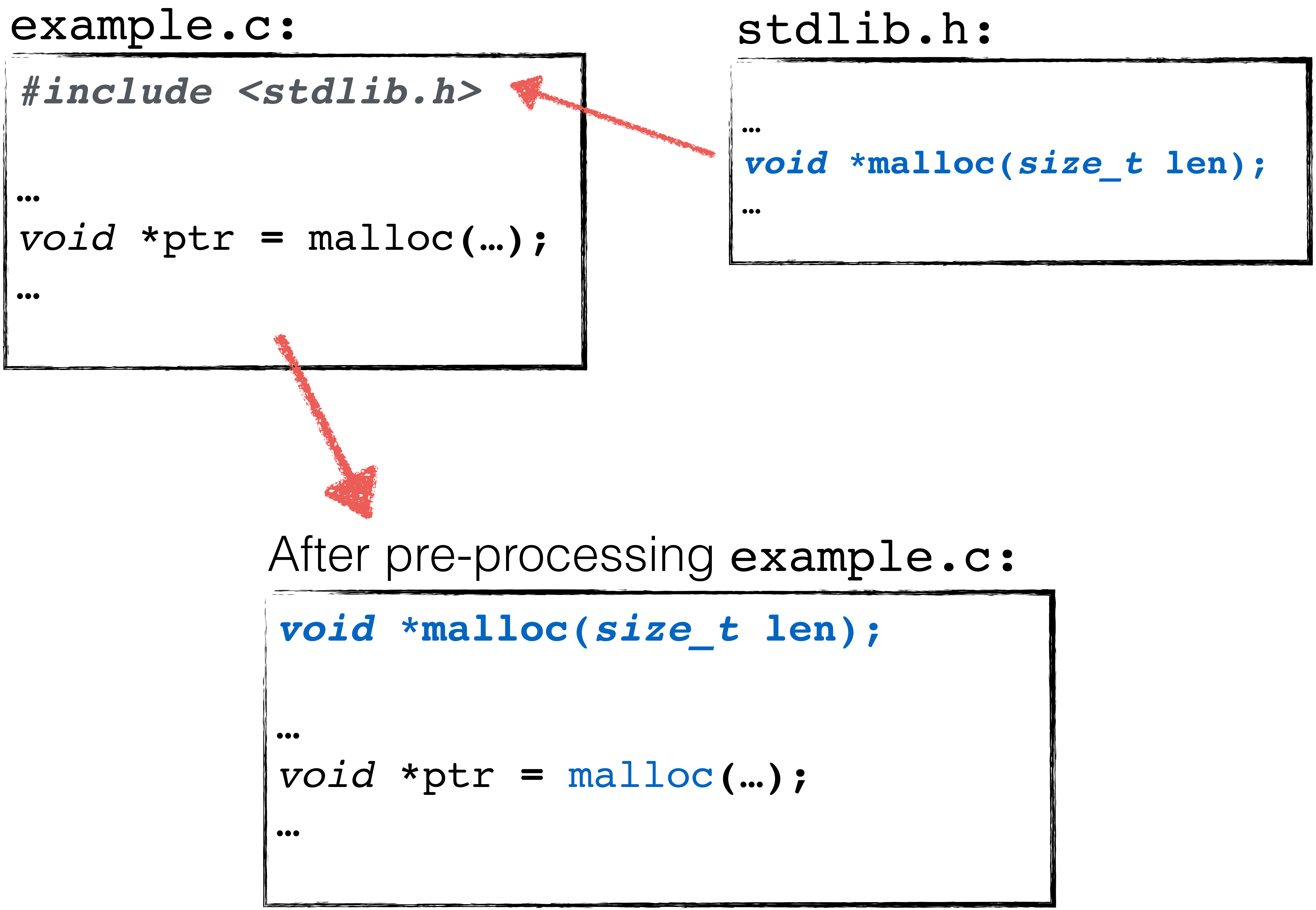
```
/* Comments before */
#include "header.h"
/* Comments after */
```

`header.h`:

```
// From `header.h`
```

After *pre-processing* `include.c`:

```
/* Comments before */
// From `header.h`
/* Comments after */
```



example.c:

