# Organisation und Architektur von Rechnern

Lecture 18

**Instructor:**

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http://www.informatik.uni-kiel.de/rtsys/teaching/v-sysinf2

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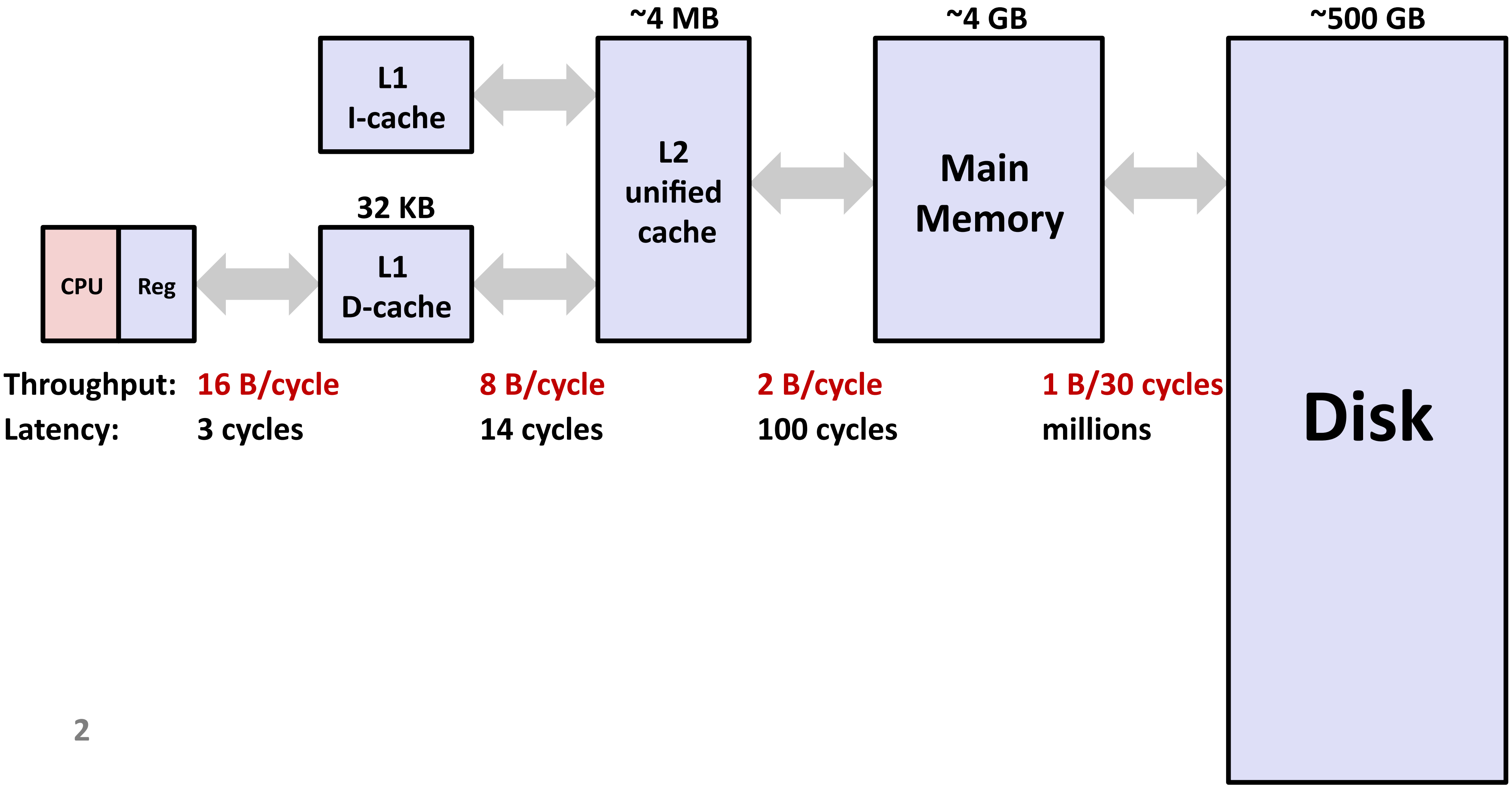
# Last Time

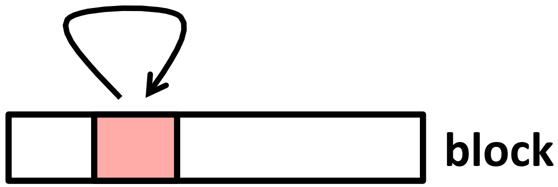
- Memory hierarchy (Here: Core 2 Duo)



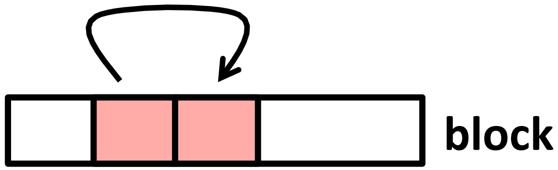
# Last Time

- **Locality**

- **Temporal locality:**
  - Recently referenced items are likely to be referenced again in the near future

