



C Tools & Compilation

Intro to Computer Systems, Fall 2022

Instructor: Travis McGaha

TAs:

| | | |
|----------------|----------------|---------------------|
| Ali Krema | Andrew Rigas | Anisha Bhatia |
| Audrey Yang | Craig Lee | Daniel Duan |
| David LuoZhang | Eddy Yang | Ernest Ng |
| Heyi Liu | Janavi Chadha | Jason Hom |
| Katherine Wang | Kyrie Dowling | Mohamed Abaker |
| Noam Elul | Patricia Agnes | Patrick Kehinde Jr. |
| Ria Sharma | Sarah Luthra | Sofia Mouchtaris |

Upcoming Due Dates

- ❖ HW07 (Deque & RPN) Due Friday 11/11 @ 11:59 pm
 - Assignments are increasing in time required to complete. Please try to not let the work accumulate
- ❖ Midsemester Survey Due Wednesday 11/9 @ 11:59 pm
- ❖ Students taking final exams through the Weingarten Center need to schedule by Nov 30th to guarantee extended time for an exam.

Lecture Outline

- ❖ **Memory Errors, Valgrind & gdb**
- ❖ C Header Files & Modules
- ❖ C compilation, definitions vs declarations, CPP
- ❖ Makefiles

Dynamic Memory Pitfalls

- ❖ Buffer Overflows
 - E.g. ask for 10 bytes, but write 11 bytes
 - Could overwrite information needed to manage the heap
 - Common when forgetting the null-terminator on malloc'd strings
- ❖ Not checking for **NULL**
 - Malloc returns NULL if out of memory
 - Should check this after every call to malloc
- ❖ Giving **free()** a pointer to the middle of an allocated region
 - Free won't recognize the block of memory and probably crash
- ❖ Giving **free()** a pointer that has already been freed
 - Will interfere with the management of the heap and likely crash
- ❖ **malloc** does NOT initialize memory
 - There are other functions like **calloc** that will zero out memory

Memory Leaks

- ❖ The most common Memory Pitfall
- ❖ What happens if we malloc something, but don't free it?
 - That block of memory cannot be reallocated, even if we don't use it anymore, until it is **freed**
 - If this happens enough, we run out of heap space and program may slow down and eventually crash
- ❖ Garbage Collection
 - Automatically “frees” anything once the program has lost all references to it
 - Affects performance, but avoid memory leaks
 - Java has this, C doesn't



Poll Everywhere

pollev.com/tqm

- ❖ Which line below is first to (most likely) cause a crash?
 - Yes, there are a lot of bugs, but not all cause a crash ☺
 - See if you can find all the bugs!

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

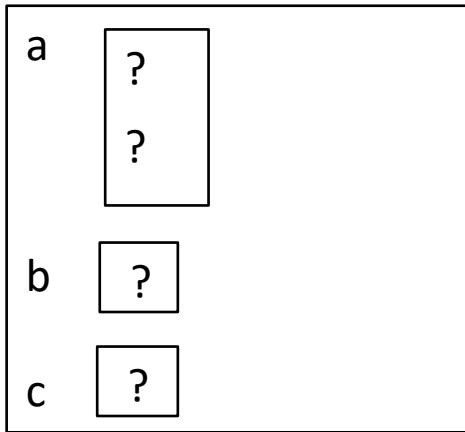
int main(int argc, char** argv) {
    int a[2];
    int* b = malloc(2*sizeof(int));
    int* c;

    1    a[2] = 5;
    2    b[0] += 2;
    3    c = b+3;
    4    free(&(a[0]));
    5    free(b);
    6    free(b);
    7    b[0] = 5;

    return 0;
}
```

Memory Corruption - What Happens?

main



heap:

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

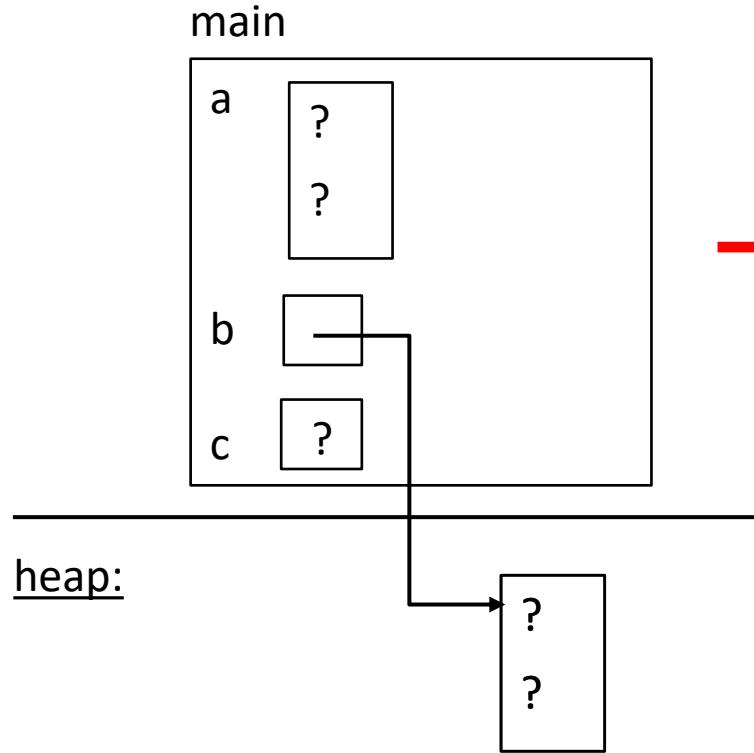
int main(int argc, char** argv) {
    int a[2];
    int* b = malloc(2*sizeof(int));
    int* c;

    a[2] = 5;    // assigns past the end of an array
    b[0] += 2;   // assumes malloc zeros out memory
    c = b+3;     // Ok, but if we use c, problem
    free(&(a[0])); // free something not malloc'ed
    free(b);
    free(b);     // double-free the same block
    b[0] = 5;    // use a freed (dangling) pointer

    // any many more!
    return 0;
}
```

Note: Arrow points
to *next* instruction.

Memory Corruption - What Happens?



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

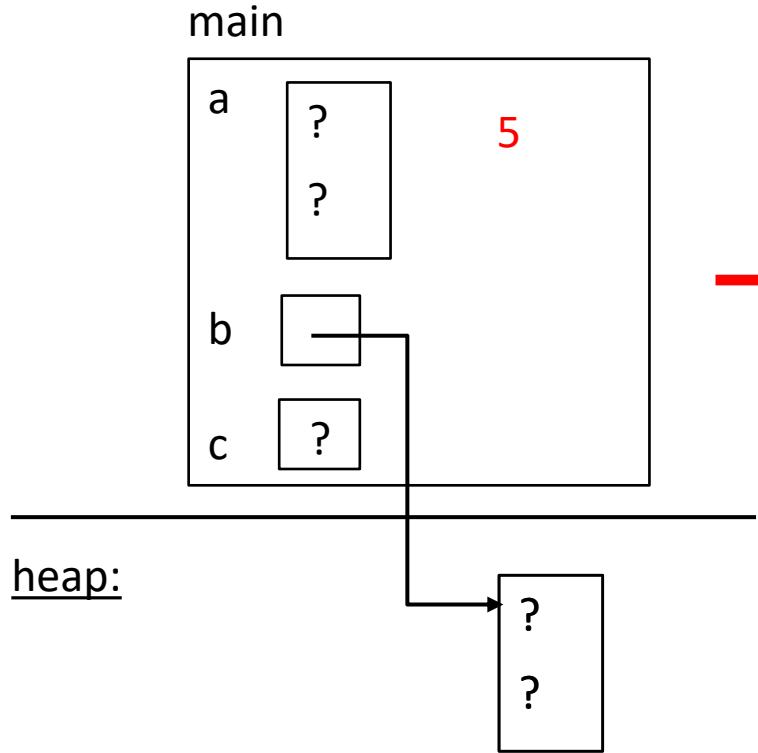
int main(int argc, char** argv) {
    int a[2];
    int* b = malloc(2*sizeof(int));
    int* c;