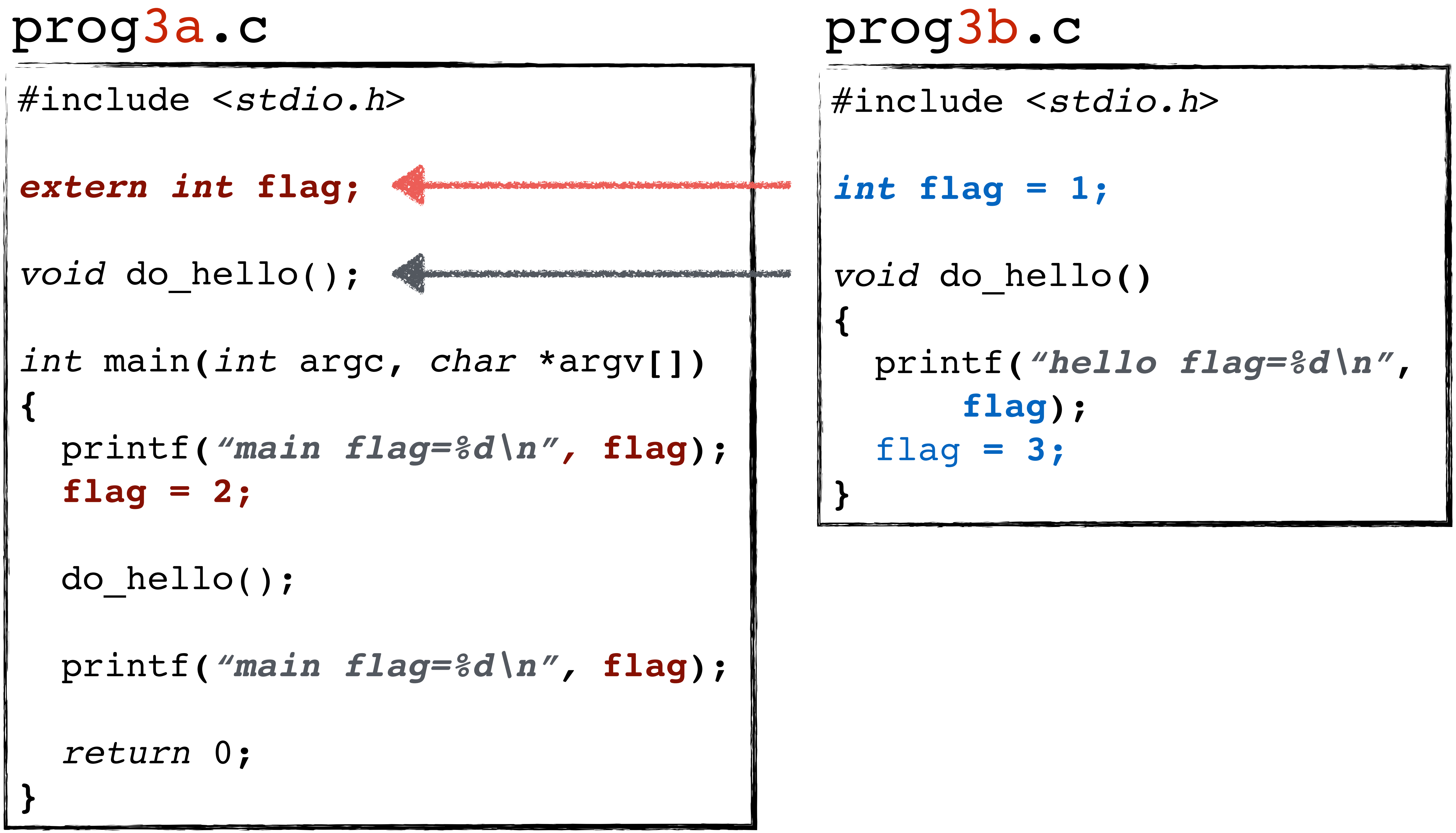
```
#include <stdlib.h>


…
void *ptr = malloc(…);
…
```

stdlib.h:

```
…
void *malloc(size_t len);
…
```

After pre-processing example.c:

```
void *malloc(size_t len);


…
void *ptr = malloc(…);
…
```



prog3a.c

```
#include <stdio.h>

extern int flag;

void do_hello();

int main(int argc, char *argv[])
{
  printf(“main flag=%d\n”, flag);
  flag = 2;

  do_hello();

  printf(“main flag=%d\n”, flag);

  return 0;
}
```

