Compiler Design

Linkers, Objects and Executables

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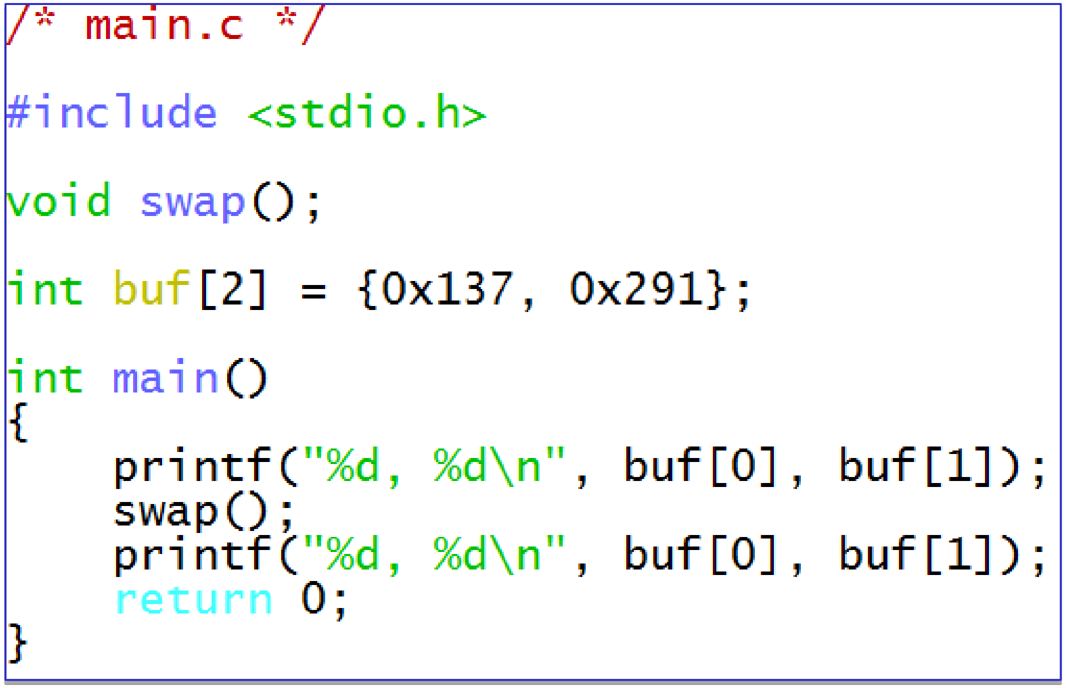
Multiple file linking in C:
A short detour

Ack: Example from slides on **Linking**

15-213: Introduction to Computer Systems
11th Lecture, Sept. 30, 2010

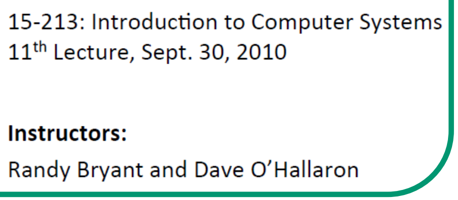
Instructors:
Randy Bryant and Dave O'Hallaron

Multiple file linking in C: A short detour



```
/* main.c */

#include <stdio.h>

void swap();

int buf[2] = {0x137, 0x291};

int main()
{
    printf("%d, %d\n", buf[0], buf[1]);
    swap();
    printf("%d, %d\n", buf[0], buf[1]);
    return 0;
}
```