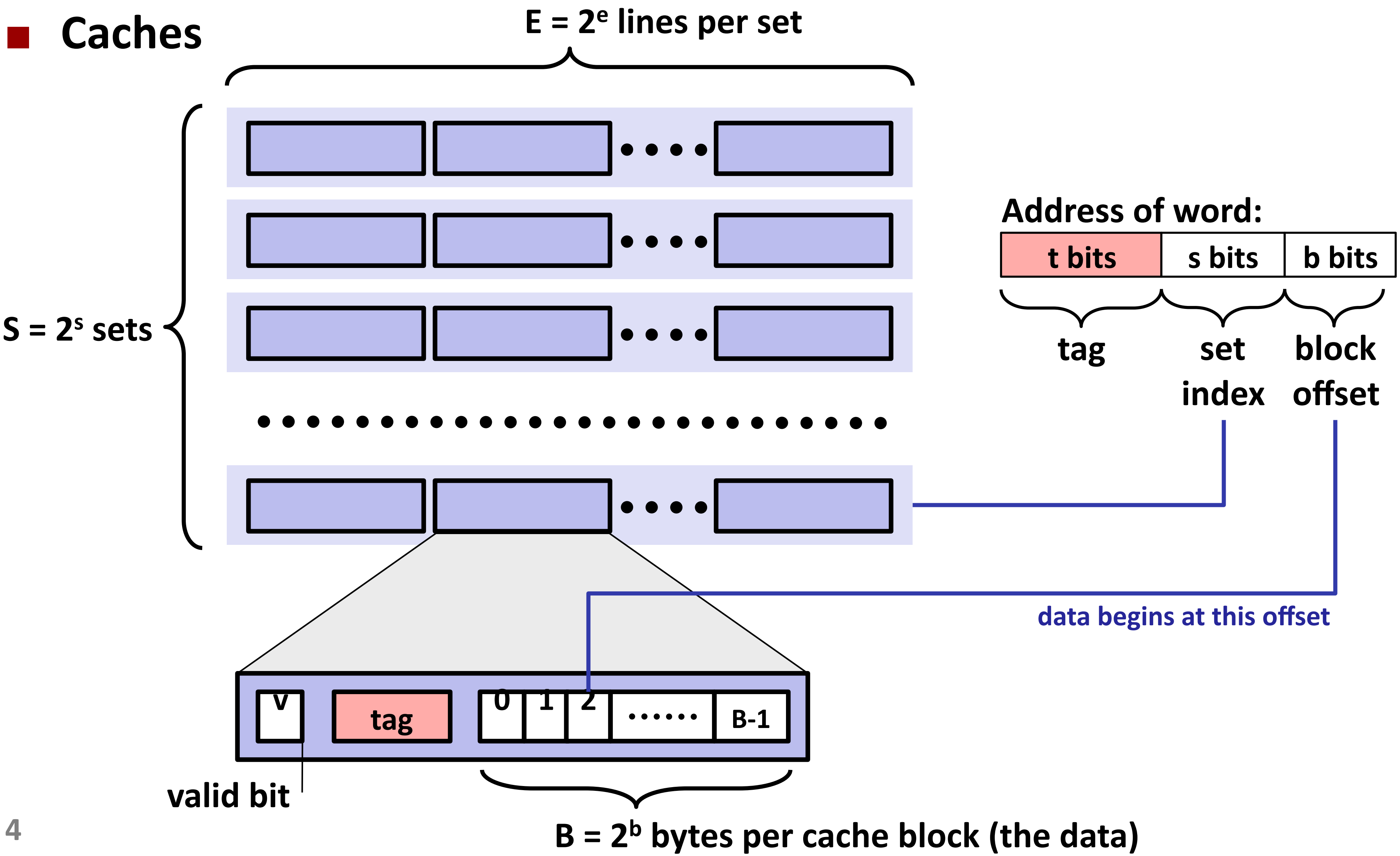



- **Spatial locality:**
  - Items with nearby addresses tend to be referenced close together in time

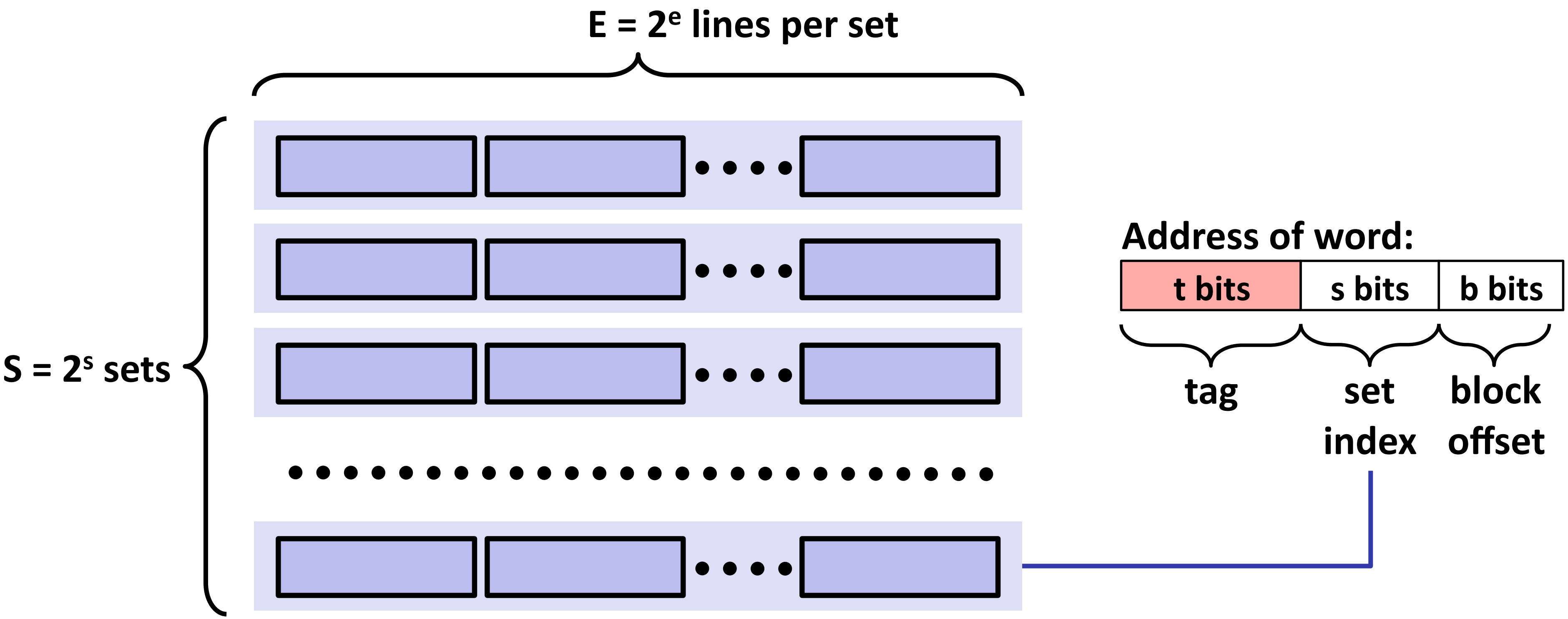


# Last Time

- Caches



# Strided Access Question




- What happens if arrays are accessed in two-power strides?
- Example on the next slide

# The Strided Access Problem (Blackboard?)

- **Example: L1 cache, Core 2 Duo**
  - 32 KB, 8-way associative, 64 byte cache block size
  - What is S, E, B?
    - *Answer:* $B = 2^6$, $E = 2^3$, $S = 2^6$.

