Linking I:
Basic Concepts and Procedures

COMP402127: Introduction to Computer Systems

Hao Li
Xi'an Jiaotong University

Today

- **Why Linking**
- **Basic Concepts and Procedures**
  - Basic Procedures
  - ELF formats
- **Procedures in Detail**
  - Symbol Resolution
  - Relocation
- **Walkthrough Example**

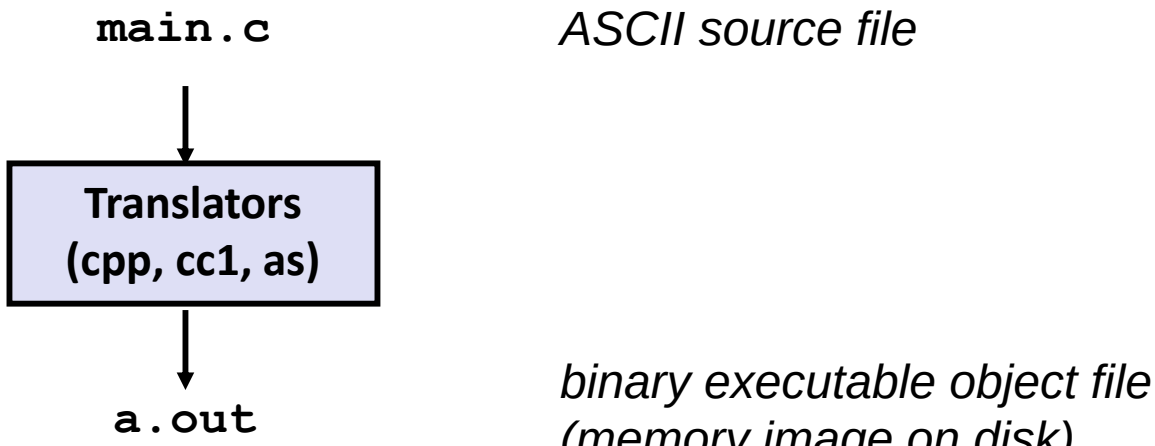
Understanding linking can help you avoid nasty errors and make you a better programmer.

Example C Program

```c
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}

int array[2] = {1, 2};

int main(int argc, char** argv)
{
    int val = sum(array, 2);
    return val;
}
```

main.c

Monolithic Compilation and its Problems



- Huge lines of code in modern software
  - Complete (slow) compilation
- Multiple developers cooperation
  - Hard for code management
- Frequent changes
  - Frequent complete compilation

Example C Program

```c
int sum(int *a, int n);

int array[2] = {1, 2};

int main(int argc, char** argv)
{
    int val = sum(array, 2);
    return val;
}
```