Ack: Example from slides on **Linking**



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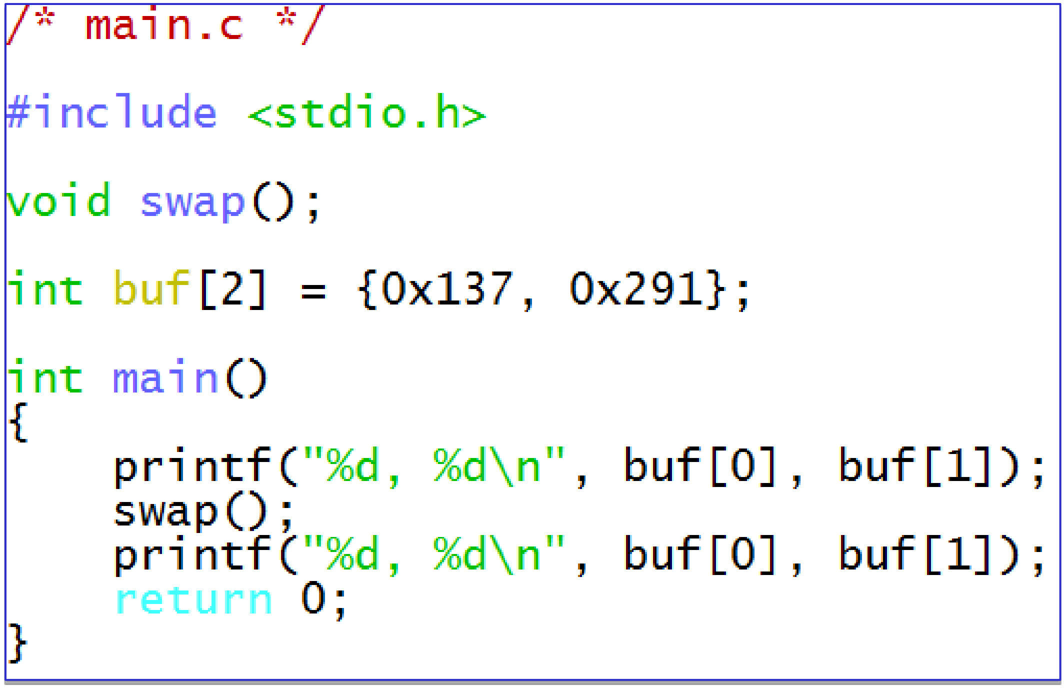
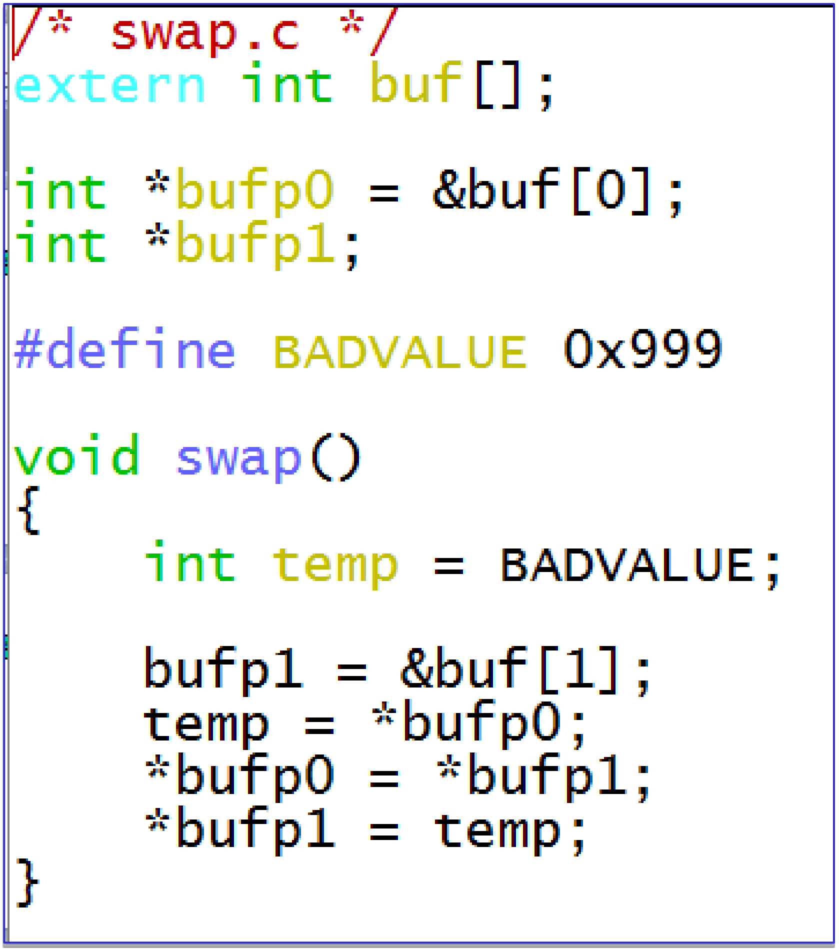
Multiple file linking in C:
A short detour

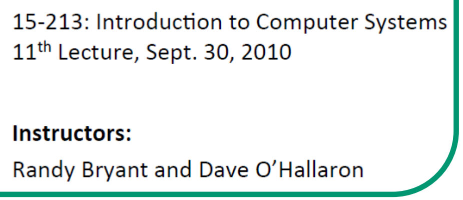


```
/* main.c */

#include <stdio.h>

void swap();

int buf[2] = {0x137, 0x291};

int main()
{
    printf("%d, %d\n", buf[0], buf[1]);
    swap();
    printf("%d, %d\n", buf[0], buf[1]);
    return 0;
}
```



```
/* swap.c */
extern int buf[];

int *bufp0 = &buf[0];
int *bufp1;

#define BADVALUE 0x999

void swap()
{
    int temp = BADVALUE;

    bufp1 = &buf[1];
    temp = *bufp0;
    *bufp0 = *bufp1;
    *bufp1 = temp;
}
```

Ack: Example from slides on **Linking**



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How to get an executable program from multiple C files?

gcc options

gcc options

- Preprocessing only

```
gcc –E main.c
```

-- Output on stdout

gcc options

- Preprocessing only

```
gcc -E main.c
```

-- Output on stdout

- Object code generation

```
gcc -c main.c
```

-- Generates main.o

gcc options

- Preprocessing only

```
gcc –E main.c
```

-- Output on stdout

- Object code generation

```
gcc –c main.c
```

-- Generates main.o

- Assembly code generation

```
gcc –S main.c
```

-- Generates main.s

gcc options

- Preprocessing only

```
gcc -E main.c
```

-- Output on stdout

- Object code generation

```
gcc -c main.c
```

-- Generates main.o

- Assembly code generation

```
gcc -S main.c
```

-- Generates main.s

- Full compilation only

```
gcc main.c swap.c
```

-- Generates a.out

gcc options

- Use –g option to enable debugging

objdump

- Usage: objdump <option(s)> <file(s)>
- Display information from object <file(s)>

objdump

- Usage: objdump <option(s)> <file(s)>
- Display information from object <file(s)>

```
objdump -d a.out
```