- **Consider an array of ints accessed at stride $2^i$, $i \geq 0$**
  - What is the smallest i such that only one set is used?
    - *Answer:* i = 10
  - What happens if the stride is $2^9$?
    - *Answer:* two sets are used

- **Source of two-power strides?**
  - Example: Column access of 2-D arrays (images!)

# Today

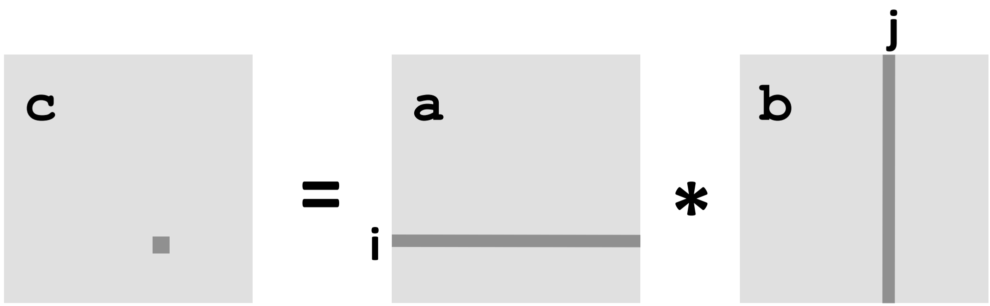
- **Program optimization:**
  - Cache optimizations
- **Linking**

# Optimizations for the Memory Hierarchy

- **Write code that has locality**
  - Spatial: access data contiguously
  - Temporal: make sure access to the same data is not too far apart in time
- **How to achieve?**
  - Proper choice of algorithm
  - Loop transformations
- **Cache versus register level optimization:**
  - In both cases locality desirable
  - Register space much smaller + requires scalar replacement to exploit temporal locality
  - Register level optimizations include exhibiting instruction level parallelism (conflicts with locality)

# Example: Matrix Multiplication

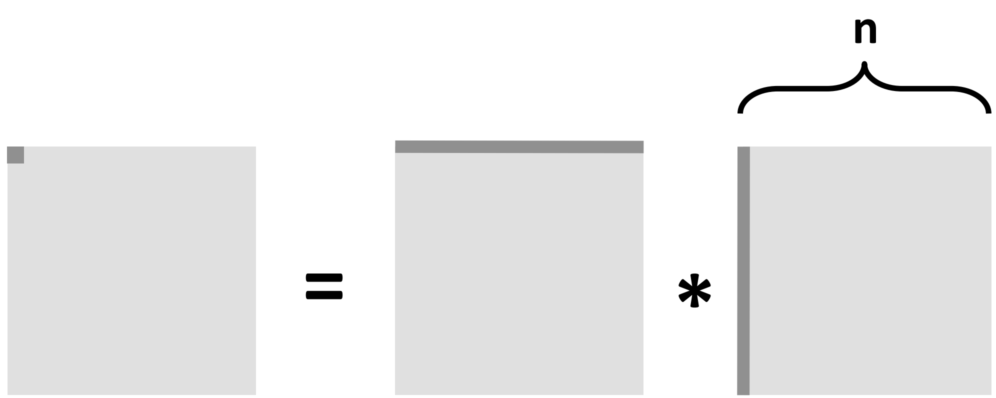
```
c = (double *) calloc(sizeof(double), n*n);

/* Multiply n x n matrices a and b  */
void mmm(double *a, double *b, double *c, int n) {
    int i, j, k;
    for (i = 0; i < n; i++)
        for (j = 0; j < n; j++)
            for (k = 0; k < n; k++)
                c[i*n+j] += a[i*n + k]*b[k*n + j];
}
```



# Cache Miss Analysis

- **Assume:**
  - Matrix elements are doubles
  - Cache block = 8 doubles (64 B as in Core 2 Duo)
  - Cache size C << n (much smaller than n)

- **First iteration:**
  - n/8 + n = 9n/8 misses

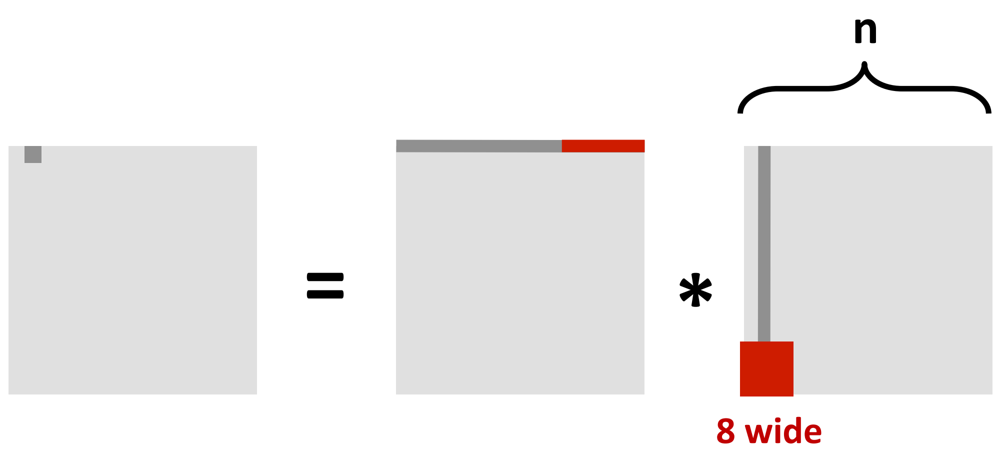



  - Afterwards in cache:
    (schematic)

# Cache Miss Analysis

- **Assume:**
  - Matrix elements are doubles
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)