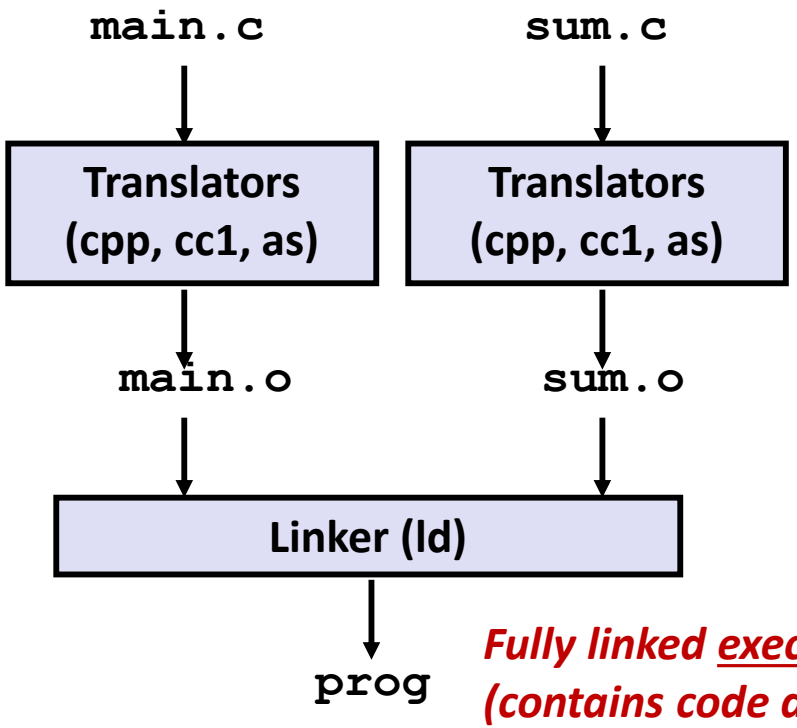
main.c

```c
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```

sum.c

Separate Compilation + Linking

- **Programs are translated and linked using a *compiler driver*:**
  - `linux> gcc -Og -o prog main.c sum.c`
  - `linux> ./prog`



Source files

Separately compiled relocatable object files

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

Why Linking: Modularity

- **Program can be written as a collection of smaller source files, rather than one monolithic mass.**
  - Code from multiple developers can be isolated

- **Can build libraries of common functions**
  - e.g., Math library, standard C library

Why Linking: Efficiency

- **Time: Separate compilation. How does that save time?**
  - Change one source file, compile, and then relink.
  - No need to recompile other source files.
  - Can compile multiple files concurrently.
- **Space: Libraries. How do libraries save space?**
  - Common functions can be aggregated into a single file...
  - **Option 1: *Static Linking***
    - Executable files and running memory images contain only the library code they actually use
  - **Option 2: *Dynamic linking***
    - Executable files contain no library code
    - During execution, single copy of library code can be shared across all executing processes

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- Procedures in Detail
  - Symbol Resolution
  - Relocation
- Walkthrough Example

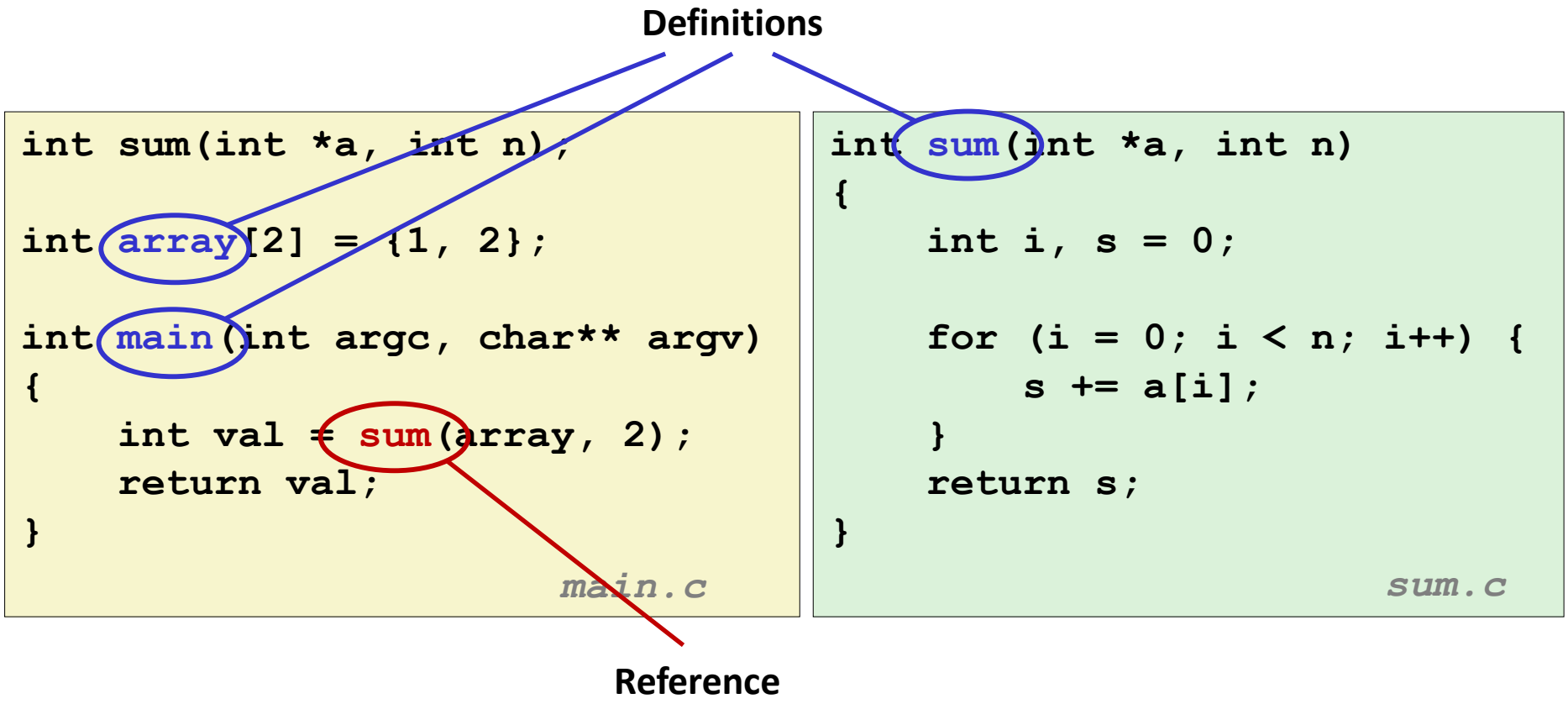
Step 1: Symbol Resolution

- **Programs define and reference *symbols* (global variables and functions):**
  - `void swap() {…}  /* define symbol swap */`
  - `swap();  /* reference symbol swap */`
  - `int *xp = &x;  /* define symbol xp, reference x */`

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

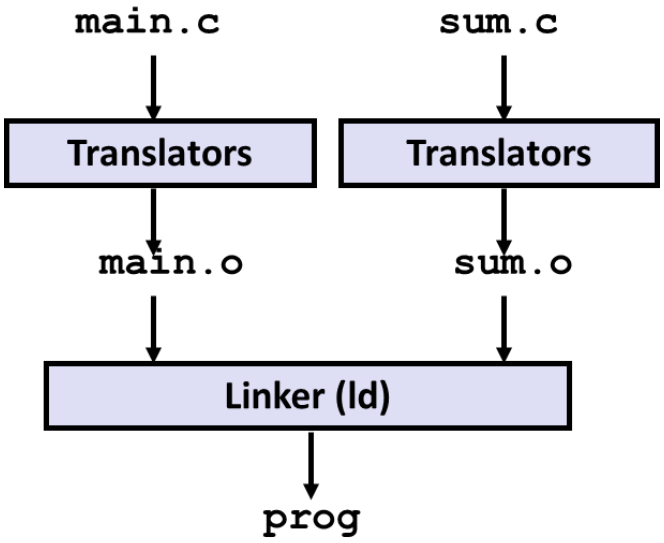
- **During symbol resolution step, the linker associates each symbol reference with exactly one symbol definition.**

Symbols in Example C Program



Step 2: Relocation

- Merges separate code and data sections into single sections
- Relocates symbols from their relative locations to their final absolute memory locations in the executable.
- Updates all references to these symbols



Three Kinds of Object Files (Modules)

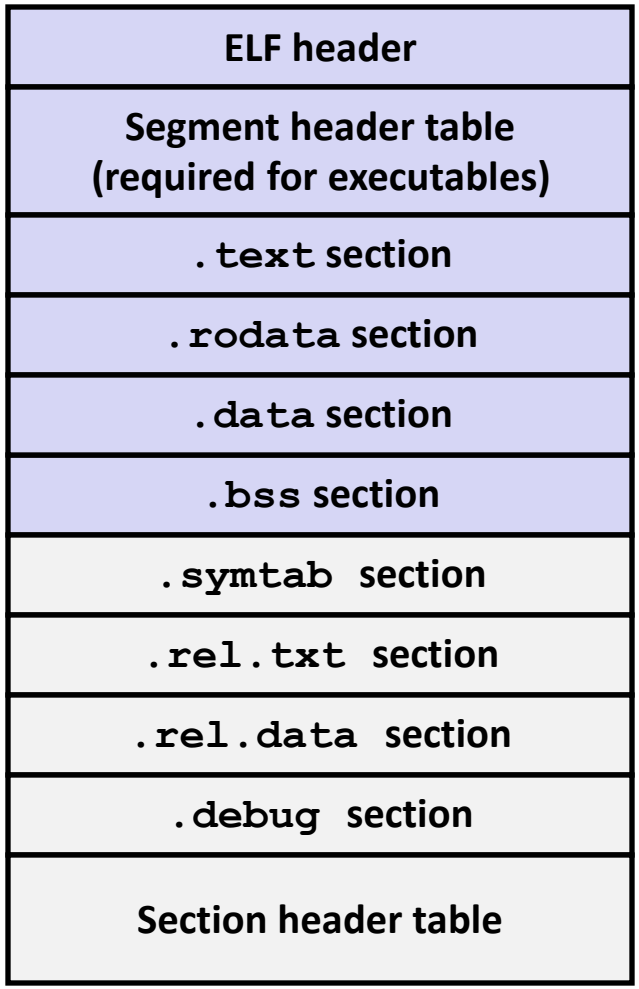
- **Relocatable object file (`.o` file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
    - Each `.o` file is produced from exactly one source (`.c`) file
- **Executable object file (`a.out` file)**
  - Contains code and 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**
- **One unified format for**
  - Relocatable object files (`.o`),
  - Executable object files (`a.out`)
  - Shared object files (`.so`)
- **Generic name: ELF binaries**

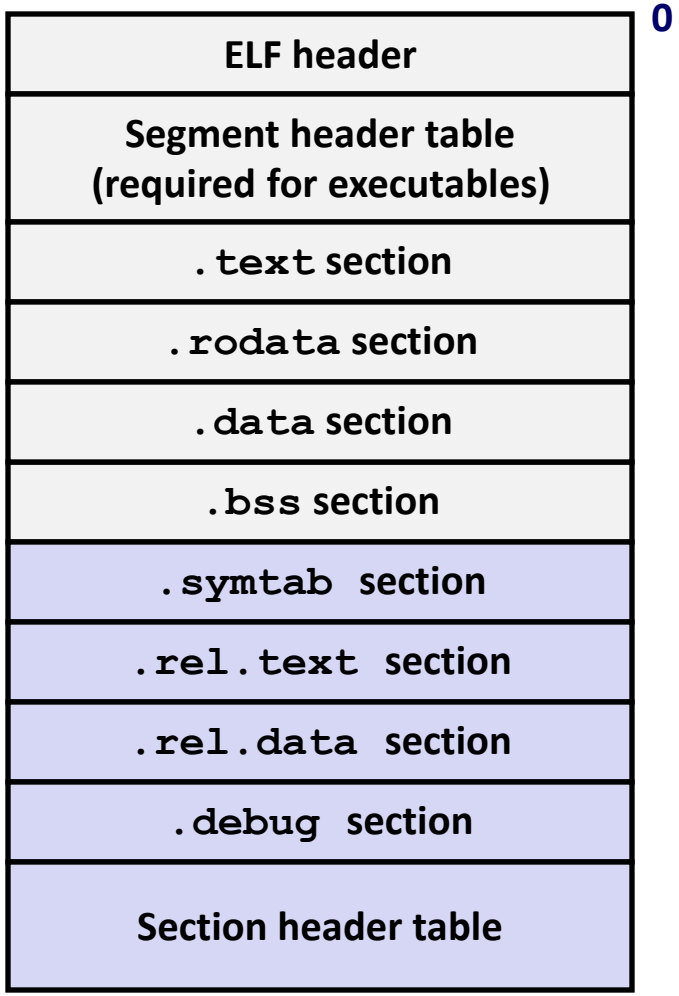
ELF Object File Format

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



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 Symbol Tables

- **Each relocatable object file has a symbol table in .symtab section**
- **A symbol table contains information about the symbols that are defined and referenced in the file**
  - Symbol table contains an array of entries
- **The symbol table records the linker symbols (next slide)**

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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 (Referenced global 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 global variables defined with the **`static`** attribute.
  - **Local linker symbols are *not* local program variables**

Symbol Identification

Which **of the following names will be in the symbol table of `symbols.o`?**

symbols.c:

```
int incr = 1;
static int foo(int a) {
  int b = a + incr;
  return b;
}

int main(int argc,
         char* argv[]) {
  printf("%d\n", foo(5));
  return 0;
}
```

Names:

- `incr`
- `foo`
- `a`
- `argc`
- `argv`
- `b`
- `main`
- `printf`
- `"%d\n"`

Can find this with readelf:

```
linux> readelf -s symbols.o
```

Symbol Identification

```
toney@DESKTOP-SGS2CTH:~/xjtu-ics/linking$ readelf -s sym.o

Symbol table '.symtab' contains 8 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS sym.c
     2: 0000000000000000     0 SECTION LOCAL  DEFAULT    1 .text
     3: 0000000000000000    30 FUNC    LOCAL  DEFAULT    1 foo
     4: 0000000000000000     0 SECTION LOCAL  DEFAULT    5 .rodata
     5: 0000000000000000     4 OBJECT  GLOBAL DEFAULT    3 incr
     6: 000000000000001e    58 FUNC    GLOBAL DEFAULT    1 main
     7: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND printf
```


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ELF Symbol Tables

- **Name**
  - byte offset into the string table that points to the null-terminated string name of the symbol.
- **Value (symbol's address)**
  - For relocatable modules
    - the value is an offset from the beginning of the section where the object is defined
  - For executable object files
    - the value is an absolute run-time address.
- **Size**
  - the size (in bytes) of the object

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ELF Symbol Tables

- **Type**
  - usually either data or function
  - The symbol table can also contain entries
    - for the individual sections
    - for the path name of the original source file.
  - So there are distinct types

- **Binding**
  - indicates whether the symbol is local or global

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ELF Symbol Tables

- **Section**
  - Each symbol is assigned to some section of the object file, denoted by the section field, which is an index into the section header table.
  - There are three special pseudosections that don't have entries in the section header table
    - ABS: symbols that should not be relocated
    - UNDEF: symbols that are referenced in this object module but defined elsewhere
    - COMMON: uninitialized data objects
    - these pseudosections exist only in relocatable object files and do not exist in executable object files

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Local Symbols

- **Local non-static C variables vs. local static C variables**
  - local non-static C variables: stored on the stack
  - local static C variables: stored in either `.bss`, or `.data`