-- dump only .text section

objdump

- Usage: objdump <option(s)> <file(s)>
- Display information from object <file(s)>

```
objdump -d a.out        -- dump only .text section
objdump -D a.out        -- dump all sections
```

objdump

- Usage: objdump <option(s)> <file(s)>
- Display information from object <file(s)>

```
objdump -d a.out
objdump -D a.out
objdump -S swap.o
```

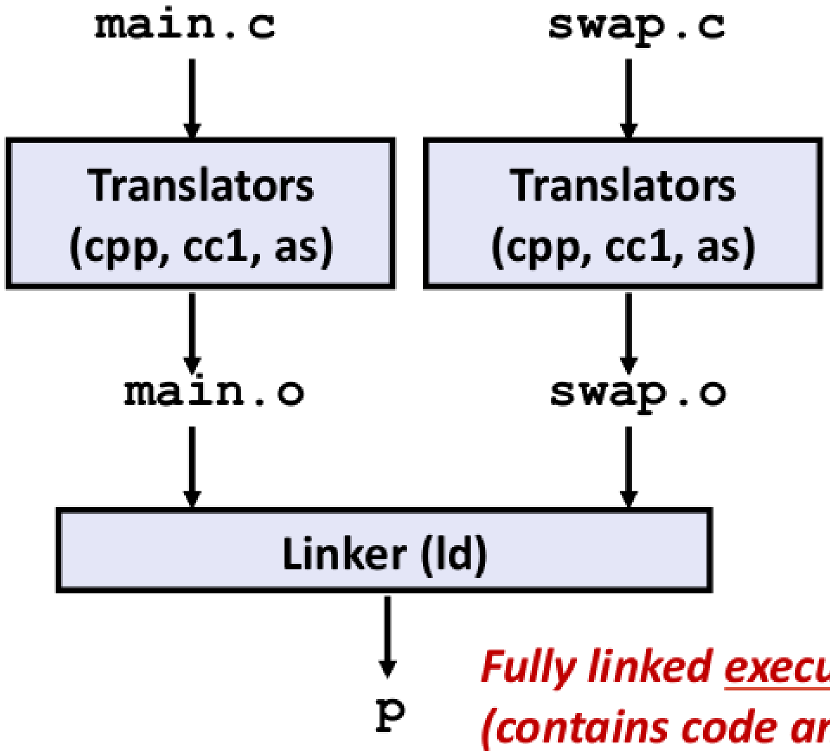
-- dump only .text section

-- dump all sections

-- If .o is created with –g
display source statements

Static Linking

- Programs are translated and linked using a *compiler driver*:
  - `unix> gcc -O2 -g -o p main.c swap.c`
  - `unix> ./p`



Source files

Separately compiled relocatable object files

Fully linked executable object file (contains code and data for all functions defined in `main.c and swap.c`)

Ack: Bryant & O'Hallaron

Multiple File Linking : WHY?

- Modularity
  - How?
- Efficiency
  - How?

What Do Linkers Do?

- **Step 1. Symbol resolution**

  - Programs define and reference *symbols* (variables and functions):

    ```
    void swap() {…}     /* define symbol swap */
    swap();             /* reference symbol a */
    int *xp = &x;   /* define xp, reference x */
    ```

  - Symbol definitions are stored (by compiler) in *symbol table*.
    - Symbol table is an array of structs
    - Each entry includes name, size, and location of symbol.

  - Linker associates each symbol reference with exactly one symbol definition.

What Do Linkers Do? (cont)

- **Step 2. Relocation**
  - Merges separate code and data sections into single sections
  - Relocates symbols from their relative locations in the `.o` files to their final absolute memory locations in the executable.
  - Updates all references to these symbols to reflect their new positions.

Three Kinds of Object Files (Modules)

- **Relocatable object file (`.o` file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
    - Each `.o` file is produced from exactly one `.c` source
- **Executable object file (`a.out` file)**
  - Contains code and data in a form that can be copied directly into memory and then executed.
- **Shared object file (`.so` file)**
  - Special type of relocatable object file that can be loaded into memory and linked dynamically, at either load time or run-time.
  - Called *Dynamic Link Libraries* (DLLs) by Windows