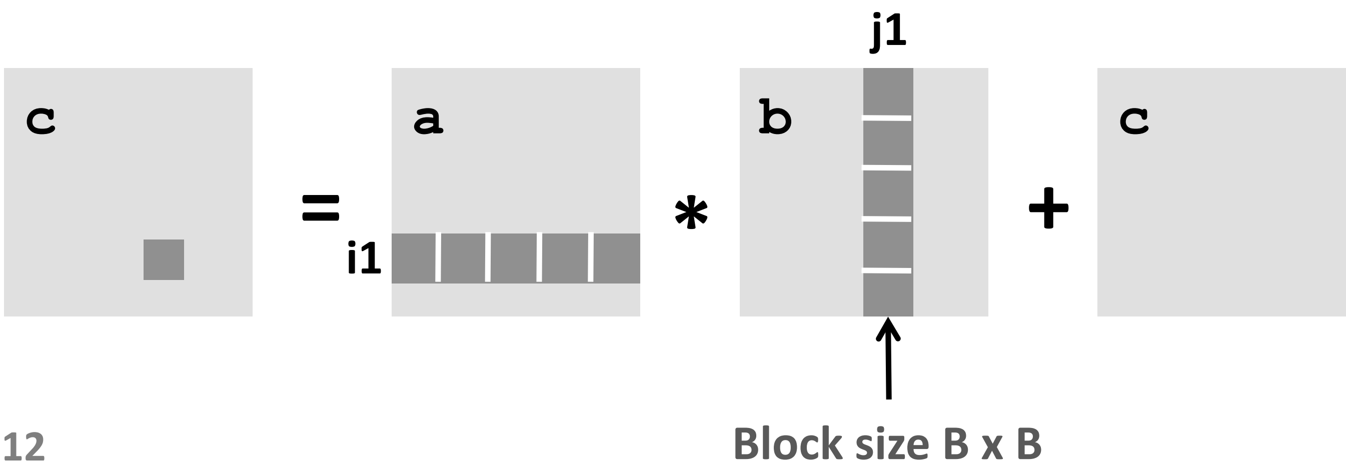
- **Second iteration:**
  - Again:
    $n/8 + n = 9n/8$ misses




- **Total misses:**
  - $9n/8 * n^2 = (9/8) * n^3$

# Blocked Matrix Multiplication

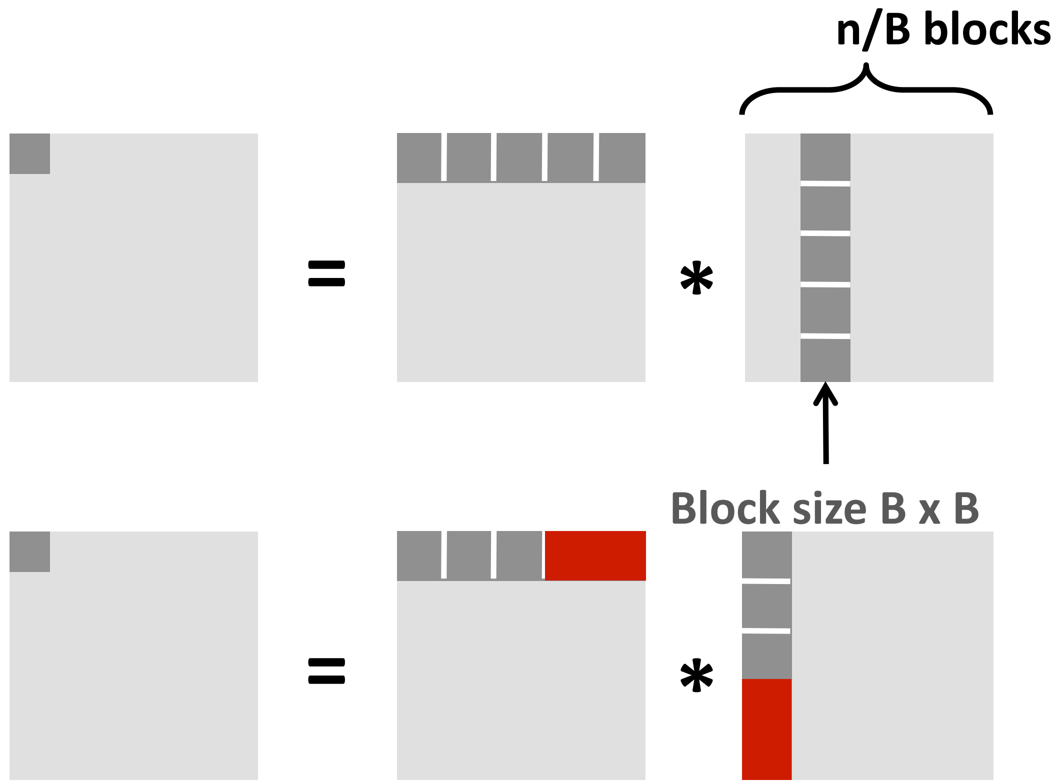
```
c = (double *) calloc(sizeof(double), n*n);

/* Multiply n x n matrices a and b  */
void mmm(double *a, double *b, double *c, int n) {
    int i, j, k;
    for (i = 0; i < n; i+=B)
        for (j = 0; j < n; j+=B)
            for (k = 0; k < n; k+=B)
                /* B x B mini matrix multiplications */
                for (i1 = i; i1 < i+B; i++)
                    for (j1 = j; j1 < j+B; j++)
                        for (k1 = k; k1 < k+B; k++)
                            c[i1*n+j1] += a[i1*n + k1]*b[k1*n + j1];
}
```



# Cache Miss Analysis

- **Assume:**
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)
  - Three blocks ■ fit into cache: $3B^2 < C$

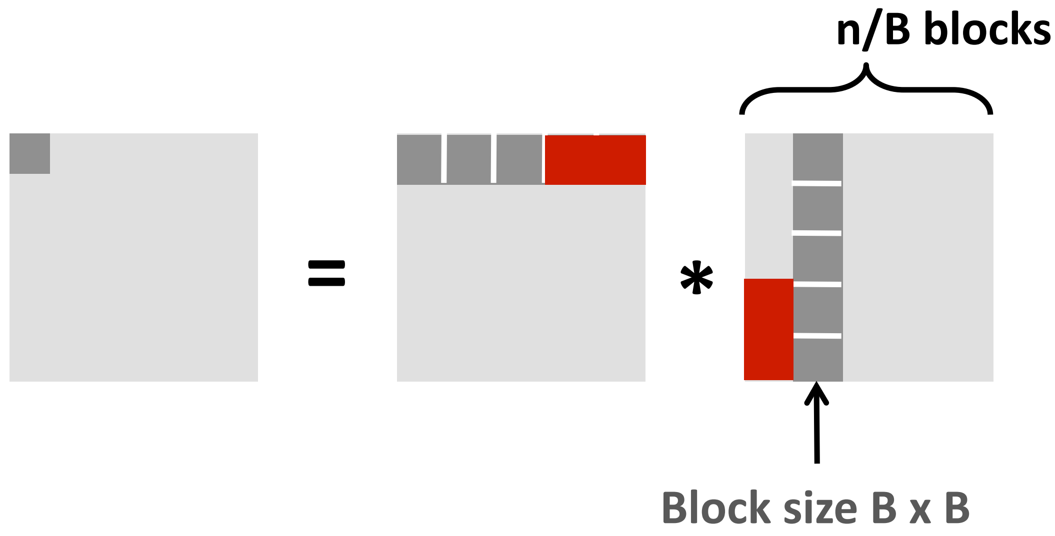
- **First (block) iteration:**
  - $B^2/8$ misses for each block
  - $2n/B * B^2/8 = nB/4$
    (omitting matrix c)
  - Afterwards in cache
    (schematic)