prog3b.c

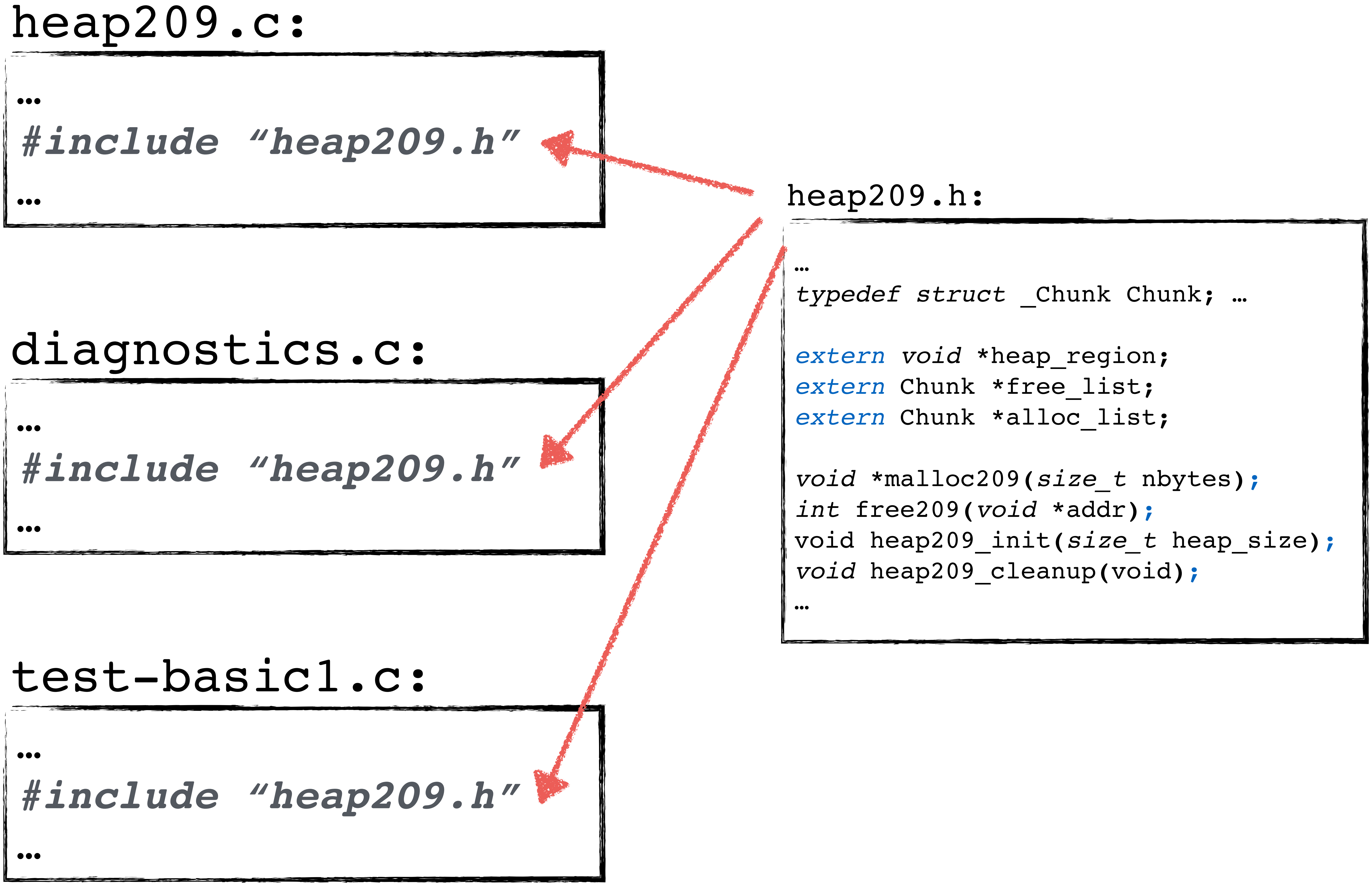
```
#include <stdio.h>

int flag = 1;

void do_hello()
{
  printf(“hello flag=%d\n”,
        flag);
  flag = 3;
}
```