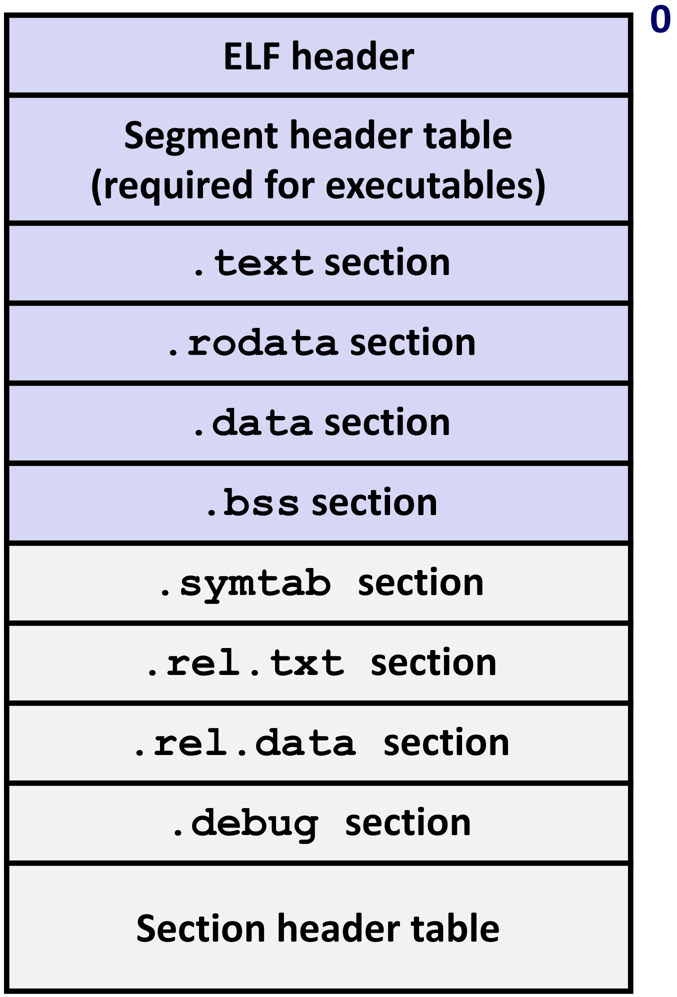
Executable and Linkable Format (ELF)

- **Standard binary format for object files**
- **Originally proposed by AT&T System V Unix**
  - Later adopted by BSD Unix variants and Linux
- **One unified format for**
  - Relocatable object files (`.o`),
  - Executable object files `(a.out`)
  - Shared object files (`.so`)

- **Generic name: ELF binaries**

ELF Object File Format

- **Elf header**
  - Word size, byte ordering, file type (.o, exec, .so), machine type, etc.
- **Segment header table**
  - Page size, virtual addresses memory segments (sections), segment sizes.
- **`.text` section**
  - Code
- **`.rodata` section**
  - Read only data: jump tables, ...
- **`.data` section**
  - Initialized global variables
- **`.bss` section**
  - Uninitialized global variables
  - "Block Started by Symbol"
  - "Better Save Space"
  - Has section header but occupies no space



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ELF header

Segment header table
(required for executables)

`.text` section

`.rodata` section

`.data` section

`.bss` section

`.symtab` section

`.rel.txt` section

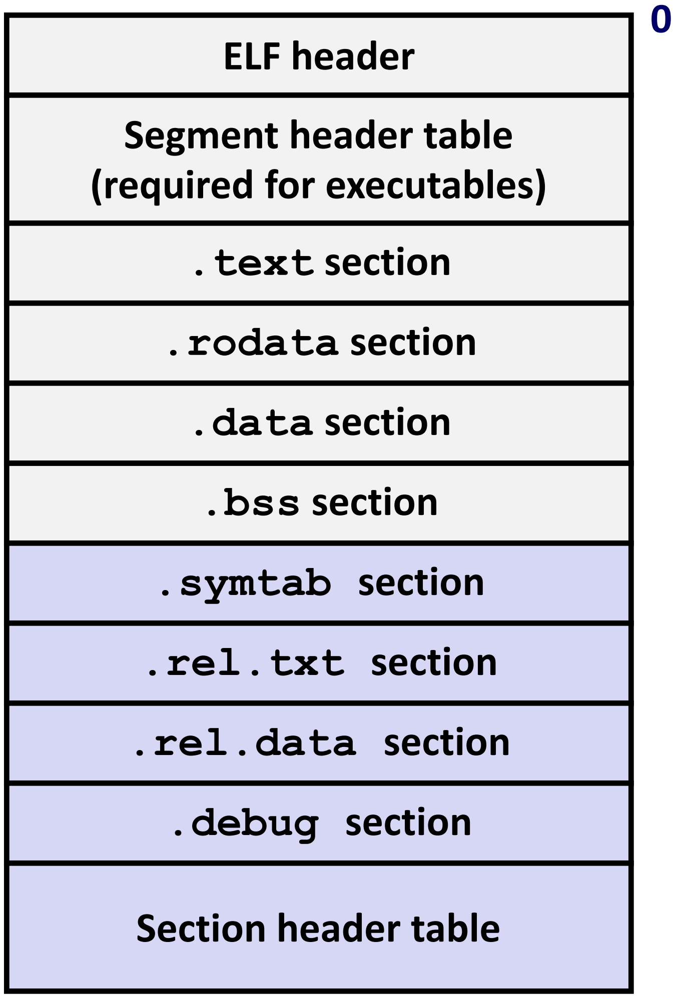
`.rel.data` section

`.debug` section

Section header table

ELF Object File Format (cont.)