# Cache Miss Analysis

- **Assume:**
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)
  - Three blocks fit into cache: $3B^2 < C$

- **Second (block) iteration:**
  - Same as first iteration
  - $2n/B * B^2/8 = nB/4$




- **Total misses:**
  - $nB/4 * (n/B)^2 = n^3/(4B)$

# Summary

- **No blocking:** **$(9/8) * n^3$**
- **Blocking:** **$1/(4B) * n^3$**

- **Suggest largest possible block size B, but limit $3B^2 < C$!**
  (can possibly be relaxed a bit, but there is a limit for B)

- **Reason for dramatic difference:**
  - Matrix multiplication has inherent temporal locality:
    - Input data: $3n^2$, computation $2n^3$
    - Every array elements used O(n) times!
  - But program has to be written properly

# Today

- **Program optimization:**
  - Cache optimizations
- **Linking**

# Example C Program

**main.c**

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

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

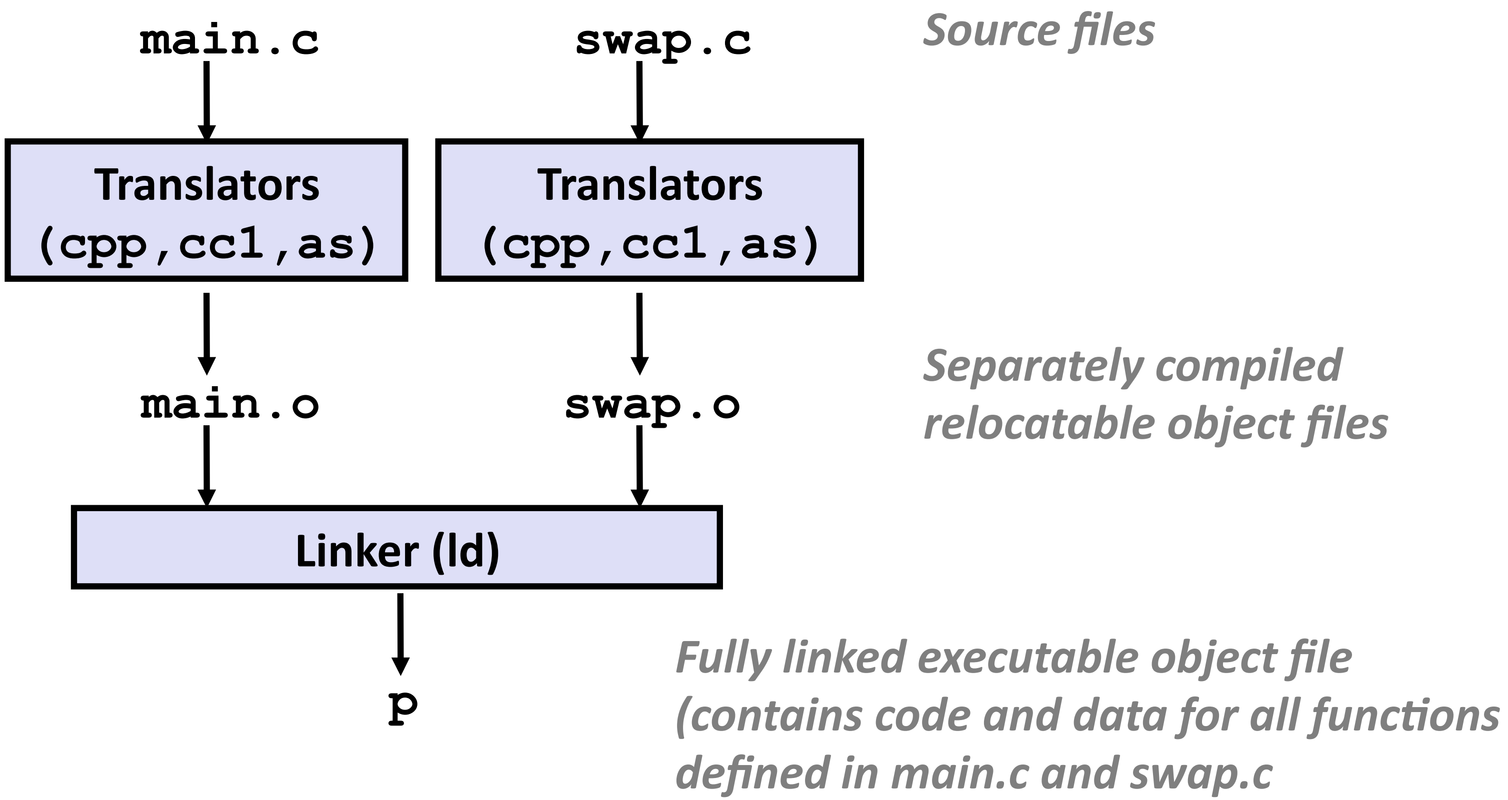
**swap.c**

```
extern int buf[];

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

void swap()
{
  int temp;

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

# Static Linking

- Programs are translated and linked using a *compiler driver*:

```
unix> gcc -O2 -g -o p main.c swap.c
unix> ./p
```



# Why Linkers? Modularity!

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

- **Can build libraries of common functions (more on this later)**
  - e.g., Math library, standard C library

# Why Linkers? Efficiency!

- **Time: Separate Compilation**
  - Change one source file, compile, and then relink.
  - No need to recompile other source files.

- **Space: Libraries**
  - Common functions can be aggregated into a single file...
  - Yet executable files and running memory images contain only code for the functions they actually use.

# What Do Linkers Do?

- **Step 1: Symbol resolution**
  - Programs define and reference *symbols* (variables and functions):
    - `void swap() {…}    /* define symbol swap */`
    - `swap();            /* reference symbol swap */`
    - `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, type, 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 source (.c) file*

- **Executable object file**
  - Contains code and data in a form that can be copied directly into memory and then executed.

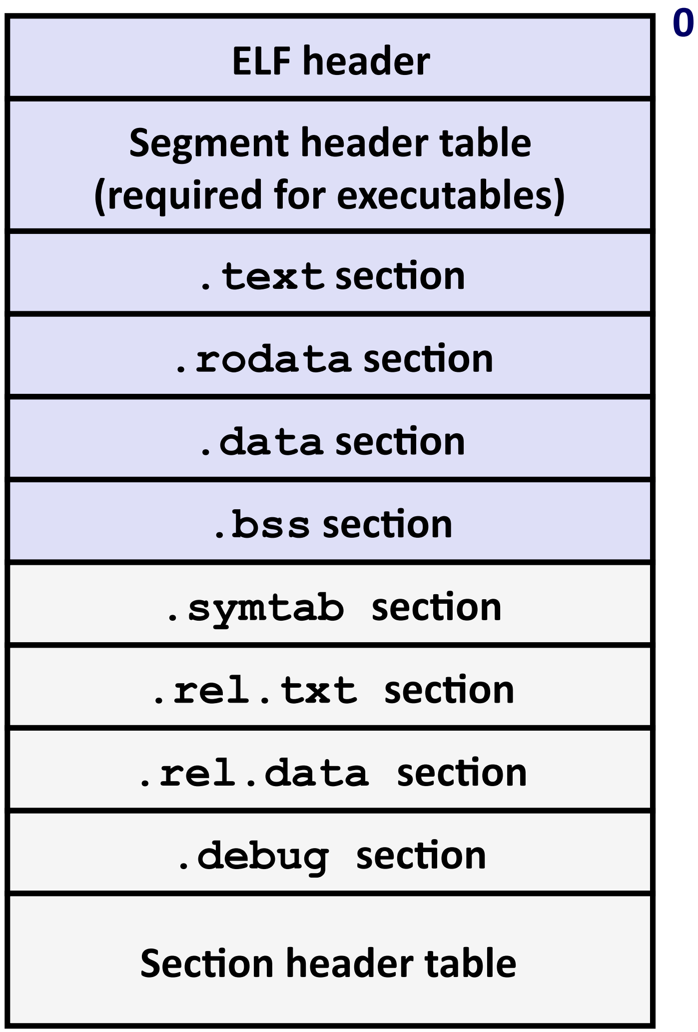
- **Shared object file (`.so` file)**
  - Special type of relocatable object file that can be loaded into memory and linked dynamically, at either load time or run-time.
  - Called *Dynamic Link Libraries* (DLLs) by Windows

# 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
  - Shared object files (`.so`)
- **Generic name: ELF binaries**

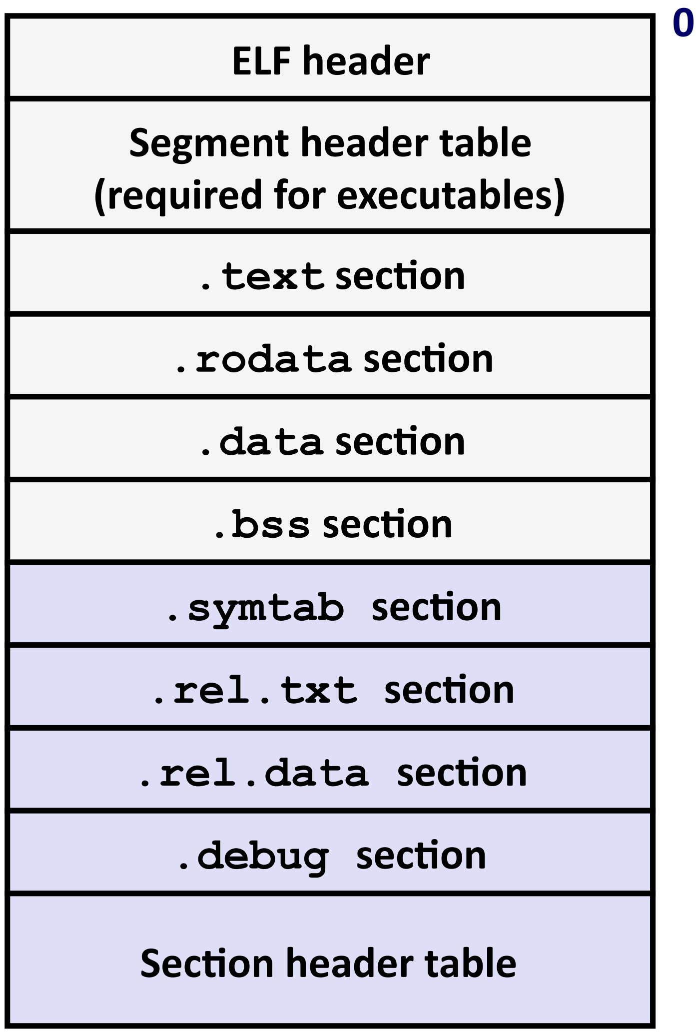
# ELF Object File Format

- **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



# 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



# 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

External

Local

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

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

*main.c*

External

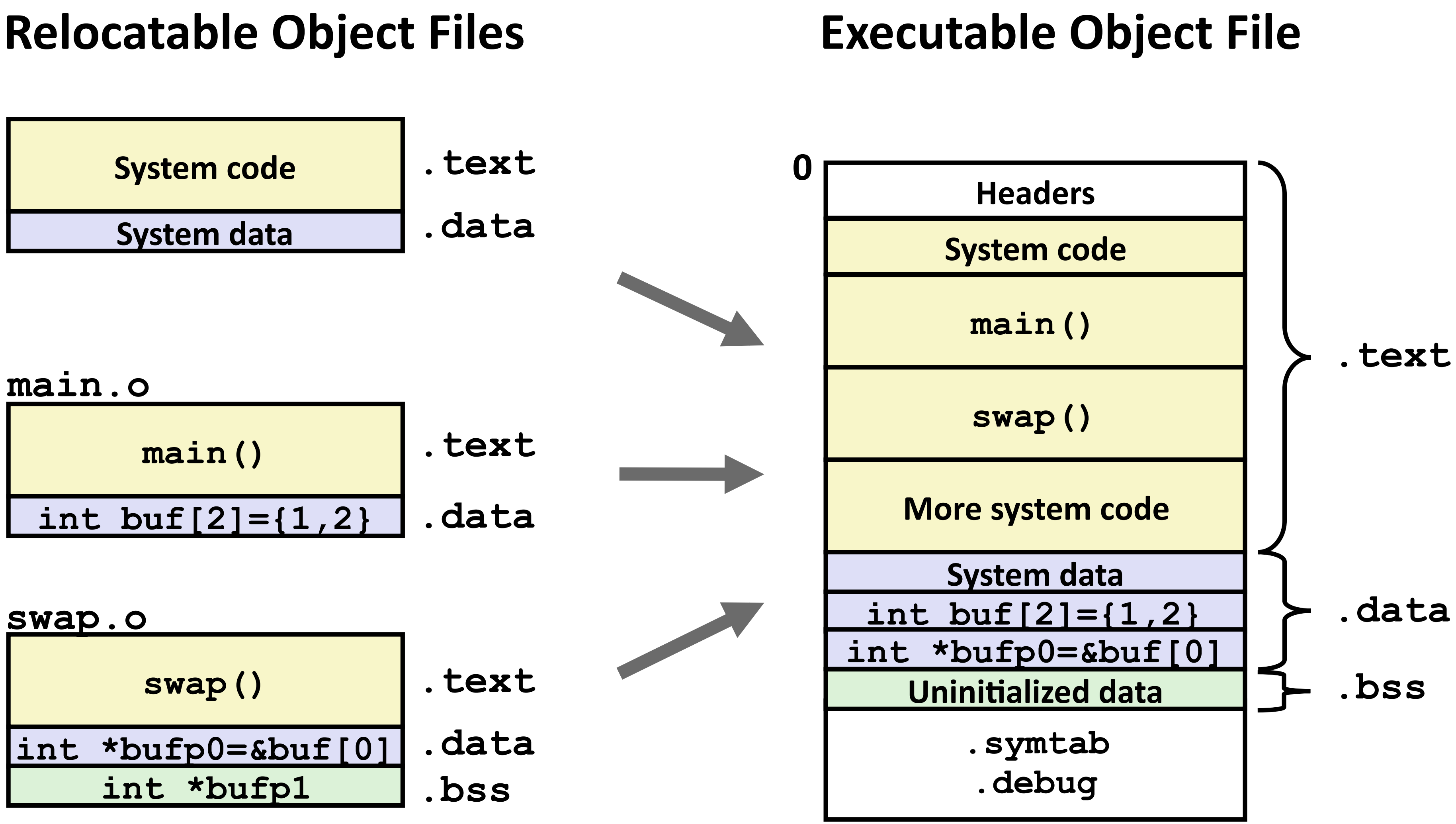
```
extern int buf[];