```
static int x = 15;

int f() {
    static int x = 17;
    return x++;
}

int g() {
    static int x = 19;
    return x += 14;
}

int h() {
    return x += 27;
}
```

static-local.c

Compiler allocates space in `.data` for each definition of `x`

Creates local symbols in the symbol table with unique names, e.g., `x`, `x.1721` and `x.1724`.

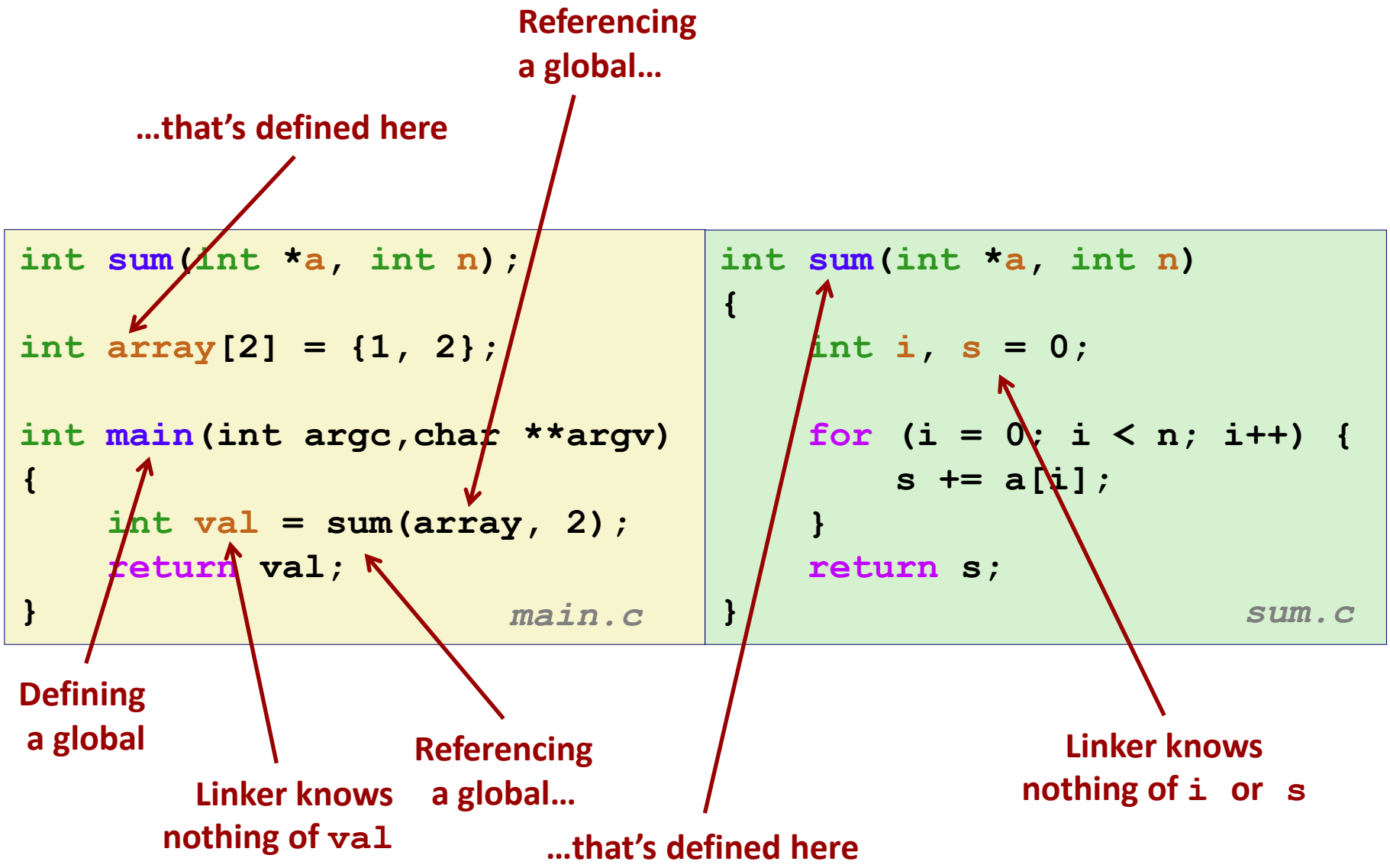
Linker Symbol Example

```
1.   extern int a ;
2.   int f()
3.    {
4.      static int x=1 ;   //x.1
5.      int b = 2;
6.      return x+b;
7.    }
8.
9.    int g()
10.   {
11.     static int x = 1;   //x.2
12.     return x + a ;
13.   }
```

Linker Symbol Examples

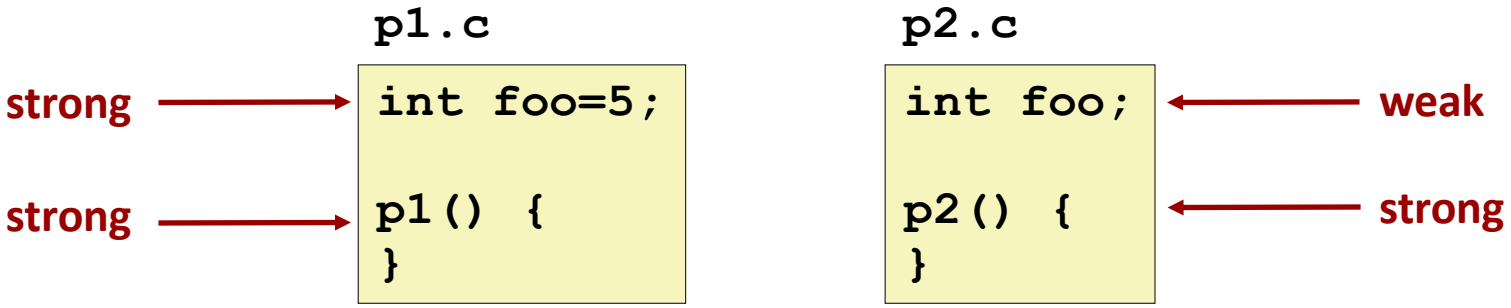
```
toney@DESKTOP-SGS2CTH:~/xjtu-ics/linking$ readelf -s sym2.o

Symbol table '.symtab' contains 9 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS sym2.c
     2: 0000000000000000     0 SECTION LOCAL  DEFAULT    1 .text
     3: 0000000000000000     0 SECTION LOCAL  DEFAULT    3 .data
     4: 0000000000000000     4 OBJECT  LOCAL  DEFAULT    3 x.1
     5: 0000000000000004     4 OBJECT  LOCAL  DEFAULT    3 x.0
     6: 0000000000000000    28 FUNC    GLOBAL DEFAULT    1 f
     7: 000000000000001c    24 FUNC    GLOBAL DEFAULT    1 g
     8: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND a
```

Step 1: Symbol Resolution



Resolve Duplicate Symbol Definitions

- **Program symbols are either *strong* or *weak***
  - ***Strong***: procedures and initialized globals
  - ***Weak***: uninitialized globals
    - Or ones declared with specifier **`extern`**



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 symbols, 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`
- **Puzzles on the next slide**

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** might overwrite **y**! Nasty!