From Assignment 2…

heap209.h:

```
…
typedef struct _Chunk Chunk; …

extern void *heap_region;
extern Chunk *free_list;
extern Chunk *alloc_list;

void *malloc209(size_t nbytes);
int free209(void *addr);
void heap209_init(size_t heap_size);
void heap209_cleanup(void);
…
```

Forward declarations of function prototypes and `extern` global variables



heap209.c:

```
…
#include “heap209.h”
…
```

diagnostics.c:

```
…
#include “heap209.h”
…
```

test-basic1.c:

```
…
#include “heap209.h”
…
```

heap209.h:

```
…
typedef struct _Chunk Chunk; …

extern void *heap_region;
extern Chunk *free_list;
extern Chunk *alloc_list;

void *malloc209(size_t nbytes);
int free209(void *addr);
void heap209_init(size_t heap_size);
void heap209_cleanup(void);
…
```

heap209.c:

```
…
#include “heap209.h”
…

void *heap_region = NULL;
Chunk *free_list = NULL;
Chunk *alloc_list = NULL;

void *malloc209(size_t nbytes)
{
   …
}


…
```

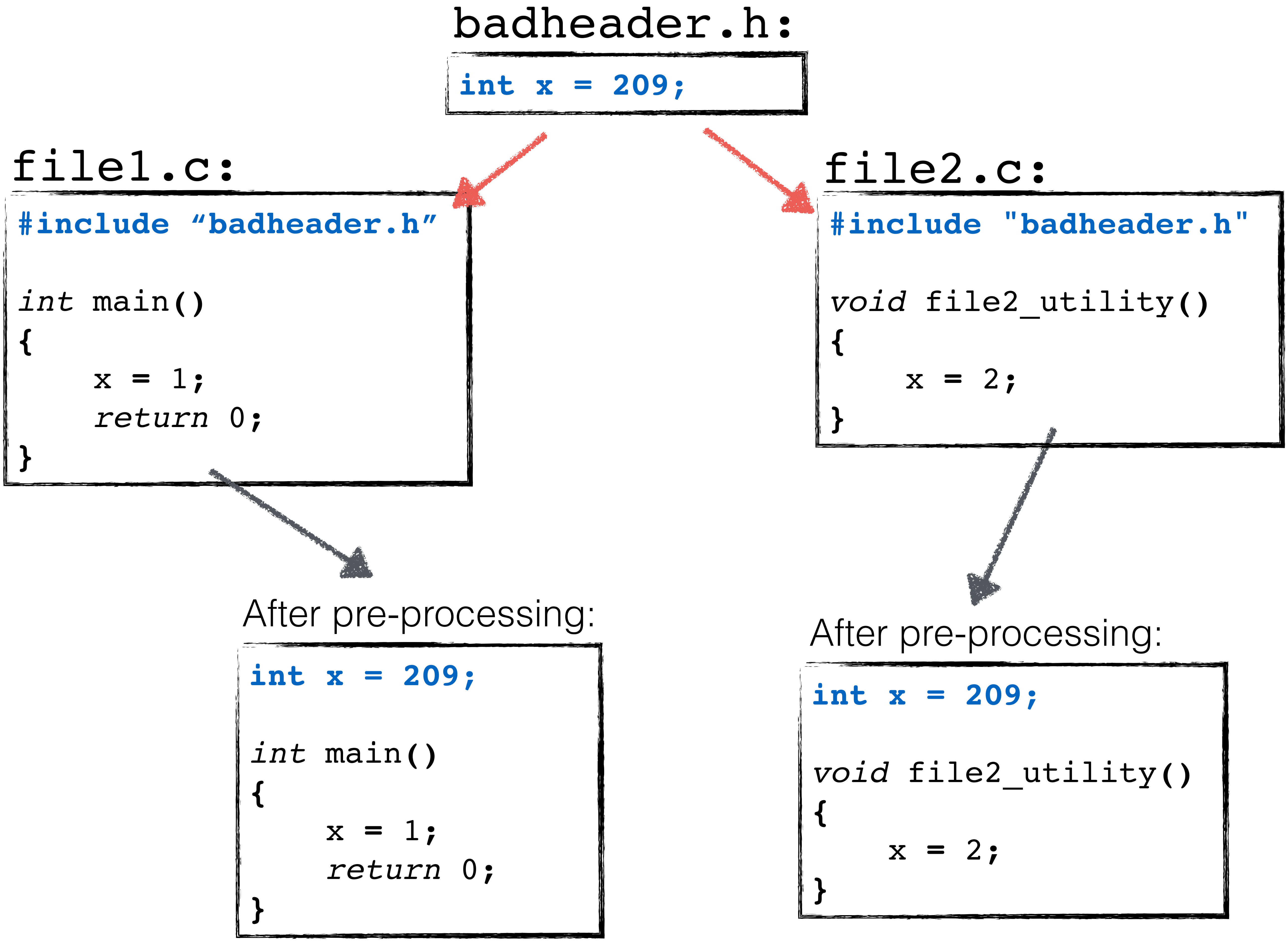
heap209.h:

```
…
typedef struct _Chunk Chunk; …

extern void *heap_region;
extern Chunk *free_list;
extern Chunk *alloc_list;

void *malloc209(size_t nbytes);
int free209(void *addr);
void heap209_init(size_t heap_size);
void heap209_cleanup(void);
…
```