- **`.symtab` section**
  - Symbol table
  - Procedure and static variable names
  - Section names and locations
- **`.rel.text` section**
  - Relocation info for `.text` section
  - Addresses of instructions that will need to be modified in the executable
  - Instructions for modifying.
- **`.rel.data` section**
  - Relocation info for `.data` section
  - Addresses of pointer data that will need to be modified in the merged executable
- **`.debug` section**
  - Info for symbolic debugging (`gcc -g`)
- **Section header table**
  - Offsets and sizes of each section



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ELF header

Segment header table
(required for executables)

`.text` section

`.rodata` section

`.data` section

`.bss` section

`.symtab` section

`.rel.txt` section

`.rel.data` section

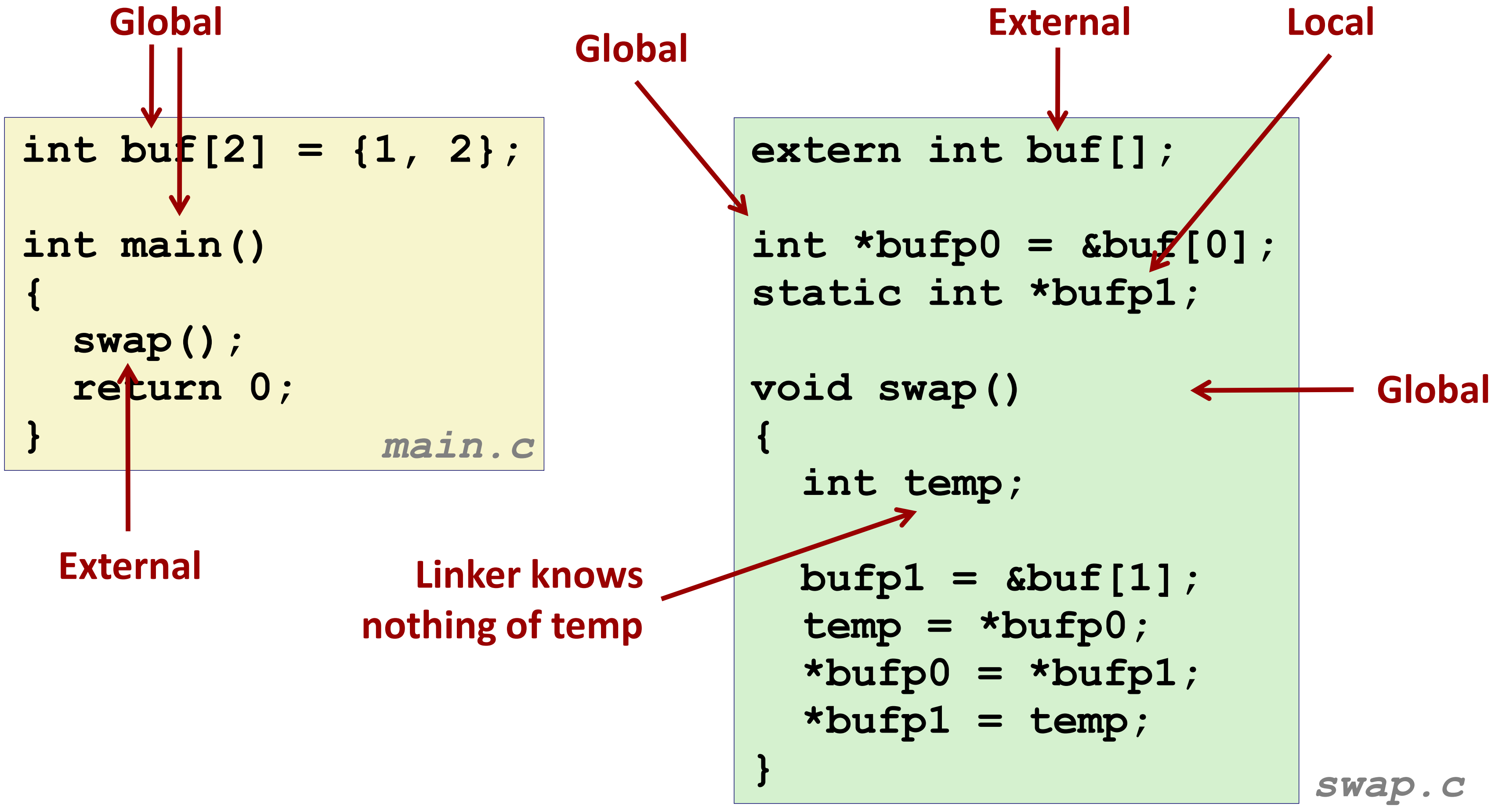
`.debug` section

Section header table

Linker Symbols

- **Global symbols**
  - Symbols defined by module *m* that can be referenced by other modules.
  - E.g.: non-**`static`** C functions and non-**`static`** global variables.
- **External symbols**
  - Global symbols that are referenced by module *m* but defined by some other module.
- **Local symbols**
  - Symbols that are defined and referenced exclusively by module *m*.
  - E.g.: C functions and variables defined with the **`static`** attribute.
  - **Local linker symbols are *not* local program variables**