```
int x=7;
p1() {}
```

```
int x;
p2() {}
```

References to **x** will refer to the same initialized variable.

Important: Linker does not do type checking.

Type Mismatch Example

```c
long int x;  /* Weak symbol */

int main(int argc,
         char *argv[]) {
    printf("%ld\n", x);
    return 0;
}
```

mismatch-main.c

```c
/* Global strong symbol */
double x = 3.14;
```

mismatch-variable.c

- Compiles without any errors or warnings
- What gets printed?

Global Variables

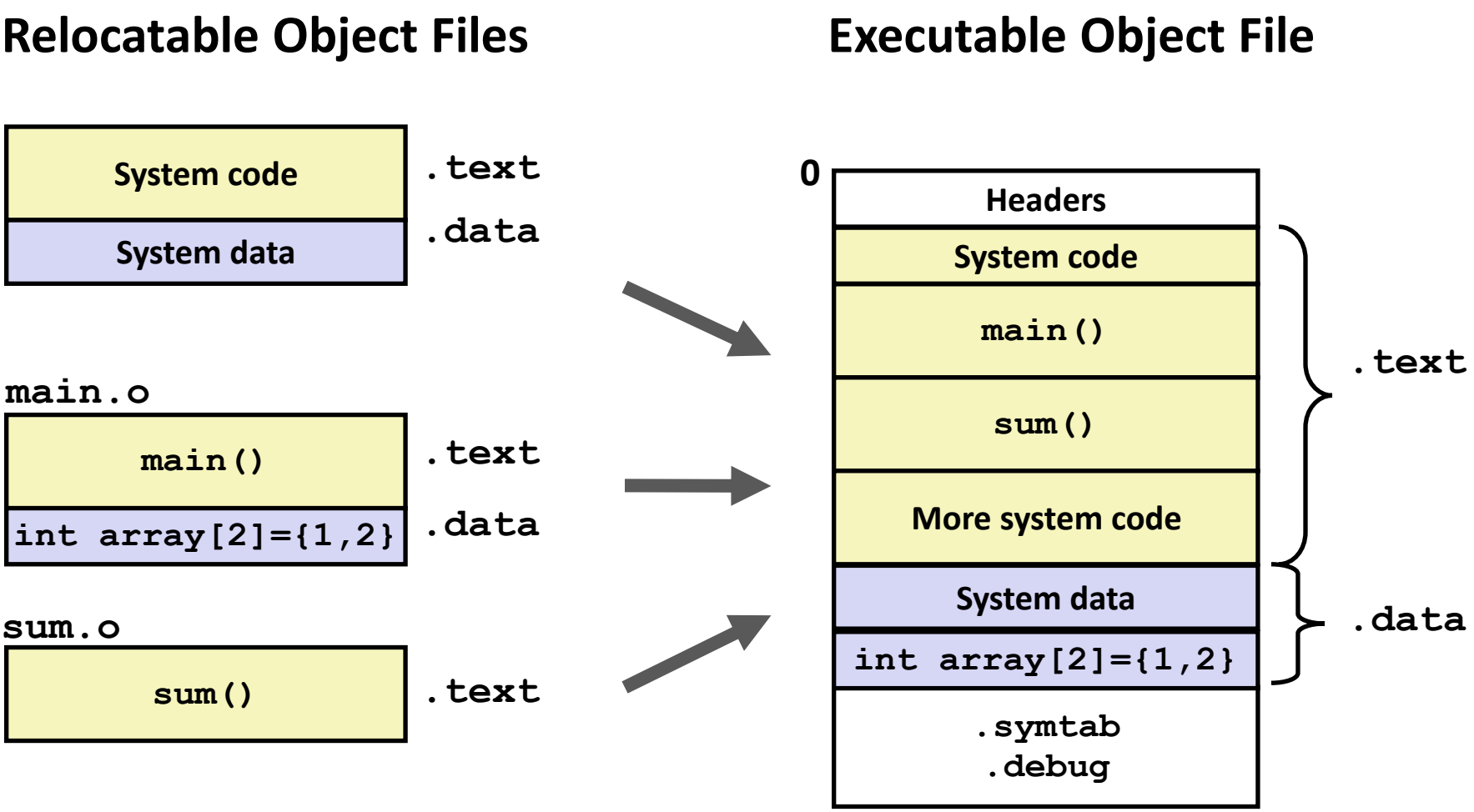
- **Avoid if you can**

- **Otherwise**
  - Use **`static`** if you can
  - Initialize if you define a global variable
  - Use **`extern`** if you reference an external global variable
    - Treated as weak symbol
    - But also causes linker error if not defined in some file

Step 2: Relocation

- **For each reference to an object with unknown location**
  - Assembler generates a relocation entry
  - Relocation entries for code are placed in .rel.text
  - Relocation entries for data are placed in .rel.data

Step 2: Relocation



Relocation Entries

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

int main(int argc, char** argv)
{
    int val = sum(array, 2);
    return val;
}
```

main.c

```
0000000000000000 <main>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   be 02 00 00 00          mov    $0x2,%esi
   9:   bf 00 00 00 00          mov    $0x0,%edi       # %edi = &array
                        a: R_X86_64_32 array          # Relocation entry

   e:   e8 00 00 00 00          callq  13 <main+0x13> # sum()
                        f: R_X86_64_PC32 sum-0x4      # Relocation entry
  13:   48 83 c4 08             add    $0x8,%rsp
  17:   c3                      retq
```