    a[2] = 5;      // assigns past the end of an array
    b[0] += 2;    // assumes malloc zeros out memory
    c = b+3;      // Ok, but if we use c, problem
    free(&(a[0])); // free something not malloc'ed
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    // any many more!
    return 0;
}
```

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Memory Corruption - What Happens?



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

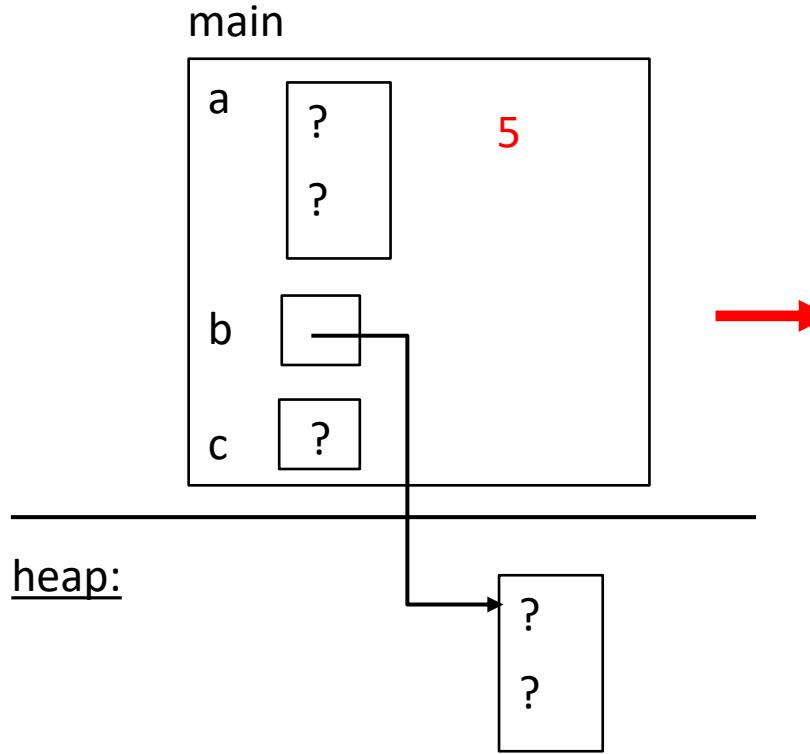
int main(int argc, char** argv) {
    int a[2];
    int* b = malloc(2*sizeof(int));
    int* c;

    a[2] = 5;      // assigns past the end of an array
    b[0] += 2;    // assumes malloc zeros out memory
    c = b+3;      // Ok, but if we use c, problem
    free(&(a[0])); // free something not malloc'ed
    free(b);
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    // any many more!
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}
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Memory Corruption - What Happens?



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#include <stdlib.h>

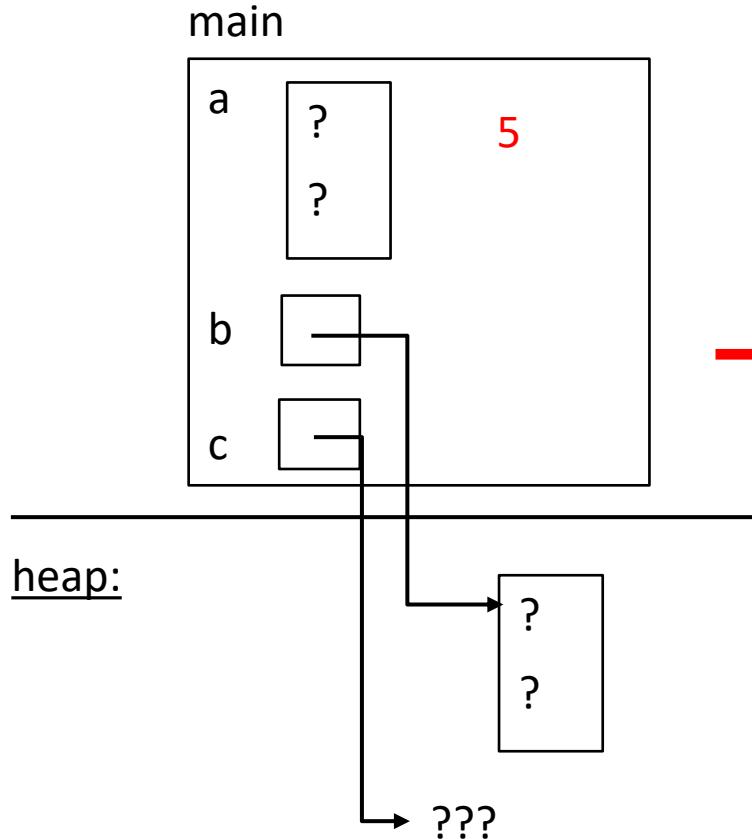
int main(int argc, char** argv) {
    int a[2];
    int* b = malloc(2*sizeof(int));
    int* c;

    a[2] = 5;      // assigns past the end of an array
    b[0] += 2;    // assumes malloc zeros out memory
    c = b+3;      // Ok, but if we use c, problem
    free(&(a[0])); // free something not malloc'ed
    free(b);
    free(b);      // double-free the same block
    b[0] = 5;      // use a freed (dangling) pointer

    // any many more!
    return 0;
}
```

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Memory Corruption - What Happens?



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

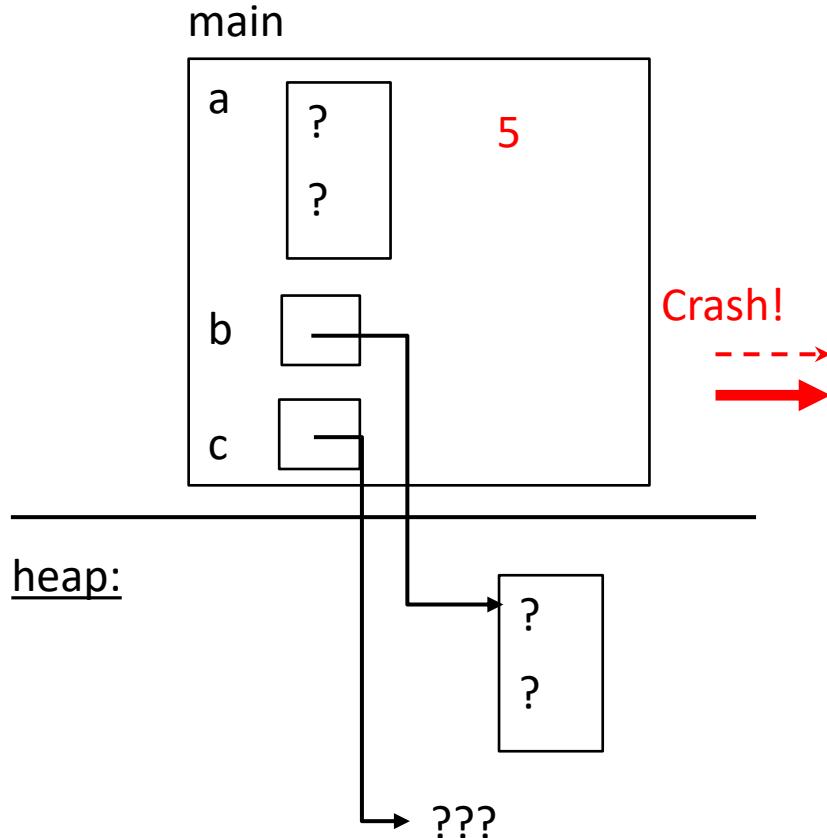
int main(int argc, char** argv) {
    int a[2];
    int* b = malloc(2*sizeof(int));
    int* c;

    a[2] = 5;      // assigns past the end of an array
    b[0] += 2;    // assumes malloc zeros out memory
    c = b+3;      // Ok, but if we use c, problem
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    return 0;
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```

Note: Arrow points to *next* instruction.

Memory Corruption - What Happens?