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

void swap()
{
  int temp;

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

*swap.c*

Global

Linker knows nothing of temp

# Relocating Code and Data



# Relocation Info (main)

`main.c`

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

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

`main.o`

```
0000000 <main>:
   0:    55                  push   %ebp
   1:    89 e5               mov    %esp,%ebp
   3:    83 ec 08            sub    $0x8,%esp
   6:    e8 fc ff ff ff      call   7 <main+0x7>
                             7: R_386_PC32 swap
   b:    31 c0               xor    %eax,%eax
   d:    89 ec               mov    %ebp,%esp
   f:    5d                  pop    %ebp
  10:    c3                  ret
```

```
Disassembly of section .data:

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

Source: `objdump`

# Relocation Info (swap, .text)

swap.c

```
extern int buf[];

static 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: 55                      push   %ebp
 1: 8b 15 00 00 00 00       mov    0x0,%edx
                            3: R_386_32 bufp0
 7: a1 0 00 00 00           mov    0x4,%eax
                            8: R_386_32 buf
 c: 89 e5                   mov    %esp,%ebp
 e: c7 05 00 00 00 00 04movl   $0x4,0x0
15: 00 00 00
                            10: R_386_32 bufp1
                            14: R_386_32 buf
18: 89 ec                   mov    %ebp,%esp
1a: 8b 0a                   mov    (%edx),%ecx
1c: 89 02                   mov    %eax,(%edx)
1e: a1 00 00 00 00          mov    0x0,%eax
                            1f: R_386_32 bufp1
23: 89 08                   mov    %ecx,(%eax)
25: 5d                      pop    %ebp
26: c3                      ret
```

# Relocation Info (swap, .data)

swap.c

```
extern int buf[];

static 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 After Relocation (.text)