Resolving Symbols



Global

Global

```
int buf[2] = {1, 2};

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

main.c

External

Global

External

Local

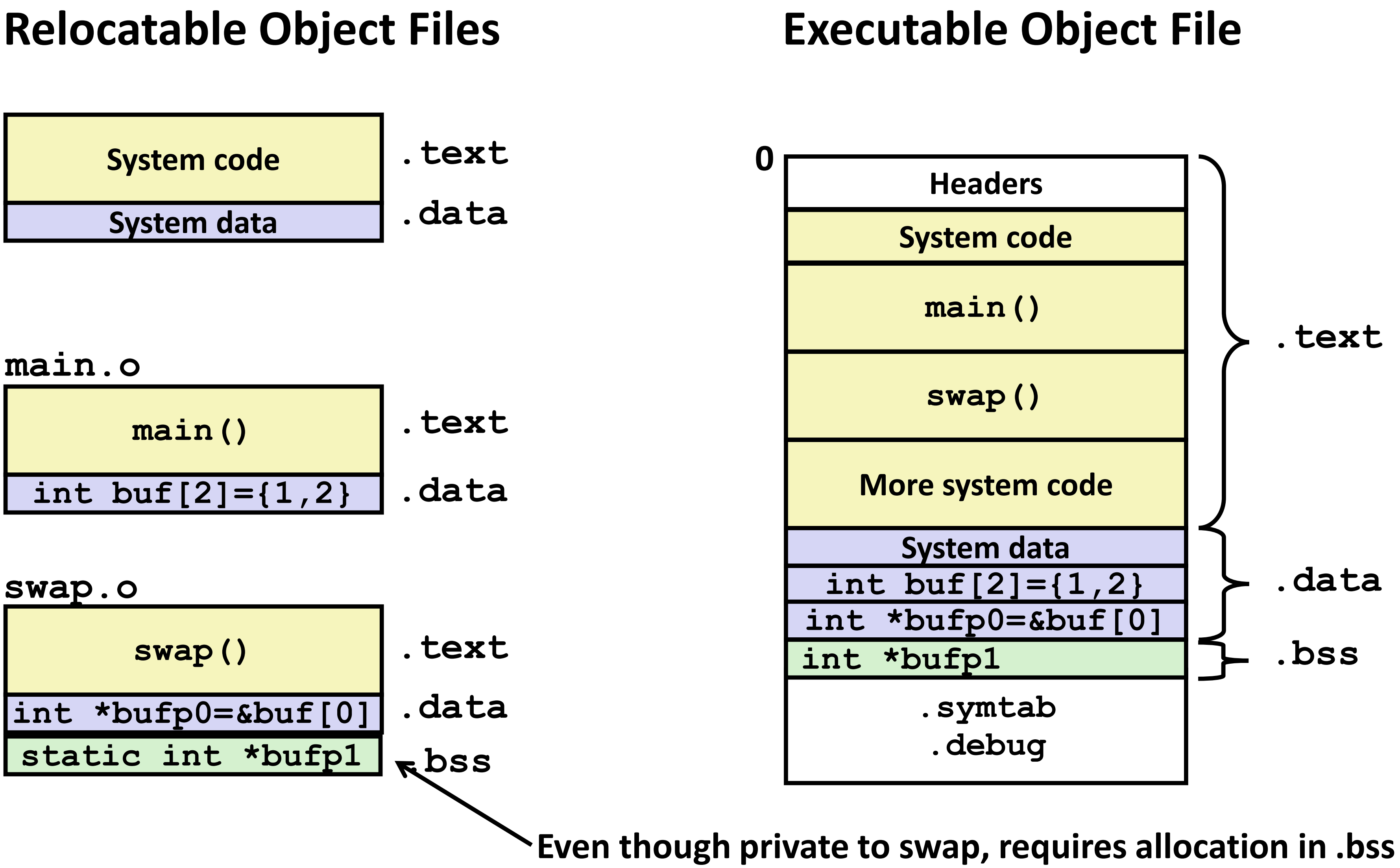
```
extern int buf[];

int *bufp0 = &buf[0];
static int *bufp1;

void swap()
{
   int temp;

   bufp1 = &buf[1];
   temp = *bufp0;
   *bufp0 = *bufp1;
   *bufp1 = temp;
}
```

Global

Linker knows nothing of temp

swap.c

Relocating Code and Data



Even though private to swap, requires allocation in .bss

Relocation Info (main)

main.c

```
int buf[2] =
  {1,2};

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

main.o

```
0000000 <main>:
   0:   8d 4c 24 04       lea    0x4(%esp),%ecx
   4:   83 e4 f0          and    $0xfffffff0,%esp
   7:   ff 71 fc          pushl  0xfffffffc(%ecx)
   a:   55                push   %ebp
   b:   89 e5             mov    %esp,%ebp
   d:   51                push   %ecx
   e:   83 ec 04          sub    $0x4,%esp
  11:   e8 fc ff ff ff    call   12 <main+0x12>
                       12: R_386_PC32 swap
  16:   83 c4 04          add    $0x4,%esp
  19:   31 c0             xor    %eax,%eax
  1b:   59                pop    %ecx
  1c:   5d                pop    %ebp
  1d:   8d 61 fc          lea    0xfffffffc(%ecx),%esp
  20:   c3                ret
```

Source: `objdump -r -d`

```
Disassembly of section .data:

 00000000 <buf>:
   0:   01 00 00 00 02 00 00 00
```