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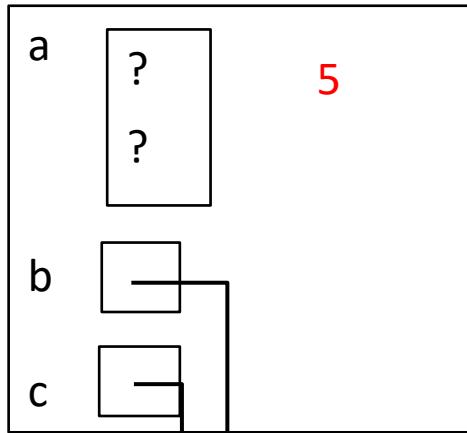
    a[2] = 5;      // assigns past the end of an array
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    free(b);
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    // any many more!
    return 0;
}
```

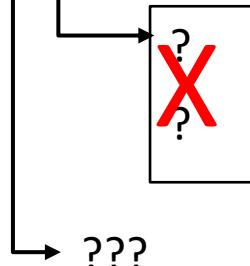
Note: Arrow points to *next* instruction.

Memory Corruption - What Happens?

main



heap:



memcorrupt.c

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

int main(int argc, char** argv) {
    int a[2];
    int* b = malloc(2*sizeof(int));
    int* c;

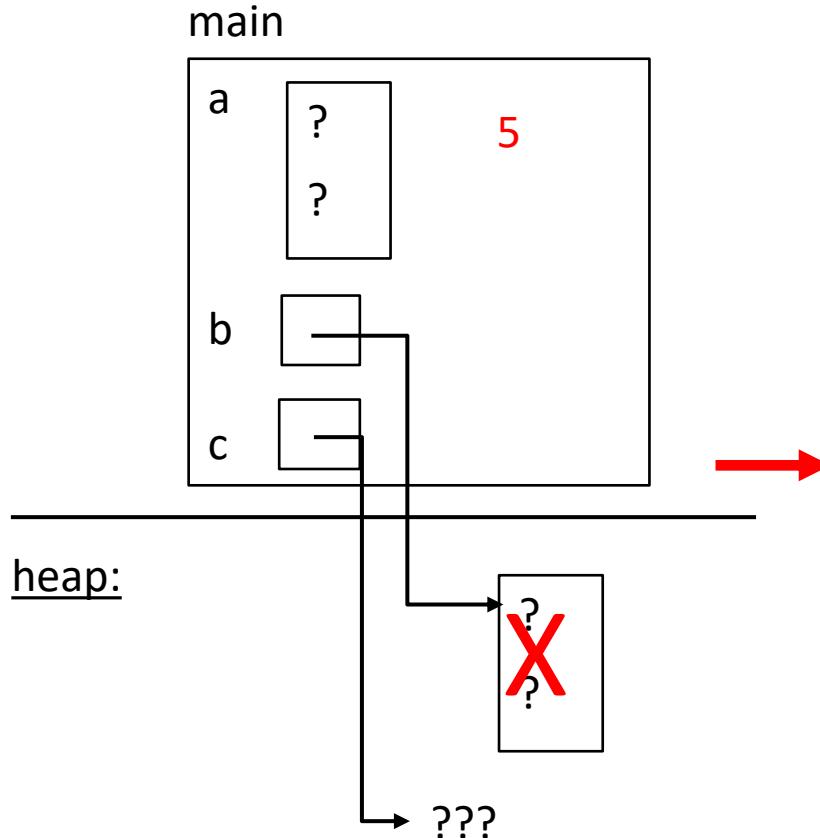
    a[2] = 5;      // assigns past the end of an array
    b[0] += 2;     // assumes malloc zeros out memory
    c = b+3;       // Ok, but if we use c, problem
    free(&(a[0])); // free something not malloc'ed
    free(b);
    free(b);       // double-free the same block
    b[0] = 5;      // use a freed (dangling) pointer

    // any many more!
    return 0;
}
```

Note: Arrow points to *next instruction*.

This “double free”
would also cause the
program to crash

Memory Corruption - What Happens?



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

int main(int argc, char** argv) {
    int a[2];
    int* b = malloc(2*sizeof(int));
    int* c;

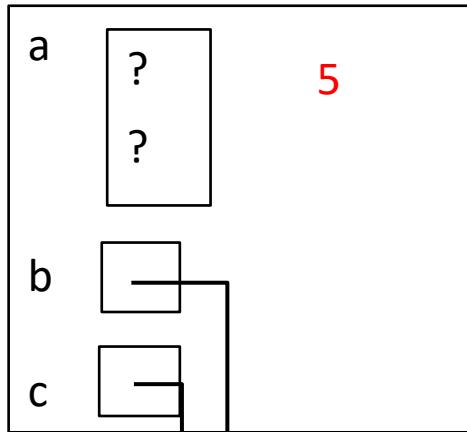
    a[2] = 5;      // assigns past the end of an array
    b[0] += 2;     // assumes malloc zeros out memory
    c = b+3;       // Ok, but if we use c, problem
    free(&(a[0])); // free something not malloc'ed
    free(b);
    free(b);       // double-free the same block
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    // any many more!
    return 0;
}
```

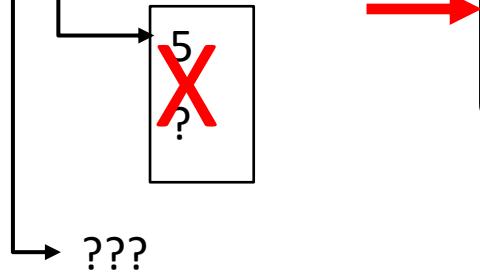
Note: Arrow points to *next* instruction.

Memory Corruption - What Happens?

main



heap:



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

int main(int argc, char** argv) {
    int a[2];
    int* b = malloc(2*sizeof(int));
    int* c;

    a[2] = 5;      // assigns past the end of an array
    b[0] += 2;    // assumes malloc zeros out memory
    c = b+3;      // Ok, but if we use c, problem
    free(&(a[0])); // free something not malloc'ed
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    // any many more!
    return 0;
}
```

Note: Arrow points to *next* instruction.

Motivation

- ❖ The assignments will start getting bigger and are more open ended. Lots of potential for bugs
- ❖ **Debugging is a skill that you will need throughout your programming career**
- ❖ gdb (GNU Debugger) is a debugging tool
 - Very useful in tracking undefined behavior
- ❖ Valgrind
 - Checks for various memory errors
 - If you have odd behavior, valgrind may point out the cause.

Segmentation Fault

- ❖ C doesn't tell you much when it crashes, usually just prints "Segmentation fault (Core Dumped)"
- ❖ Causes:
 - Dereferencing an uninitialized pointer
 - Dereferencing NULL
 - Using a previously freed pointer
 - Writing beyond the bounds of an array
 - ...
- ❖ GDB is incredibly useful for debugging a segmentation fault

GDB “Cheat Sheet”

- ❖ `run <command_line_args>`
 - Runs the program with specified command line arguments
- ❖ `backtrace`
 - Prints out the “trace” of where functions were invoked to get to the current spot in the program
- ❖ `up/down`
 - Can be used to look at the function who called us/we are calling
- ❖ `print <expression>`
 - Prints out a value so that we can examine it
- ❖ `quit`
 - Quit the program

GDB “Cheat Sheet” Part 2

- ❖ tui enable
 - Used to enable the Text User Interface
- ❖ step
 - Move forward a line, steps into a function if we call one
- ❖ next
 - Moves forward a line, doesn't step into a function if called
- ❖ continue
 - Run until we crash, hit a breakpoint, or program finishes
- ❖ breakpoints
 - Next slide

gdb breakpoints

- ❖ Usage:
 - `break <function_name>`
 - `break <filename:line#>`
 - Example: `break main.c:20`
 - `info break`
 - Prints out information of all breakpoints
 - `del <id>`
 - Deletes the breakpoint with specified num.
 - Get breakpoint num with `info break`

Valgrind

- ❖ Tool used for identifying memory errors
- ❖ **Will be used on your HW submissions going forward**
- ❖ Detects:
 - Use of uninitialized memory
 - Reading/writing memory after it has been freed
 - Reading/writing to the end of malloc'd blocks
 - Reading/writing to inappropriate areas on the stack
 - Memory leaks where pointers to malloc'd blocks are lost
- ❖ Run with
 - valgrind --leak-check=full ./executable

Brief GDB & Valgrind Demo: Seg Faults

- ❖ IF NOTHING ELSE FROM GDB: GDB is very useful for finding a segmentation fault
 - Run the code on gdb till segmentation fault
 - Type in the command <backtrace>