- **`heap209.h`**
  - Forward declarations of function prototypes, `struct` definition and `extern` declarations
  - No actual function implementations or global variables defined
- **`heap209.c`**
  - *Implementations* of all the forward declarations in `heap209.h`
- **`diagnostics.h`**
  - Forward declarations of function prototypes for heap debugging functions
- **`diagnostics.c`**
  - *Implementations* of heap debugging functions defined in `diagnostics.h`
  - Uses the `struct` definition and `extern` global variables defined in `heap209.h`
- **`test-basic1.c`**
  - Uses the functions defined in `heap209.h` and `diagnostics.h`

What *should* go into header files?

- Function prototypes
- Type definitions: `struct`, `union` and `typedef`
- `extern` global variables
- *Don’t declare actual global variables*



badheader.h:

```
int x = 209;
```

file1.c:

```
#include “badheader.h”

int main()
{
     x = 1;
     return 0;
}
```

file2.c:

```
#include "badheader.h"

void file2_utility()
{
     x = 2;
}
```

After pre-processing:

```
int x = 209;

int main()
{
     x = 1;
     return 0;
}
```

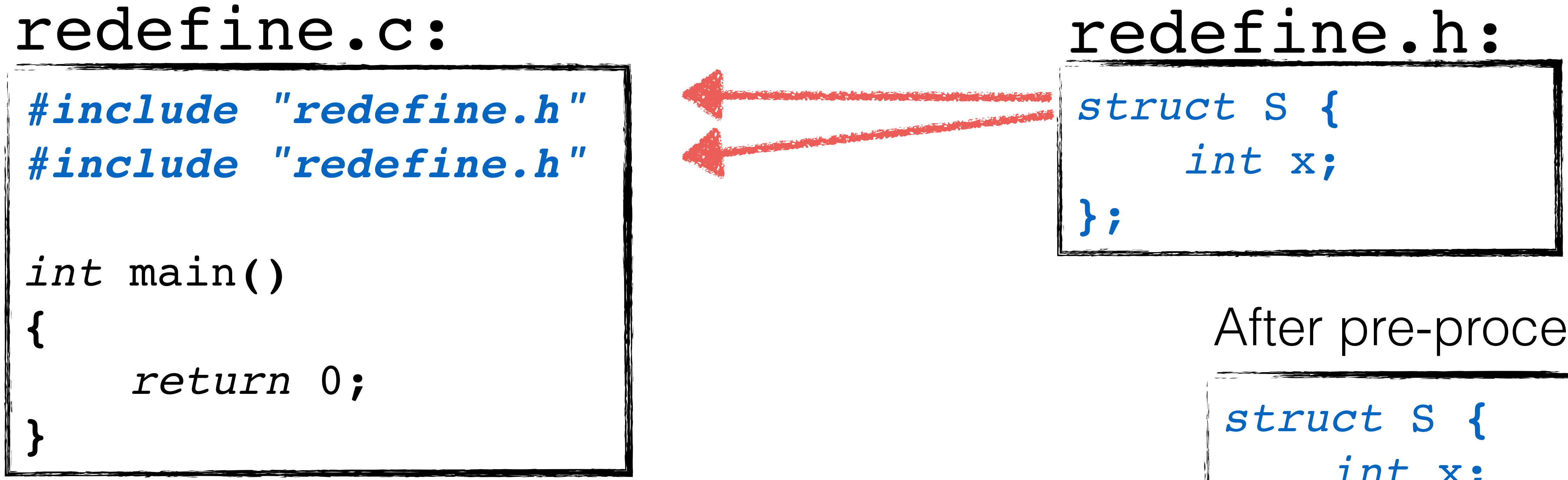
After pre-processing:

```
int x = 209;

void file2_utility()
{
     x = 2;
}
```

```
wolf:~$ gcc -Wall -g file1.c file2.c -o prog
/tmp/ccdpcL9T.o:(.data+0x0): multiple definition of `x'
/tmp/ccrZRBlf.o:(.data+0x0): first defined here
collect2: ld returned 1 exit status
```