main.o

Source: `objdump -r -d main.o`

Relocated .text section

```
0000000004004d0 <main>:
  4004d0:       48 83 ec 08          sub    $0x8,%rsp
  4004d4:       be 02 00 00 00       mov    $0x2,%esi
  4004d9:       bf 18 10 60 00       mov    $0x601018,%edi   # %edi = &array
  4004de:       e8 05 00 00 00       callq  4004e8 <sum>     # sum()
  4004e3:       48 83 c4 08          add    $0x8,%rsp
  4004e7:       c3                   retq

0000000004004e8 <sum>:
  4004e8:       b8 00 00 00 00           mov    $0x0,%eax
  4004ed:       ba 00 00 00 00           mov    $0x0,%edx
  4004f2:       eb 09                    jmp    4004fd <sum+0x15>
  4004f4:       48 63 ca                 movslq %edx,%rcx
  4004f7:       03 04 8f                 add    (%rdi,%rcx,4),%eax
  4004fa:       83 c2 01                 add    $0x1,%edx
  4004fd:       39 f2                    cmp    %esi,%edx
  4004ff:       7c f3                    jl     4004f4 <sum+0xc>
  400501:       f3 c3                    repz retq
```

`callq` instruction uses PC-relative addressing for sum():

0x4004e8 = 0x4004e3 + 0x5

Source: objdump -d prog

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- **Walkthrough Example**

Example

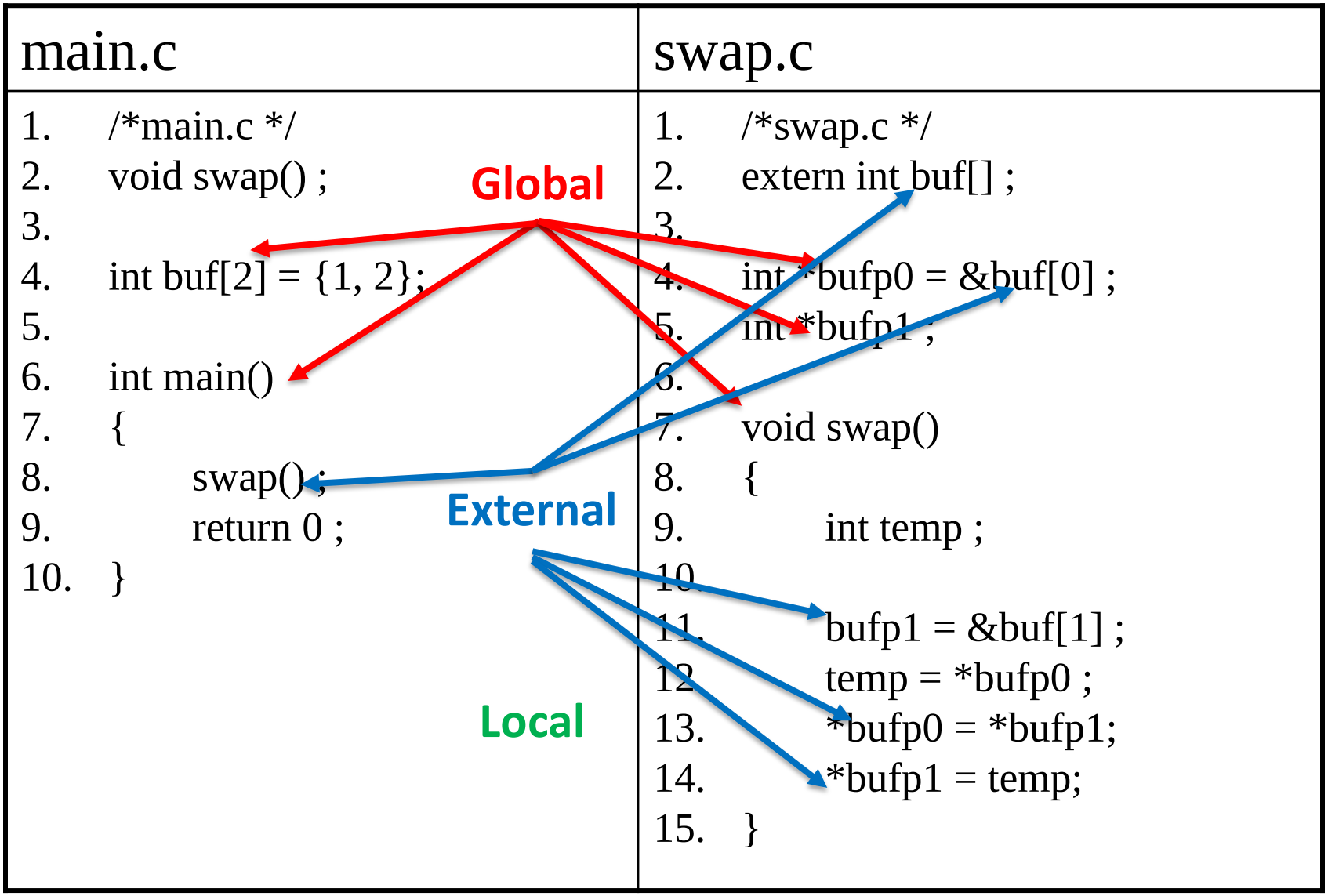
main.c

```
1.  /*main.c */
2.  void swap() ;
3.
4.  int buf[2] = {1, 2};
5.
6.  int main()
7.  {
8.          swap() ;
9.          return 0 ;
10. }
```