- ❖ Commands:
 - `gdb ./executable`
 - `run`
 - `backtrace`

Lecture Outline

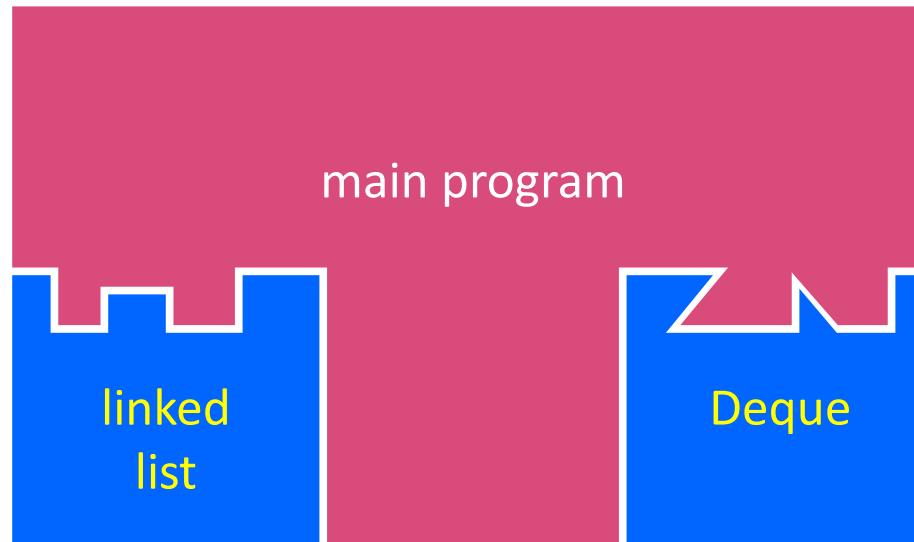
- ❖ Memory Errors, Valgrind & gdb
- ❖ **C Header Files & Modules**
- ❖ C compilation, definitions vs declarations, CPP
- ❖ Makefiles

Multi-File C Programs

- ❖ Let's create a queue *module*
 - A module is a self-contained piece of an overall program
 - Has externally visible functions that customers can invoke
 - Has externally visible `typedefs`, and perhaps global variables, that customers can use
 - May have internal functions, `typedefs`, or global variables that customers should *not* look at
 - The module's *interface* is its set of public functions, `typedefs`, and global variables

Modularity

- ❖ The degree to which components of a system can be separated and recombined
 - “Loose coupling” and “separation of concerns”
 - Modules can be developed independently
 - Modules can be re-used in different projects



C Header Files

- ❖ **Header:** a file whose only purpose is to be `#include`'d
 - Generally has a filename `.h` extension
 - Holds the variables, types, and function prototype declarations that make up the interface to a module
 - There are <system-defined> and "programmer-defined" headers

```
#include <stdio.h>           #include "my_linkedlist.h"
```
- ❖ **Main Idea:**
 - Every name `.c` is intended to be a module that has a name `.h`
 - name `.h` declares the interface to that module
 - Other modules can use name by `#include`-ing name `.h`
 - They should assume as little as possible about the implementation in name `.c`

C Module Conventions (1 of 2)

- ❖ File contents:
 - .h files only contain *declarations*, never *definitions*
 - .c files never contain prototype declarations for functions that are intended to be exported through the module interface
 - Public-facing functions are **ModuleName**^{Deque_Push_Back}**_functionname** () and take a pointer to “this” as their first argument
- ❖ Including: ↑
 The “object” we are calling the function on
 - **NEVER** #include a .c file – only #include .h files
 - #include all of headers you reference, even if another header (transitively) includes some of them
- ❖ Compiling:
 - Any .c file with an associated .h file should be able to be compiled into a .o file
 - The .c file should #include the .h file; the compiler will check definitions and declarations for consistency

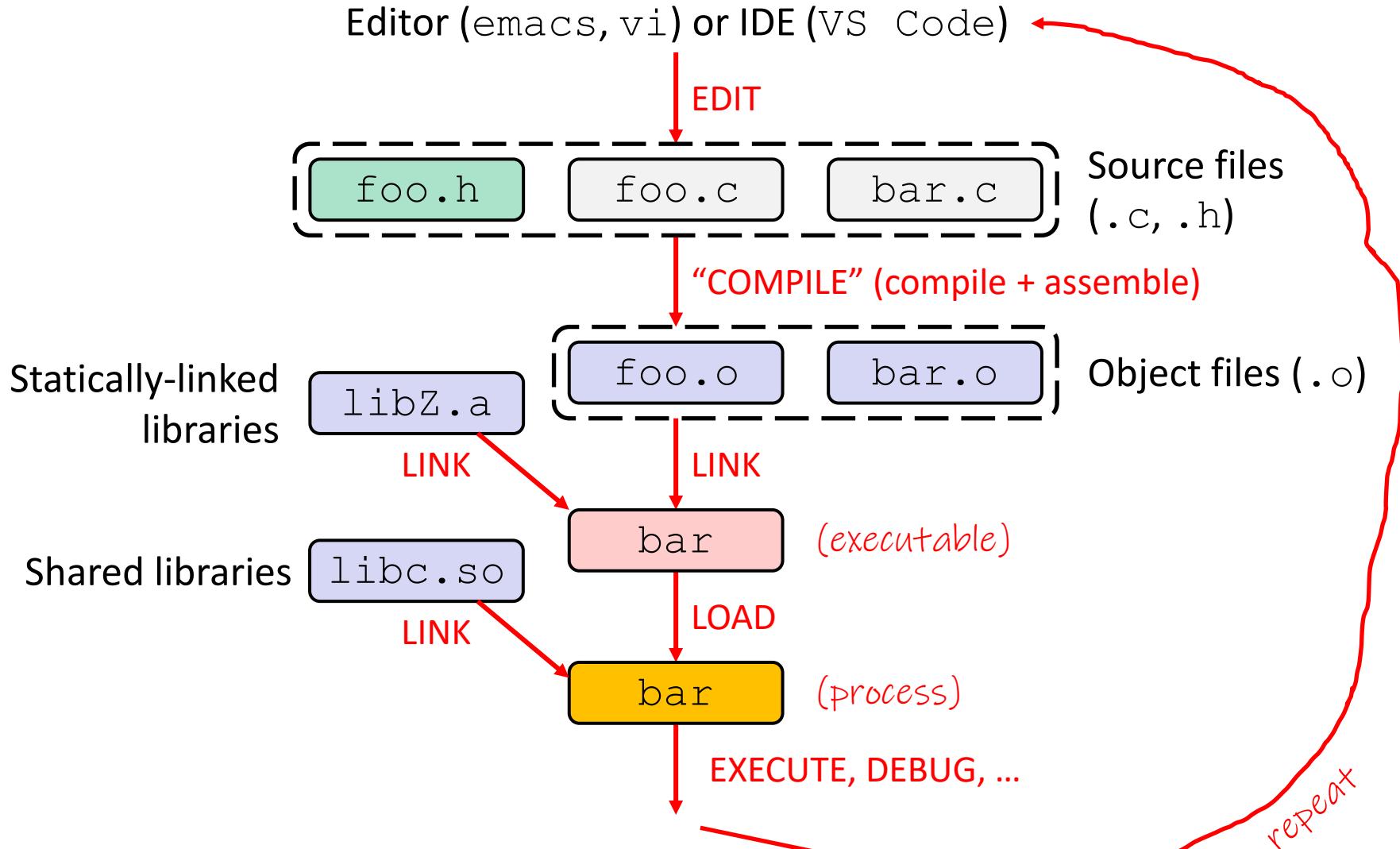
C Module Conventions (2 of 2)

- ❖ Commenting:
 - If a function is declared in a header file (.h) and defined in a C file (.c), *the header needs full documentation because it is the public specification*
 - Don't copy-paste the comment into the C file (don't want two copies that can get out of sync)
 - If prototype and implementation are in the same C file:
 - School of thought #1: Full comment on the prototype at the top of the file, no comment (or "declared above") on code
 - School of thought #2: Prototype is for the compiler and doesn't need comment; comment the code to keep them together

Lecture Outline

- ❖ Memory Errors, Valgrind & gdb
- ❖ C Header Files & Modules
- ❖ **C compilation, definitions vs declarations, CPP**
- ❖ Makefiles

C Workflow



C to Machine Code

```
void sumstore(int x, int y,  
              int* dest) {  
    *dest = x + y;  
}
```

C source file
(sumstore.c)