Protecting Headers from Multiple Inclusion

- Sometimes the same header file can be included multiple times inadvertently:
  - `prog.c` includes `foo.h`
  - `prog.c` also includes `bar.h`
  - `bar.h` includes `foo.h`
  - `prog.c` will see the contents of `foo.h` twice!



redefine.c:

```c
#include "redefine.h"
#include "redefine.h"

int main()
{
	return 0;
}
```

redefine.h:

```c
struct S {
	int x;
};
```

After pre-processing:

```c
struct S {
	int x;
};
struct S {
	int x;
};

int main()
{
	return 0;
}
```

```
In file included from redefine.c:2:
./redefine.h:1:8: error: redefinition of 'S'
struct S {
       ^

./redefine.h:1:8: note: previous definition is here
struct S {
       ^

1 error generated.
```

`redefine.h:`

```
#ifndef REDEFINE_H
  #define REDEFINE_H

  struct S {
      int x;
  };
#endif
```

- On first inclusion:
    - Is **`REDEFINE_H`** a currently defined preprocessor symbol? **No** (**`ifndef`** directive is *true*)
    - Define a preprocessor symbol **`REDEFINE_H`**
    - Emit body of header file (the **`struct`** definition)
- On second, third, fourth, etc… inclusion:
    - Is **`REDEFINE_H`** a currently defined preprocessor symbol? **Yes** (**`ifndef`** directive is *false*)
        - Skip to **`endif`** directive

Summary

- Put common definitions into `*.h` (header) files
- Protect your header files from multiple inclusion
- For each function prototype or external global variable, there should be some `*.c` source code file that provides the actual definition/declaration