Relocation Info (swap, .text)

swap.c

```
extern int buf[];

int
  *bufp0 = &buf[0];

static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

swap.o

```
Disassembly of section .text:

00000000 <swap>:
   0:   8b 15 00 00 00 00        mov    0x0,%edx
                     2: R_386_32      buf
   6:   a1 04 00 00 00           mov    0x4,%eax
                     7: R_386_32      buf
   b:   55                       push   %ebp
   c:   89 e5                    mov    %esp,%ebp
   e:   c7 05 00 00 00 00 04     movl   $0x4,0x0
  15:   00 00 00
                     10: R_386_32     .bss
                     14: R_386_32     buf
  18:   8b 08                    mov    (%eax),%ecx
  1a:   89 10                    mov    %edx,(%eax)
  1c:   5d                       pop    %ebp
  1d:   89 0d 04 00 00 00        mov    %ecx,0x4
                     1f: R_386_32     buf
  23:   c3                       ret
```

Relocation Info (swap, .data)

swap.c

```
extern int buf[];

int *bufp0 =
           &buf[0];
static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

```
Disassembly of section .data:

00000000 <bufp0>:
   0:    00 00 00 00

         0: R_386_32 buf
```

Executable Before/After Relocation (.text)

```
0000000 <main>:
   . . .
   e:   83 ec 04           sub    $0x4,%esp
  11:   e8 fc ff ff ff     call   12 <main+0x12>
                        12: R_386_PC32 swap
  16:   83 c4 04           add    $0x4,%esp
  . . .
```

```
0x8048396 + 0x1a
= 0x80483b0
```

```
08048380 <main>:
 8048380:      8d 4c 24 04          lea    0x4(%esp),%ecx
 8048384:      83 e4 f0             and    $0xfffffff0,%esp
 8048387:      ff 71 fc             pushl  0xfffffffc(%ecx)
 804838a:      55                   push   %ebp
 804838b:      89 e5                mov    %esp,%ebp
 804838d:      51                   push   %ecx
 804838e:      83 ec 04             sub    $0x4,%esp
 8048391:      e8 1a 00 00 00       call   80483b0 <swap>
 8048396:      83 c4 04             add    $0x4,%esp
 8048399:      31 c0                xor    %eax,%eax
 804839b:      59                   pop    %ecx
 804839c:      5d                   pop    %ebp
 804839d:      8d 61 fc             lea    0xfffffffc(%ecx),%esp
 80483a0:      c3                   ret
```

```
  0:   8b 15 00 00 00 00       mov    0x0,%edx
                       2: R_386_32    buf
  6:   a1 04 00 00 00          mov    0x4,%eax
                       7: R_386_32    buf
  ...
  e:   c7 05 00 00 00 00 04    movl   $0x4,0x0
 15:   00 00 00
                       10: R_386_32    .bss
                       14: R_386_32   buf
  . . .
 1d:   89 0d 04 00 00 00       mov    %ecx,0x4
                       1f: R_386_32   buf
 23:   c3                      ret
```

```
080483b0 <swap>:
 80483b0:      8b 15 20 96 04 08     mov    0x8049620,%edx
 80483b6:      a1 24 96 04 08        mov    0x8049624,%eax
 80483bb:      55                    push   %ebp
 80483bc:      89 e5                 mov    %esp,%ebp
 80483be:      c7 05 30 96 04 08 24  movl   $0x8049624,0x8049630
 80483c5:      96 04 08
 80483c8:      8b 08                 mov    (%eax),%ecx
 80483ca:      89 10                 mov    %edx,(%eax)
 80483cc:      5d                    pop    %ebp
 80483cd:      89 0d 24 96 04 08     mov    %ecx,0x8049624
 80483d3:      c3                    ret
```

Executable After Relocation (.data)

```
Disassembly of section .data:

08049620 <buf>:
 8049620:       01 00 00 00 02 00 00 00

08049628 <bufp0>:
 8049628:       20 96 04 08
```

Strong and Weak Symbols

- **Program symbols are either strong or weak**
  - ***Strong***: procedures and initialized globals
  - ***Weak***: uninitialized globals

	p1.c	p2.c	
strong	`int foo=5;`	`int foo;`	weak

strong	`p1() {`
	`}`
		`p2() {`
		`}`
			strong

Linker's Symbol Rules

- **Rule 1: Multiple strong symbols are not allowed**
  - Each item can be defined only once
  - Otherwise: Linker error
- **Rule 2: Given a strong symbol and multiple weak symbol, choose the strong symbol**
  - References to the weak symbol resolve to the strong symbol
- **Rule 3: If there are multiple weak symbols, pick an arbitrary one**
  - Can override this with `gcc –fno-common`

Linker Puzzles

`int x;`
`p1() {}`
	`p1() {}`	Link time error: two strong symbols (`p1`)

`int x;`
`p1() {}`
	`int x;`
	`p2() {}`
		References to `x` will refer to the same uninitialized int. Is this what you really want?

`int x;`
`int y;`
`p1() {}`
	`double x;`
	`p2() {}`
		Writes to `x` in `p2` might overwrite `y`!
		Evil!