C compiler (gcc -S)

sumstore:

```
addl    %edi, %esi  
movl    %esi, (%rdx)  
ret
```

Assembly file
(sumstore.s)

C compiler
(gcc -c)

Assembler (gcc -c or as)

```
400575: 01 fe  
         89 32  
         c3
```

Machine code
(sumstore.o)

Function Definitions

- ❖ Generic format:

```
returnType fname(type param1, ..., type paramN) {  
    // statements  
}
```

```
// sum of integers from 1 to max  
int sumTo(int max) {  
    int i, sum = 0;  
  
    for (i = 1; i <= max; i++) {  
        sum += i;  
    }  
  
    return sum;  
}
```

Function Ordering

- ❖ You *shouldn't* call a function that hasn't been declared yet

C compiler goes line by line

```
int main(int argc, char** argv) { ←  
    printf("sumTo(5) is: %d\n", sumTo(5)); ←  
    return EXIT_SUCCESS;           "What is sumTo()?"  
}  
  
// sum of integers from 1 to max  
int sumTo(int max) {  
    int i, sum = 0;  
  
    for (i = 1; i <= max; i++) {  
        sum += i;  
    }  
    return sum;  
}
```

Solution 1: Reverse Ordering

- ❖ Simple solution; however, imposes ordering restriction on writing functions (who-calls-what?)

```
// sum of integers from 1 to max
int sumTo(int max) {           ← defined
    int i, sum = 0;

    for (i = 1; i <= max; i++) {
        sum += i;
    }
    return sum;
}

int main(int argc, char** argv) { Seen later
    printf("sumTo(5) is: %d\n", sumTo(5)); ←
    return EXIT_SUCCESS;
}
```

Solution 2: Function Declaration

- ❖ Teaches the compiler arguments and return types; function definitions can then be in a logical order
 - Function comment usually by the *prototype* Parameter names optional

(1) Declare functions first

(2) Main function

(3) Define functions later

```
// sum of integers from 1 to max
int sumTo(int); // func prototype

int main(int argc, char** argv) {
    printf("sumTo(5) is: %d\n", sumTo(5));
    return EXIT_SUCCESS;
}

int sumTo(int max) {
    int i, sum = 0;
    for (i = 1; i <= max; i++) {
        sum += i;
    }
    return sum;
}
```

Function Declaration vs. Definition

- ❖ C makes a careful distinction between these two
- ❖ **Definition:** the thing itself
 - e.g. code for function, variable definition that creates storage
 - Must be **exactly one** definition of each thing (no duplicates)
- ❖ **Declaration:** description of a thing
 - e.g. function prototype, external variable declaration
 - Often in header files and incorporated via #include
 - Should also #include declaration in the file with the actual definition to check for consistency
 - Needs to appear in **all files** that use that thing
 - Should appear before first use

More on header files & #include
in this lecture

#include and the C Preprocessor

- ❖ The C preprocessor (cpp) transforms your source code before the compiler runs – it's a simple copy-and-replace text processor(!) with a memory
 - Input is a C file (text) and output is still a C file (text)
 - Processes the directives it finds in your code (`#directive`)
 - e.g. `#include "ll.h"` is replaced by the post-processed content of ll.h
 - e.g. `#define PI 3.1415` defines a symbol (a string!) and replaces later occurrences
 - Several others that we'll see soon...
 - Run on your behalf by `gcc` during compilation
 - Note: `#include <foo.h>` looks in system (library) directories; `#include "foo.h"` looks first in current directory, then system

C Preprocessor Example

- ❖ What do you think the preprocessor output will be?

```
#define BAR 2 + FOO  
  
typedef long long int verylong;  
  
cpp_example.h
```

```
#define FOO 1  
  
#include "cpp_example.h"  
  
int main(int argc, char** argv) {  
    int x = FOO;      // a comment  
    int y = BAR;  
    verylong z = FOO + BAR;  
    return 0;  
}
```

cpp_example.c

Keep in mind:

1. Pre-processor goes line by line
2. builds up "state" as it processes directives

C Preprocessor Example

Arrow points to
next line to process

- ❖ We can manually run the preprocessor:
 - `cpp` is the preprocessor (can also use `gcc -E`)
 - “`-P`” option suppresses some extra debugging annotations

```
#define BAR 2 + FOO

typedef long long int verylong;
```

cpp_example.h

```
#define FOO 1

#include "cpp_example.h"

int main(int argc, char** argv) {
    int x = FOO;    // a comment
    int y = BAR;
    verylong z = FOO + BAR;
    return 0;
}
```

cpp_example.c

```
bash$ cpp -P cpp_example.c out.c
bash$ cat out.c
```

C Preprocessor Example

Arrow points to
next line to process

- We can manually run the preprocessor:

- `cpp` is the preprocessor (can also use `gcc -E`)
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Pre-processor state

| | |
|-----|---|
| FOO | 1 |
| | |

```
#define BAR 2 + FOO  
  
typedef long long int verylong;
```

cpp_example.h

```
#define FOO 1  
  
#include "cpp_example.h"  
  
int main(int argc, char** argv) {  
    int x = FOO; // a comment  
    int y = BAR;  
    verylong z = FOO + BAR;  
    return 0;  
}
```

cpp_example.c

```
bash$ cpp -P cpp_example.c out.c  
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```

C Preprocessor Example

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Pre-processor state

| | |
|-----|---|
| FOO | 1 |
| | |

```
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cpp_example.h

```
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#include "cpp_example.h"

int main(int argc, char** argv) {
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    int y = BAR;
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}
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cpp_example.c

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next line to process

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- `cpp` is the preprocessor (can also use `gcc -E`)
- “`-P`” option suppresses some extra debugging annotations

Pre-processor state

| | |
|-----|---------|
| FOO | 1 |
| BAR | $2 + 1$ |

```
#define BAR 2 + FOO

typedef long long int verylong;
```

cpp_example.h

```
#define FOO 1

#include "cpp_example.h"

int main(int argc, char** argv) {
    int x = FOO;    // a comment
    int y = BAR;
    verylong z = FOO + BAR;
    return 0;
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Arrow points to
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Pre-processor state

| | |
|-----|---------|
| FOO | 1 |
| BAR | $2 + 1$ |

```
#define BAR 2 + FOO

typedef long long int verylong;
```

cpp_example.h

```
#define FOO 1

#include "cpp_example.h"

int main(int argc, char** argv) {
    int x = FOO;    // a comment
    int y = BAR;
    verylong z = FOO + BAR;
    return 0;
}
```

cpp_example.c

```
bash$ cpp -P cpp_example.c out.c
bash$ cat out.c
```

```
typedef long long int verylong;
```

C Preprocessor Example

Arrow points to
next line to process

- We can manually run the preprocessor:

- `cpp` is the preprocessor (can also use `gcc -E`)
- “`-P`” option suppresses some extra debugging annotations

Pre-processor state

| | |
|-----|---------|
| FOO | 1 |
| BAR | $2 + 1$ |

```
#define BAR 2 + FOO

typedef long long int verylong;
```

cpp_example.h

```
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#include "cpp_example.h"

int main(int argc, char** argv) {
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typedef long long int verylong;
```

cpp_example.h

```
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#include "cpp_example.h"

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    int y = BAR;
    verylong z = FOO + BAR;
    return 0;
}
```

cpp_example.c

```
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bash$ cat out.c
```

```
typedef long long int verylong;
int main(int argc, char **argv) {
    int x = 1;
```

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typedef long long int verylong;

cpp_example.h
```

```
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int main(int argc, char** argv) {
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    verylong z = FOO + BAR;
    return 0;
}
```

cpp_example.c