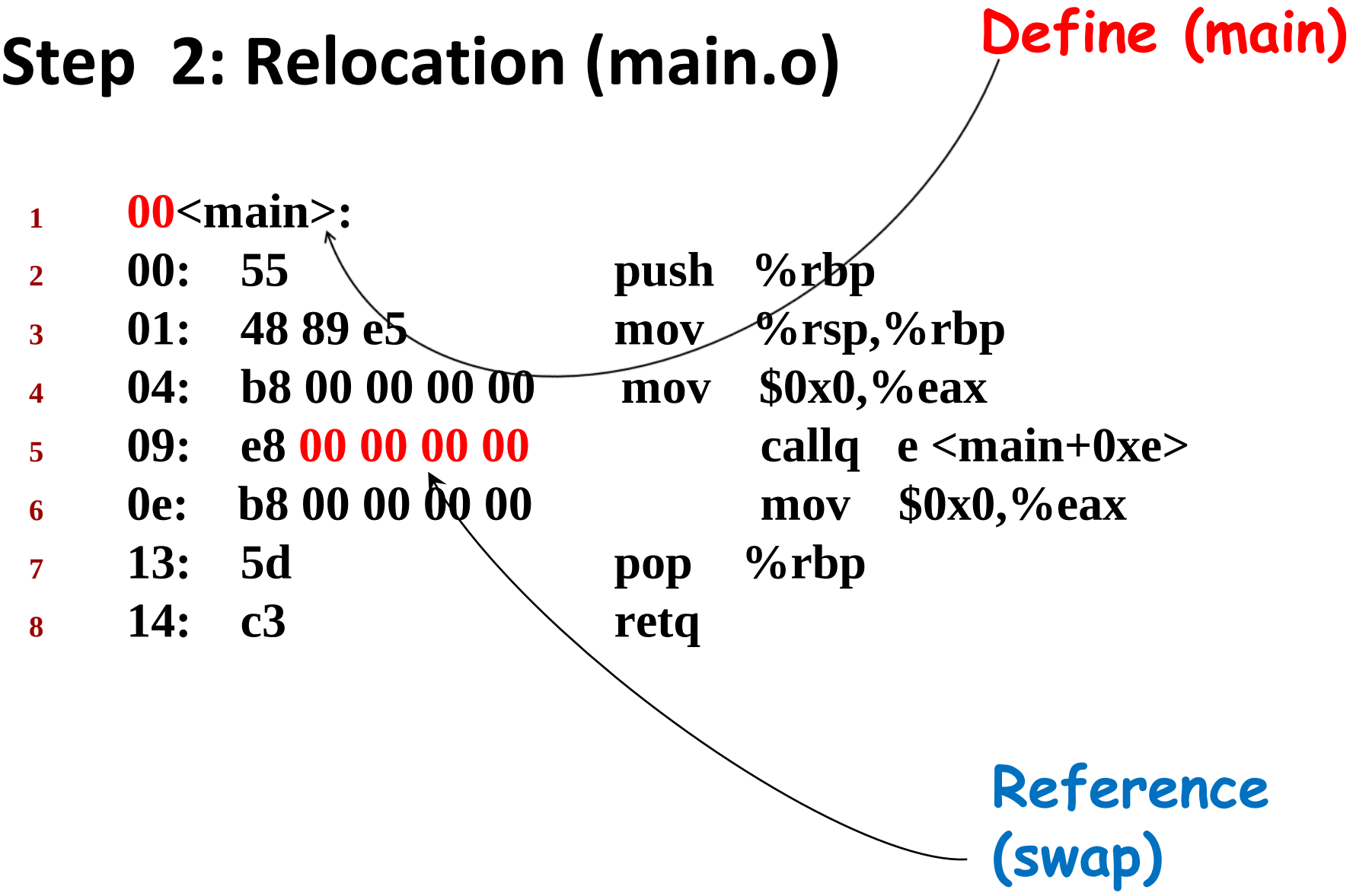
swap.c

```
1.  /*swap.c */
2.  extern int buf[] ;
3.
4.  int *bufp0 = &buf[0] ;
5.  int *bufp1 ;
6.
7.  void swap()
8.  {
9.          int temp ;
10.
11.         bufp1 = &buf[1] ;
12.         temp = *bufp0 ;
13.         *bufp0 = *bufp1;
14.         *bufp1 = temp;
15. }
```

Step 1: Symbol Resolution



Step 2: Relocation (main.o)