Summary

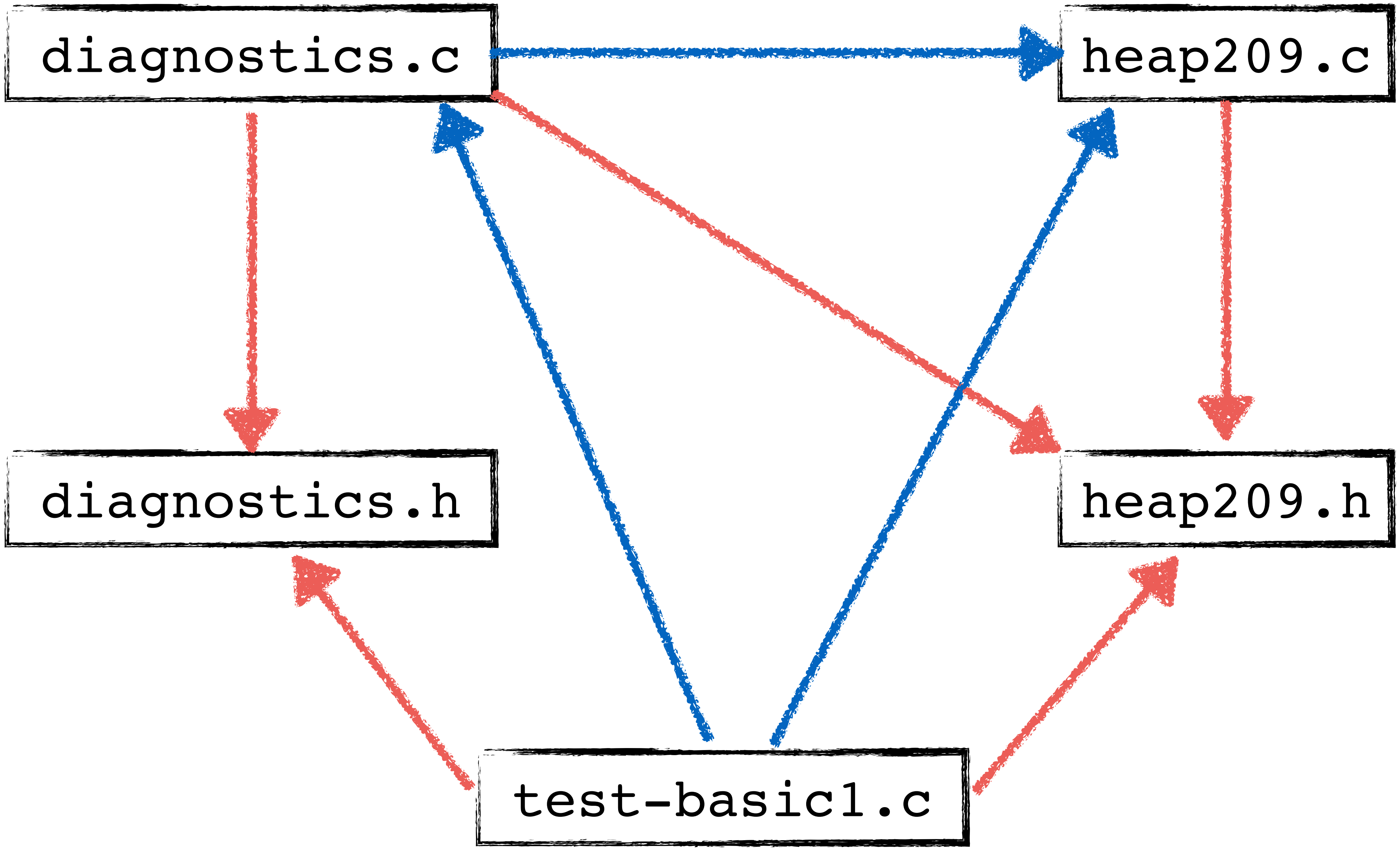
- This is one of the core tools for modularity and code reuse when programming in C