```
bash$ cpp -P cpp_example.c out.c
bash$ cat out.c
```

```
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int main(int argc, char **argv) {
    int x = 1;
    int y = 2 + 1;
```

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cpp_example.h

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C Preprocessor Example

Arrow points to
next line to process

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Pre-processor state

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typedef long long int verylong;
```

cpp_example.h

```
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int main(int argc, char** argv) {
    int x = FOO; // a comment
    int y = BAR;
    verylong z = FOO + BAR;
    return 0;
}
```

```
bash$ cpp -P cpp_example.c out.c
bash$ cat out.c
```

```
typedef long long int verylong;
int main(int argc, char **argv) {
    int x = 1;
    int y = 2 + 1;
    verylong z = 1 + 2 + 1;
    return 0;
}
```

cpp_example.c

Program Using a Linked List

```
#include <stdlib.h>
#include <assert.h>
#include "ll.h"

Node* Push(Node* head,
           void* element) {
    ... // implementation here
}
```

ll.c

```
typedef struct node_st {
    void* element;
    struct node_st* next;
} Node;

Node* Push(Node* head,
           void* element);
```

ll.h

Need definitions for code to compile

```
#include "ll.h"

int main(int argc, char** argv) {
    Node* list = NULL;
    char* hi = "hello";
    char* bye = "goodbye";

    list = Push(list, (void*)hi);
    list = Push(list, (void*)bye);

    ...

    return 0;
}
```

example_ll_customer.c

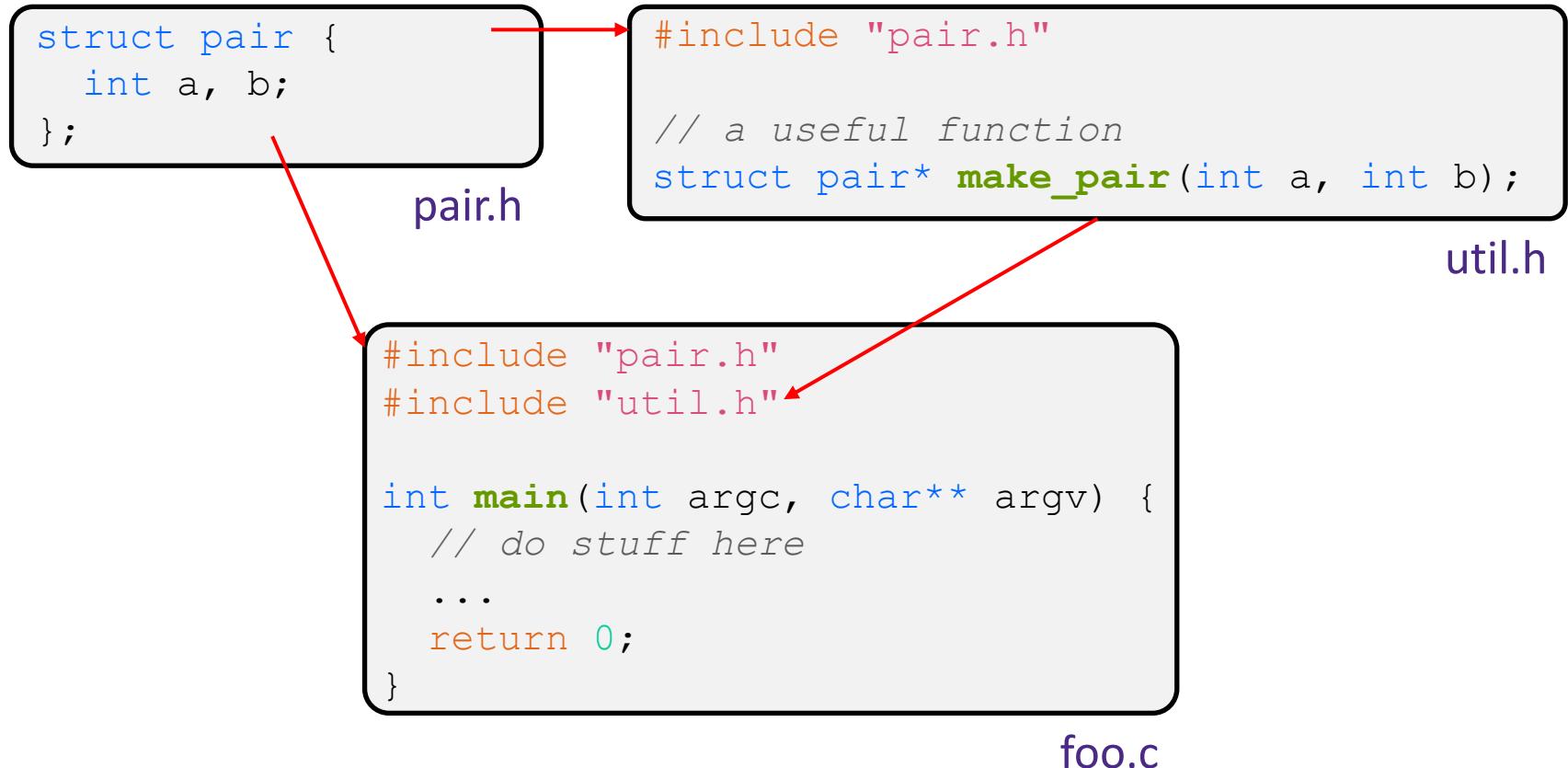
Compiling the Program

- ❖ Four parts:
 - 1/2) Compile `example_ll_customer.c` into an object file
 - 2/1) Compile `ll.c` into an object file
 - 3) Link both object files into an executable
 - 4) Test, Debug, Rinse, Repeat

```
1 bash$ gcc -Wall -g -c example_ll_customer.c
2 bash$ gcc -Wall -g -c ll.c
3 bash$ gcc -g -o example_ll_customer ll.o example_ll_customer.o
4 bash$ ./example_ll_customer
Payload: 'yo!'
Payload: 'goodbye'
Payload: 'hello'
4 bash$ valgrind -leak-check=full ./example_ll_customer
... etc ...
```

But There's a Problem with #include

- ❖ What happens when we compile foo.c?

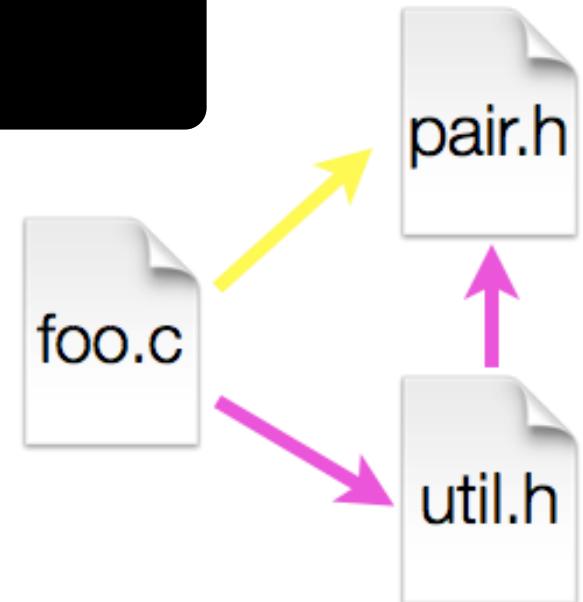


A Problem with #include

- ❖ What happens when we compile `foo.c`?

```
bash$ gcc -Wall -g -o foo foo.c
In file included from util.h:1:0,
                 from foo.c:2:
pair.h:1:8: error: redefinition of 'struct pair'
  struct pair { int a, b; };
          ^
In file included from foo.c:1:0:
pair.h:1:8: note: originally defined here
  struct pair { int a, b; };
          ^
```

- ❖ `foo.c` includes `pair.h` twice!
 - Second time is indirectly via `util.h`
 - Struct definition shows up twice
 - Can see using `cpp`



Preprocessor Tricks: Header Guards

- ❖ A standard C Preprocessor trick to deal with this [Pre-processor state](#)
 - Uses macro definition (`#define`) in combination with conditional compilation (`#ifndef` and `#endif`)

```
#ifndef PAIR_H_
#define PAIR_H_

struct pair {
    int a, b;
};

#endif // PAIR_H_
```

pair.h

```
#ifndef UTIL_H_
#define UTIL_H_

#include "pair.h"

// a useful function
struct pair* make_pair(int a, int b);

#endif // UTIL_H_
```

util.h

foo.c

```
#include "pair.h"
#include "util.h"

int main(int argc, char** argv) {
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    int a, b;
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| | |
|---------|---------|
| PAIR_H_ | defined |
| | |

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#define PAIR_H_

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Preprocessor Tricks: Header Guards

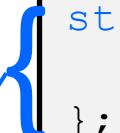
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```
#ifndef PAIR_H_
#define PAIR_H_

{
```



```
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    };

#endif // PAIR_H_
```