`int x=7;`
`int y=5;`
`p1() {}`
	`double x;`
	`p2() {}`
		Writes to `x` in `p2` will overwrite `y`!
		Nasty!

`int x=7;`
`p1() {}`
	`int x;`
	`p2() {}`
		References to `x` will refer to the same initialized variable.

Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.

Role of .h Files

c1.c

```c
#include "global.h"

int f() {
  return g+1;
}
```

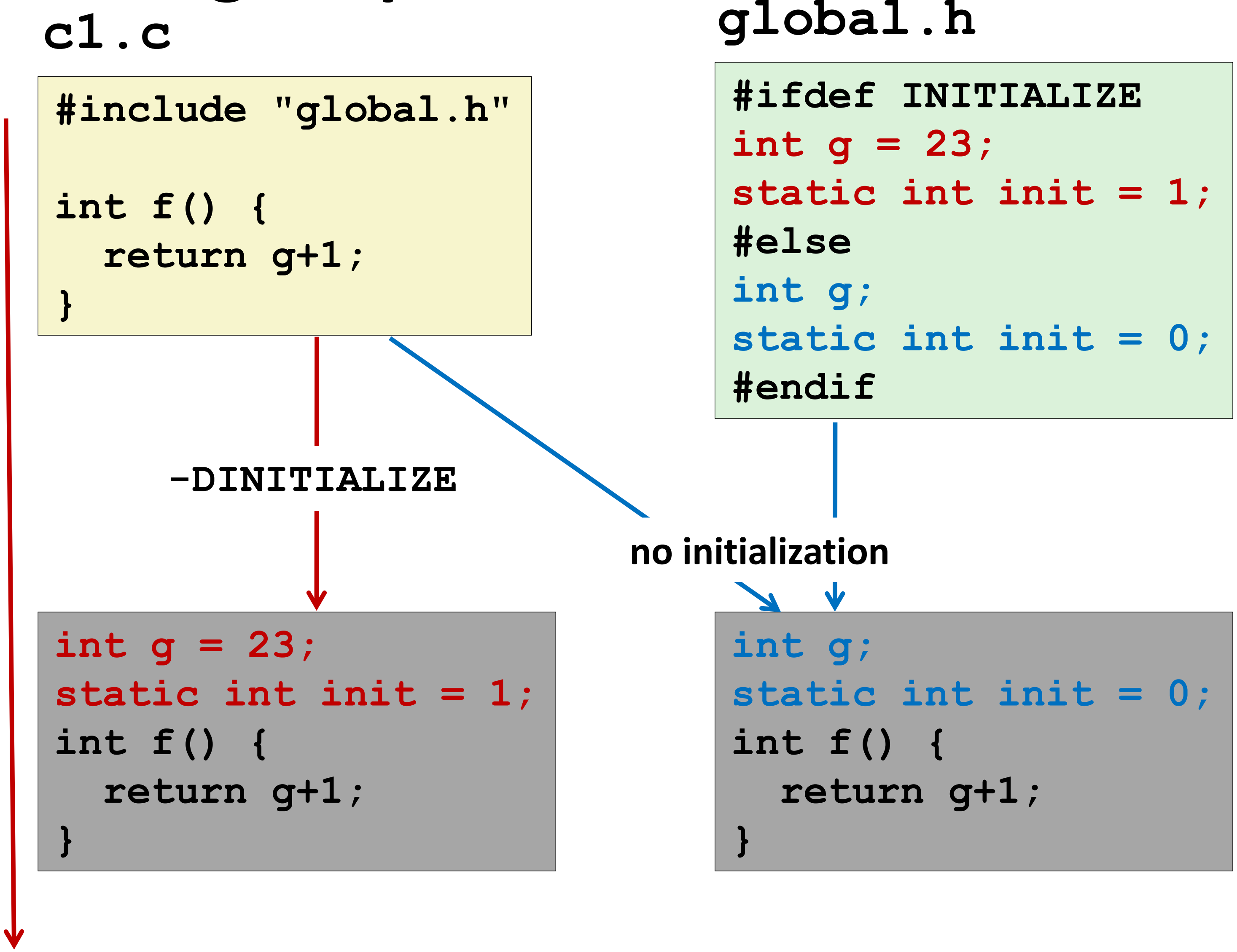
global.h

```c
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

c2.c

```c
#include <stdio.h>
#include "global.h"

int main() {
  if (!init)
    g = 37;
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

Running Preprocessor



c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

-DINITIALIZE

```
int g = 23;
static int init = 1;
int f() {
  return g+1;
}
```

no initialization

```
int g;
static int init = 0;
int f() {
  return g+1;
}
```

#include causes C preprocessor to insert file verbatim

Role of .h Files (cont.)

c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

c2.c

```
#include <stdio.h>
#include "global.h"

int main() {
  if (!init)
    g = 37;
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

What happens:

```
gcc -o p c1.c c2.c
   ??
gcc -o p c1.c c2.c \
  -DINITIALIZE
   ??
```

Global Variables

- **Avoid if you can**

- **Otherwise**
  - Use **`static`** if you can
  - Initialize if you define a global variable
  - Use **`extern`** if you use external global variable