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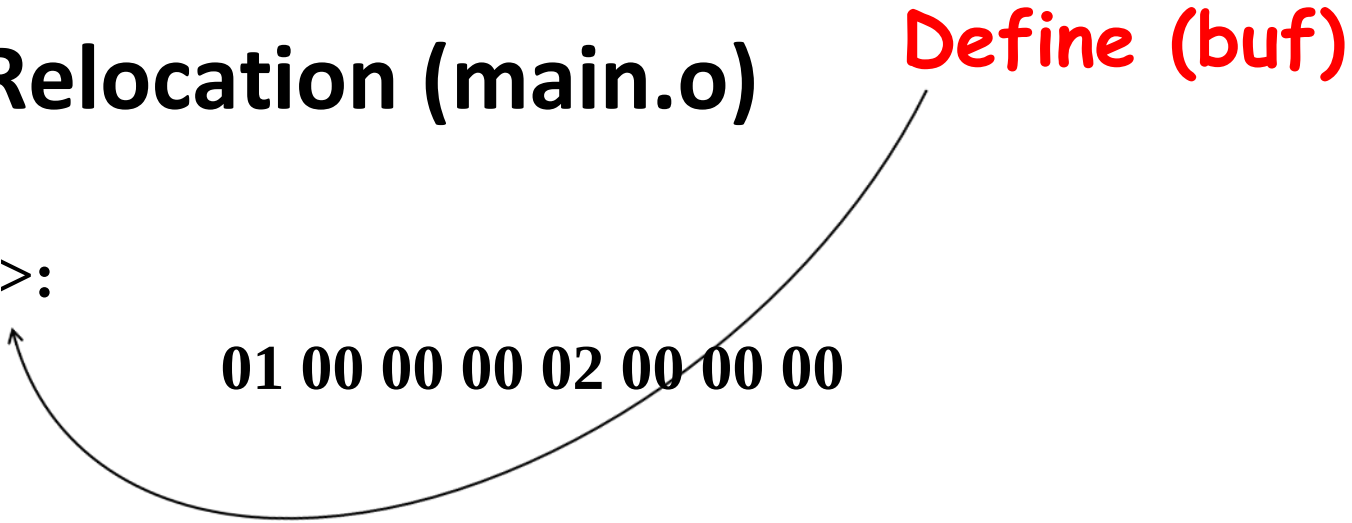
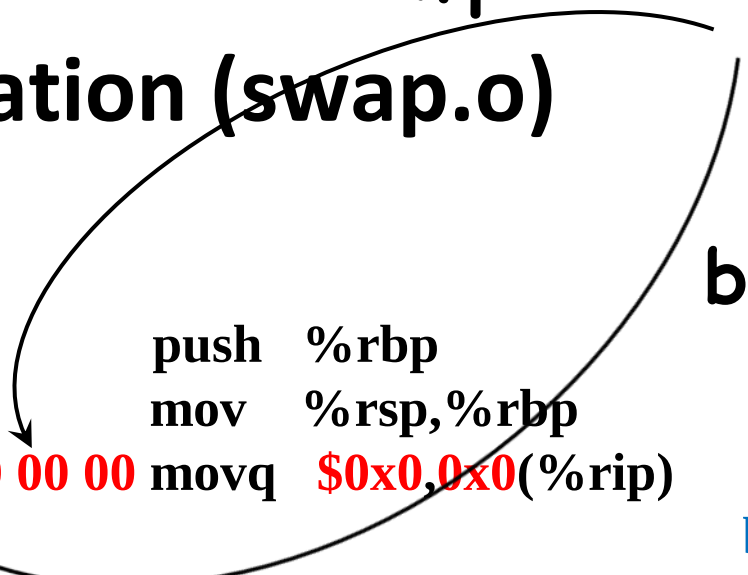
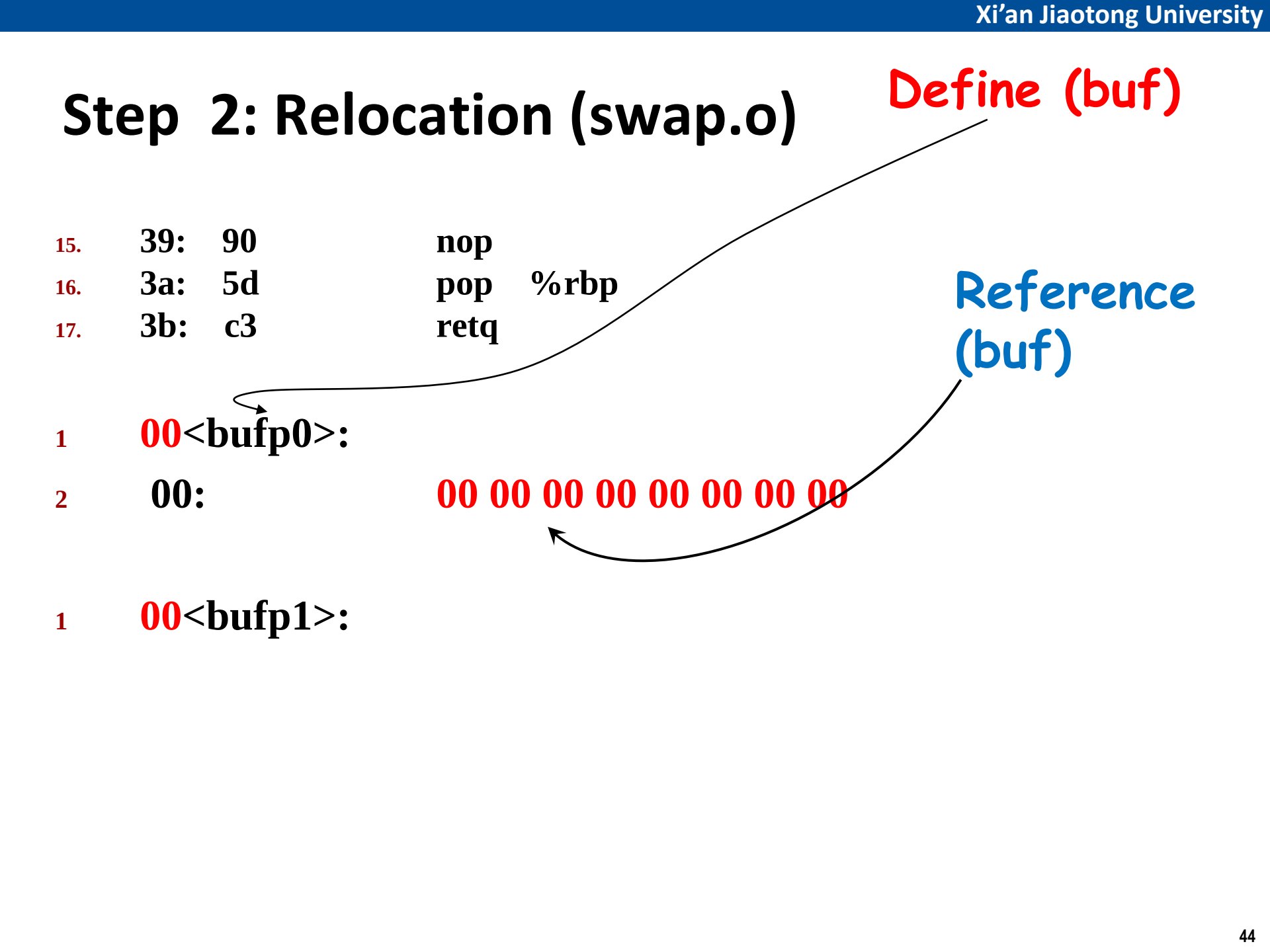


Step 2: Relocation (swap.o)




```
1.  00<swap>:
2.  00:   55                          push   %rbp
3.  01:   48 89 e5                    mov    %rsp,%rbp
4.  04:   48 c7 05 00 00 00 00 movq   $0x0,0x0(%rip)
5.  0b:   00 00 00 00                                      bufp1= &buf[1]
6.  0f:   48 8b 05 00 00 00 00  mov    0x0(%rip),%rax      get bufp0
7.  16:   8b 00                       mov    (%rax),%eax
8.  18:   89 45 fc                    mov    %eax,-0x4(%rbp)
9.  1b:   48 8b 05 00 00 00 00 mov    0x0(%rip),%rax      get bufp0
10. 22:   48 8b 15 00 00 00 00 mov    0x0(%rip),%rdx      get bufp1
11. 29:   8b 12                       mov    (%rdx),%edx
12. 2b:   89 10                       mov    %edx,(%rax)         *bufp0 = *bufp1
13. 2d:   48 8b 05 00 00 00 00 mov    0x0(%rip),%rax      get bufp1
13. 34:   8b 55 fc                    mov    -0x4(%rbp),%edx
14. 37:   89 10                       mov    %edx,(%rax)
```

Step 2: Relocation (swap.o)




```
15.    39:   90              nop
16.    3a:   5d              pop    %rbp
17.    3b:   c3              retq

1      00<bufp0>:
2       00:                  00 00 00 00 00 00 00 00

1      00<bufp1>:
```

Loading Executable Object Files