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```

util.h

```
#include "pair.h"
#include "util.h"

int main(int argc, char** argv) {
```

foo.c

Preprocessor Tricks: Constants

- ❖ A way to deal with “magic constants”

```
int globalbuffer[1000];

void circalc(float rad,
             float* circumf,
             float* area) {
    *circumf = rad * 2.0 * 3.1415;
    *area = rad * 3.1415 * 3.1415;
}
```

Bad code
(littered with magic constants)

```
#define BUFSIZE 1000
#define PI 3.14159265359

int globalbuffer[BUFSIZE];

void circalc(float rad,
             float* circumf,
             float* area) {
    *circumf = rad * 2.0 * PI;
    *area = rad * PI * PI;
}
```

Better code

Lecture Outline

- ❖ Memory Errors, Valgrind & gdb
- ❖ C Header Files & Modules
- ❖ C compilation, definitions vs declarations, CPP
- ❖ **Makefiles**

make

- ❖ make is a classic program for controlling what gets (re)compiled and how
 - Many other such programs exist (*e.g.*, ant, maven, IDE “projects”)
- ❖ make has tons of fancy features, but only two basic ideas:
 - 1) Scripts for executing commands
 - 2) Dependencies for avoiding unnecessary work
- ❖ To avoid “just teaching make features” (boring and narrow), let’s focus more on the concepts...

Building Software

- ❖ Programmers spend a lot of time “building”
 - Creating programs from source code
 - Both programs that they write and other people write
- ❖ Programmers like to automate repetitive tasks
 - Repetitive: gcc -Wall -g -std=c17 -o widget foo.c bar.c baz.c

- Retype this every time:



- Use up-arrow or history:



(still retype after logout)

- Have an alias or bash script:



- Have a Makefile:



(you're ahead of us)

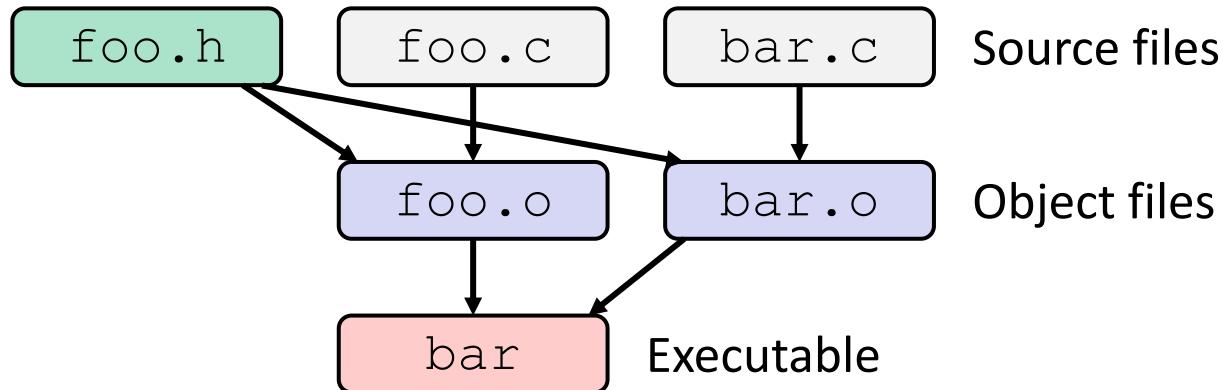
“Real” Build Process

- ❖ On larger projects, you can't or don't want to have one big (set of) command(s) that are all run every time you change anything. To do things “smarter,” consider:
 - 1) It could be worse: If `gcc` didn't combine steps for you, you'd need to preprocess, compile, and link on your own (along with anything you used to generate the C files)
 - 2) Source files could have multiple outputs (*e.g.*, `javadoc`). You may have to type out the source file name(s) multiple times
 - 3) You don't want to have to document the build logic when you distribute source code; make it relatively simple for others to build
 - 4) You don't want to recompile everything every time you change something (especially if you have 10^5 - 10^7 files of source code)
- ❖ A script can handle 1-3 (use a variable for filenames for 2), but 4 is trickier

Recompilation Management

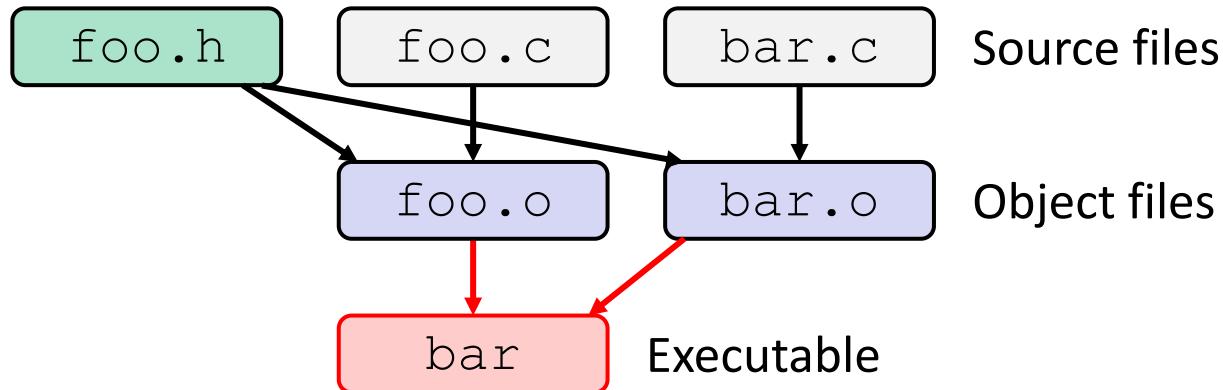
- ❖ The “theory” behind avoiding unnecessary compilation is a *dependency dag* (directed, acyclic graph)
- ❖ To create a target t , you need sources s_1, s_2, \dots, s_n and a command c that directly or indirectly uses the sources
 - If t is newer than every source (file-modification times), assume there is no reason to rebuild it
 - Recursive building: if some source s_i is itself a target for some other sources, see if it needs to be rebuilt...
 - Cycles “make no sense”!

Theory Applied to C



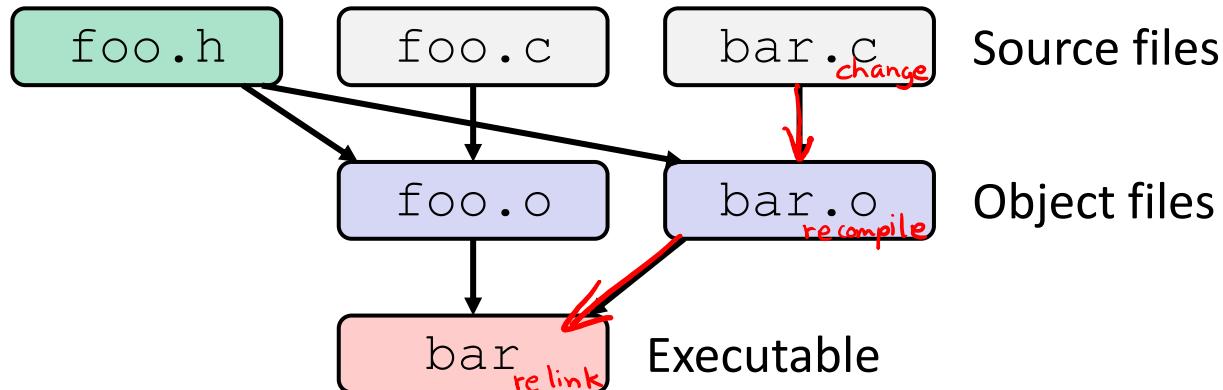
- ❖ Compiling a `.c` creates a `.o` – the `.o` depends on the `.c` and all included files (`.h`, recursively/transitively)

Theory Applied to C



- ❖ Compiling a `.c` creates a `.o` – the `.o` depends on the `.c` and all included files (`.h`, recursively/transitively)
- ❖ Creating an executable (“linking”) depends on `.o` files

Theory Applied to C



- ❖ If one `.c` file changes, just need to recreate one `.o` file, maybe a library, and re-link
- ❖ If a `.h` file changes, may need to rebuild more
- ❖ Many more possibilities!

make Basics

- ❖ A makefile contains a bunch of **triples**:

① **target**: sources ②
 ← Tab → command ③

- Colon after target is *required*
- Command lines must start with a **TAB**, NOT SPACES
- Multiple commands for same target are executed *in order*
 - Can split commands over multiple lines by ending lines with ‘\’

- ❖ Example:

```
foo.o: foo.c foo.h bar.h
      gcc -Wall -o foo.o -c foo.c
```

Using make

```
bash$ make <target>
```

- ❖ **Defaults:**
 - If no target specified, will use the first one in the file
 - Will interpret commands in your default shell
- ❖ **Target execution:**
 - Check each source in the source list:
 - If the source is a target in the makefile, then process it recursively
 - If some source does not exist, then error
 - If any source is newer than the target (or target does not exist), run command (presumably to update the target)

“Phony” Targets

- ❖ A make target whose command does not create a file of the target’s name (*i.e.*, a “recipe”)
 - As long as target file doesn’t exist, the command(s) will be executed because the target must be “remade”
- ❖ e.g., target `clean` is a convention to remove generated files to “start over” from just the source

```
clean:
```

```
    rm foo.o bar.o baz.o widget *~
```

- ❖ e.g., target `all` is a convention to build all “final products” in the makefile
 - Lists all of the “final products” as sources

“all” Example

```
1 all: prog B.class someLib.a
      5
2 # notice no commands this time
      6
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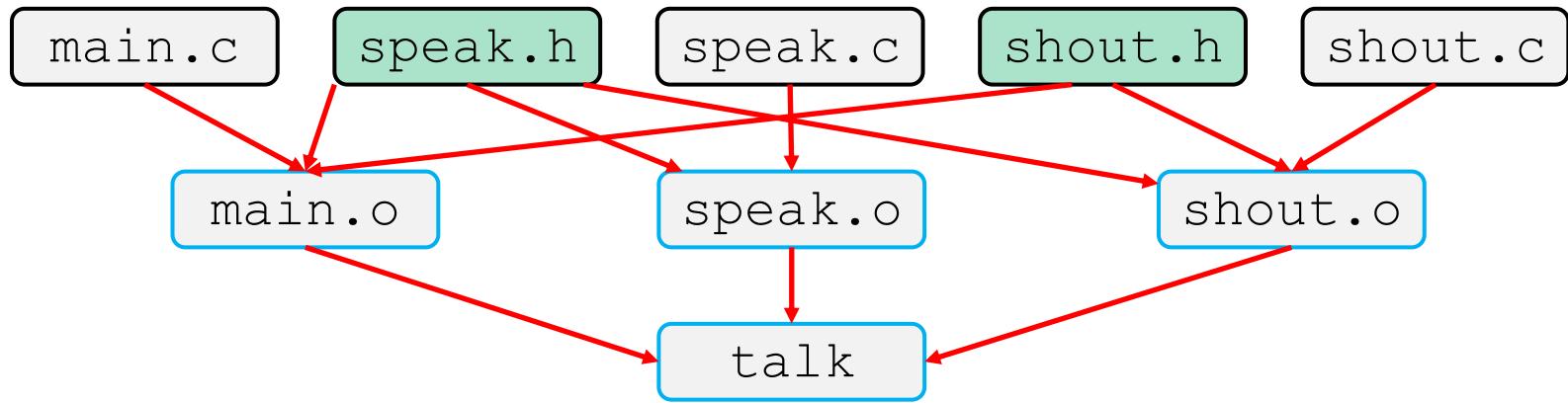
```

Makefile Writing Tips

- ❖ *When creating a Makefile, first draw the dependencies!!!*
- ❖ C Dependency Rules:
 - .c and .h files are never targets, only sources.
 - Each .c file will be compiled into a corresponding .o file
 - Header files will be implicitly used via #include
 - Executables will typically be built from one or more .o file
- ❖ Good Conventions:
 - Include a clean rule
 - If you have more than one “final target,” include an all rule
 - The first/top target should be your singular “final target” or all

Writing a Makefile Example

- ❖ “talk” program (find files on web with lecture slides)



```
#include "speak.h"  
#include "shout.h"
```

```
int main(int argc, char** argv) { ... }
```

main.c

```
#include "speak.h"  
...
```

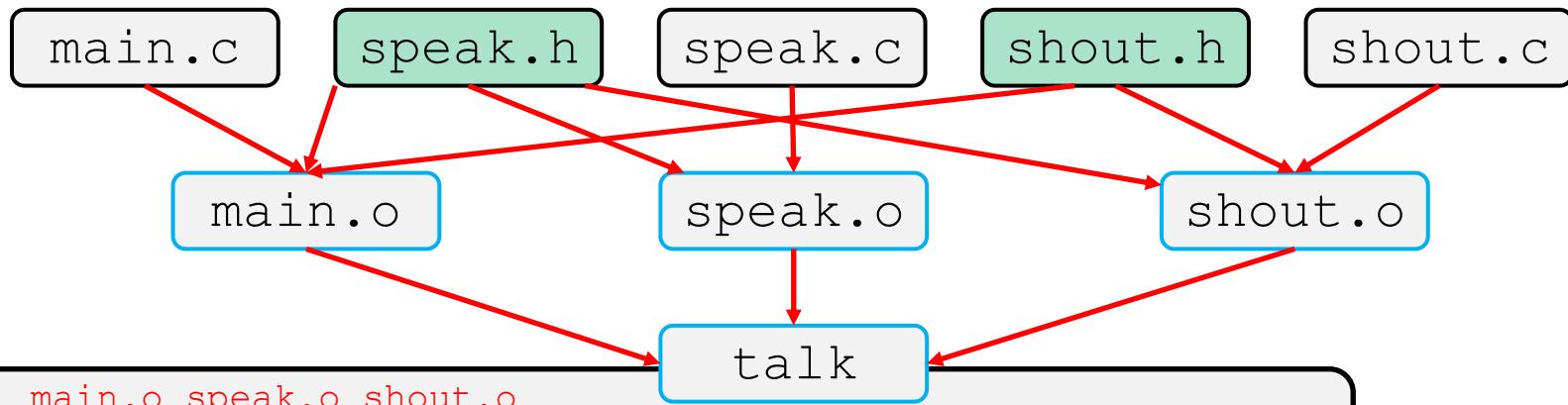
speak.c

```
#include "speak.h"  
#include "shout.h"  
...
```

shout.c

Writing a Makefile Example

- ❖ “talk” program (find files on web with lecture slides)



```
talk: main.o speak.o shout.o  
      gcc -g -Wall -o talk main.o speak.o shout.o
```

```
main.o: main.c speak.h shout.h  
      gcc -g -Wall -c main.c
```

```
speak.o: speak.c speak.h  
      gcc -g -Wall -c speak.c
```

```
shout.o: shout.c speak.h shout.h  
      gcc -g -Wall -c shout.c
```

```
clean:  
      rm talk *.o
```

make Variables

- ❖ You can define variables in a makefile:
 - All values are strings of text, no “types”
 - Variable names are case-sensitive and can’t contain ‘:’, ‘#’, ‘=’, or whitespace

- ❖ Example:

```
CC = gcc
CFLAGS = -Wall -std=c17
OBJFILES = foo.o bar.o baz.o
widget: $(OBJFILES)
        $(CC) $(CFLAGS) -o widget $(OBJFILES)
```

- ❖ Advantages:

- Easy to change things (especially in multiple commands)
 - It’s common to use variables to hold lists of filenames
- Can also specify/overwrite variables on the command line:
(e.g., make CC=clang CFLAGS=-g)

Revenge of the Funny Characters

- ❖ Special variables:
 - \$@ for target name
 - \$^ for all sources
 - \$< for left-most source
 - Lots more! – see the documentation

- ❖ Examples:

```
# CC and CFLAGS defined above
widget: foo.o bar.o
          $(CC) $(CFLAGS) -o $@ $^
foo.o:  foo.c foo.h bar.h
          $(CC) $(CFLAGS) -c $<
```

And more...

- ❖ There are a lot of “built-in” rules – see documentation
- ❖ There are “suffix” rules and “pattern” rules
 - Example: `% .class: %.java
javac $< # we need the $< here`
- ❖ Remember that you can put *any* shell command – even whole scripts!
- ❖ You can repeat target names to add more dependencies
- ❖ Often this stuff is more useful for reading makefiles than writing your own (until some day...)