Makefiles

Makefiles

- Originally designed to support *separate compilation* of C files

A2 Dependency Graph



diagnostics.c

heap209.c

diagnostics.h

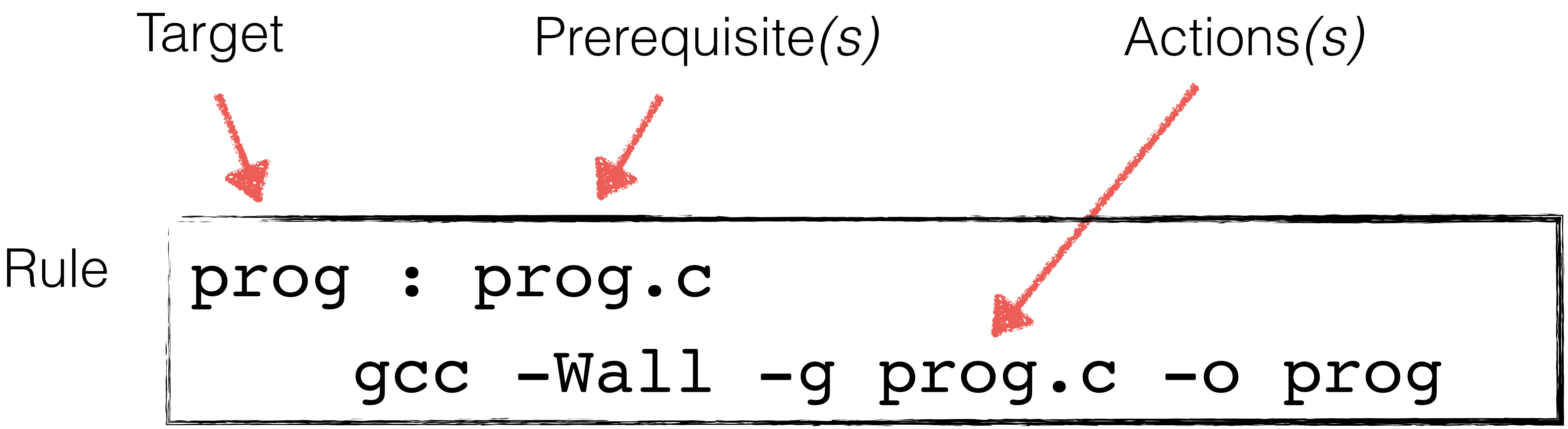
heap209.h

test-basic1.c

Compiling `test-basic1` by hand

```
wolf:~$ gcc -Wall -g -c heap209.c -o heap209.o

wolf:~$ gcc -Wall -g -c diagnostics.c -o diagnostics.o

wolf:~$ gcc -Wall -g -c test-basic1.c -o test-basic1.o

wolf:~$ gcc test-basic1.o heap209.o diagnostics.o \
         -o test-basic1
```

Anatomy of a `Makefile`



Target

Prerequisite*(s)*

Actions*(s)*

Rule

```
prog : prog.c
	gcc -Wall -g prog.c -o prog
```

- A `Makefile` contains 1 or more *rules*
- Each rule has one *target*, and 1 or more *prerequisites*
- Each rule may have 0 or more *actions* (one per line)

Running `make(1)`

- `$ make`
  - With no options looks for a file called `Makefile`, and evaluates the *first* rule
- `$ make test-basic2`
  - Looks for a file called `Makefile` and looks for a rule with the target `test-basic2` and evaluates it
- `$ make -f` ***`foo`*** **…**
  - Looks for a Makefile with the name *`foo`*

How it works

- Make looks at the when the target and its prerequisites were **last modified**
  - It assumes targets are files and checks the dates of the files
- Make does nothing…
  - If the target exists, and
  - Is more recent than all its prerequisites
- Make executes the actions…
  - If the target doesn't exist, or
  - If any prerequisite is more recent than the target

Variables — User defined

Define common parts of action commands that you are likely to repeat multiple places:

```
CFLAGS= -Wall -g

prog : prog.c
    gcc $(CFLAGS) prog.c -o prog

prog2 : prog2.c
    gcc ${CFLAGS} prog.c -o prog
```

Variables — Built-ins

Make defines variables to represent parts of rules:

$@	Target
$<	First prerequisite
$?	All out of date prerequisites
$^	All prerequisites

```
CFLAGS= -Wall -g
prog : main.c util.c
    gcc ${CFLAGS} $^ -o $@
```

```
CFLAGS= -Wall -g
prog : main.o util.o
    gcc $^ -o $@

main.o : main.c
    gcc ${CFLAGS} -c $^ -o $@

util.o : util.c
    gcc ${CFLAGS} -c $^ -o $@
```

Wildcard Substitutions

```
CFLAGS= -Wall -g
prog : main.o util.o
     gcc $^ -o $@

%.o : %.c
     gcc ${CFLAGS} -c $< -o $@
```

A2 Makefile

```
CC=gcc
CFLAGS=-Wall -g
LDFLAGS=
OBJS=heap209.o diagnostics.o

all: test-basic1

test-basic1: test-basic1.o $(OBJS)
    $(CC) $(LDFLAGS) $^ -o $@

%.o: %.c heap209.h
    $(CC) $(CFLAGS) -c $< -o $@

clean:
    rm -f test-basic1 *.o
```

Makefile Summary

- They provide a higher level of abstraction than writing out shell commands in a script file
- They simplify the process of building larger projects

Midterm

- Shell *usage*
- C language:
  - Syntax
  - Data types (including structures and unions)
  - *Pointers and Memory*
- File I/O using streams
- C-style strings
- Makefiles

Midterm

- Be aware of the differences in this course and the courses that previous midterms reflect
  - Our midterm date falls in a different week
  - We have not yet covered shell *programming*, just emphasized *usage*

- **Labs:** Everyone attending show go to either **BA2210** or **BA2220** (they are conjoined)
- **Extra Office Hours:**
  - Friday, June 19, 1-3pm in BA3289
  - Monday, June 22, 1-3pm in BA3201
- **Midterm:** Tuesday, June 23 from 7-8pm in UC 266
- **Assignment 2:** Due on July 1, 2015