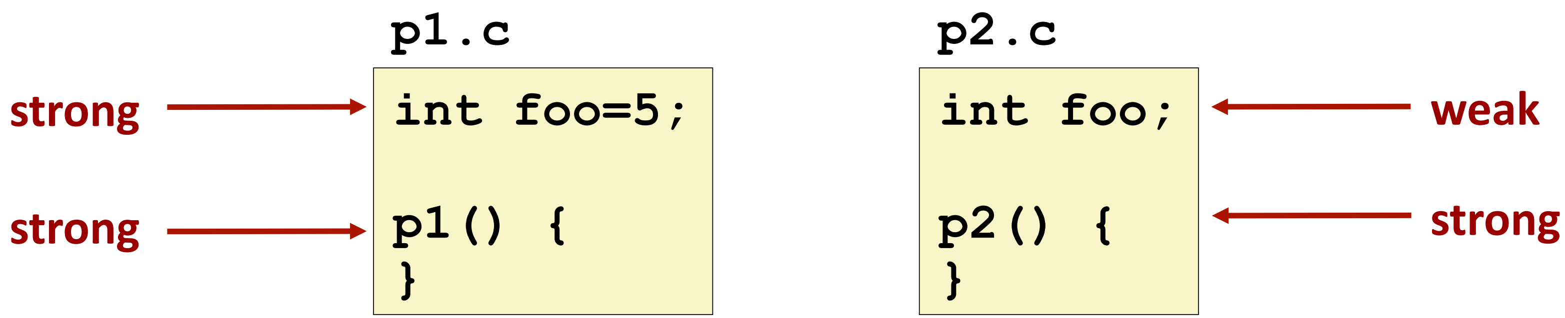
```
080483b4 <main>:
 80483b4:       55                          push   %ebp
 80483b5:       89 e5                       mov    %esp,%ebp
 80483b7:       83 ec 08                    sub    $0x8,%esp
 80483ba:       e8 09 00 00 00              call   80483c8 <swap>
 80483bf:       31 c0                       xor    %eax,%eax
 80483c1:       89 ec                       mov    %ebp,%esp
 80483c3:       5d                          pop    %ebp
 80483c4:       c3                          ret
080483c8 <swap>:
 80483c8:       55                          push   %ebp
 80483c9:       8b 15 5c 94 04 08           mov    0x804945c,%edx
 80483cf:       a1 58 94 04 08              mov    0x8049458,%eax
 80483d4:       89 e5                       mov    %esp,%ebp
 80483d6:       c7 05 48 95 04 08 58        movl   $0x8049458,0x8049548
 80483dd:       94 04 08
 80483e0:       89 ec                       mov    %ebp,%esp
 80483e2:       8b 0a                       mov    (%edx),%ecx
 80483e4:       89 02                       mov    %eax,(%edx)
 80483e6:       a1 48 95 04 08              mov    0x8049548,%eax
 80483eb:       89 08                       mov    %ecx,(%eax)
 80483ed:       5d                          pop    %ebp
 80483ee:       c3                          ret
```

# Executable After Relocation (.data)

```
Disassembly of section .data:

08049454 <buf>:
 8049454:       01 00 00 00 02 00 00 00

0804945c <bufp0>:
 804945c:       54 94 04 08
```

# Strong and Weak Symbols

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



# 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;`<br>`p1() {}` | `p1() {}` | Link time error: two strong symbols (**`p1`**) |
| `int x;`<br>`p1() {}` | `int x;`<br>`p2() {}` | References to **`x`** will refer to the same uninitialized int. Is this what you really want? |
| `int x;`<br>`int y;`<br>`p1() {}` | `double x;`<br>`p2() {}` | Writes to **`x`** in **`p2`** might overwrite **`y`**!<br>Evil! |
| `int x=7;`<br>`int y=5;`<br>`p1() {}` | `double x;`<br>`p2() {}` | Writes to **`x`** in **`p2`** will overwrite **`y`**!<br>Nasty! |
| `int x=7;`<br>`p1() {}` | `int x;`<br>`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.**

# 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

# Packaging Commonly Used Functions

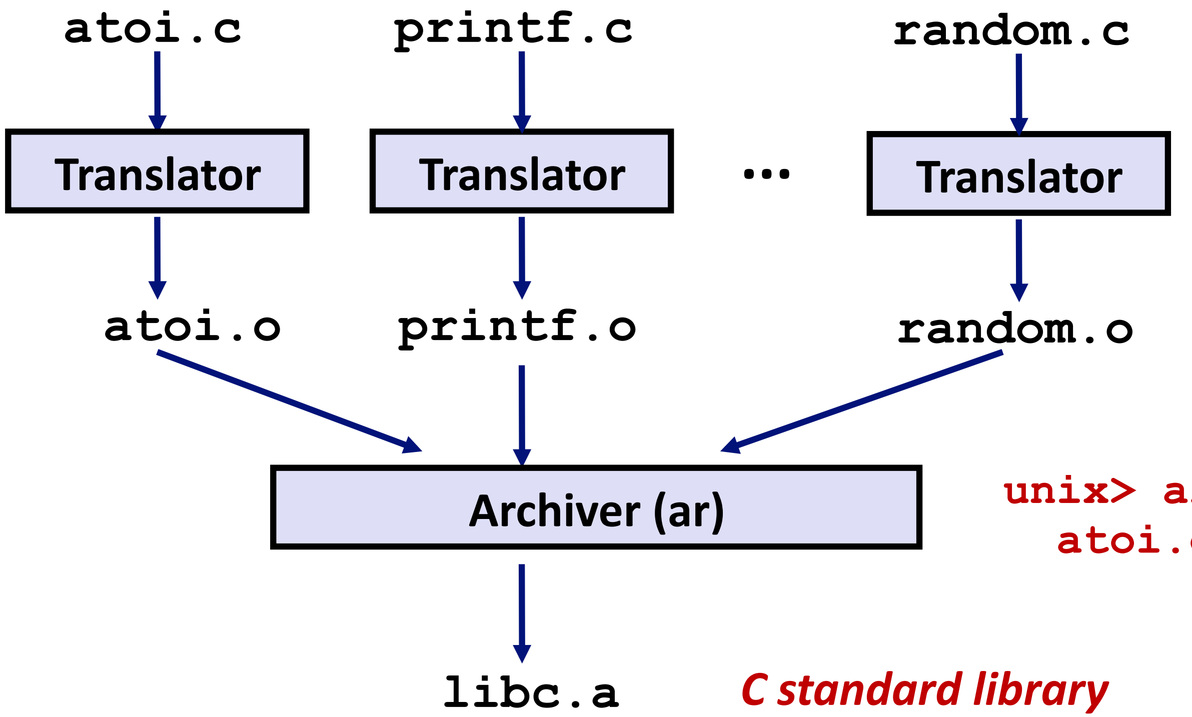
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **Awkward, given the linker framework so far:**
  - **Option 1:** Put all functions into a single source file
    - Programmers link big object file into their programs
    - Space and time inefficient
  - **Option 2:** Put each function in a separate source file
    - Programmers explicitly link appropriate binaries into their programs
    - More efficient, but burdensome on the programmer

# Solution: Static Libraries

- **Static libraries (`.a` archive files)**
  - Concatenate related relocatable object files into a single file with an index (called an *archive*).
  - Enhance linker so that it tries to resolve unresolved external references by looking for the symbols in one or more archives.
  - If an archive member file resolves reference, link into executable.

# Creating Static Libraries




```
unix> ar rs libc.a \
  atoi.o printf.o … random.o
```

- **Archiver allows incremental updates**
- **Recompile function that changes and replace .o file in archive.**

# Commonly Used Libraries

## `libc.a` (the C standard library)

- 8 MB archive of 900 object files.
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

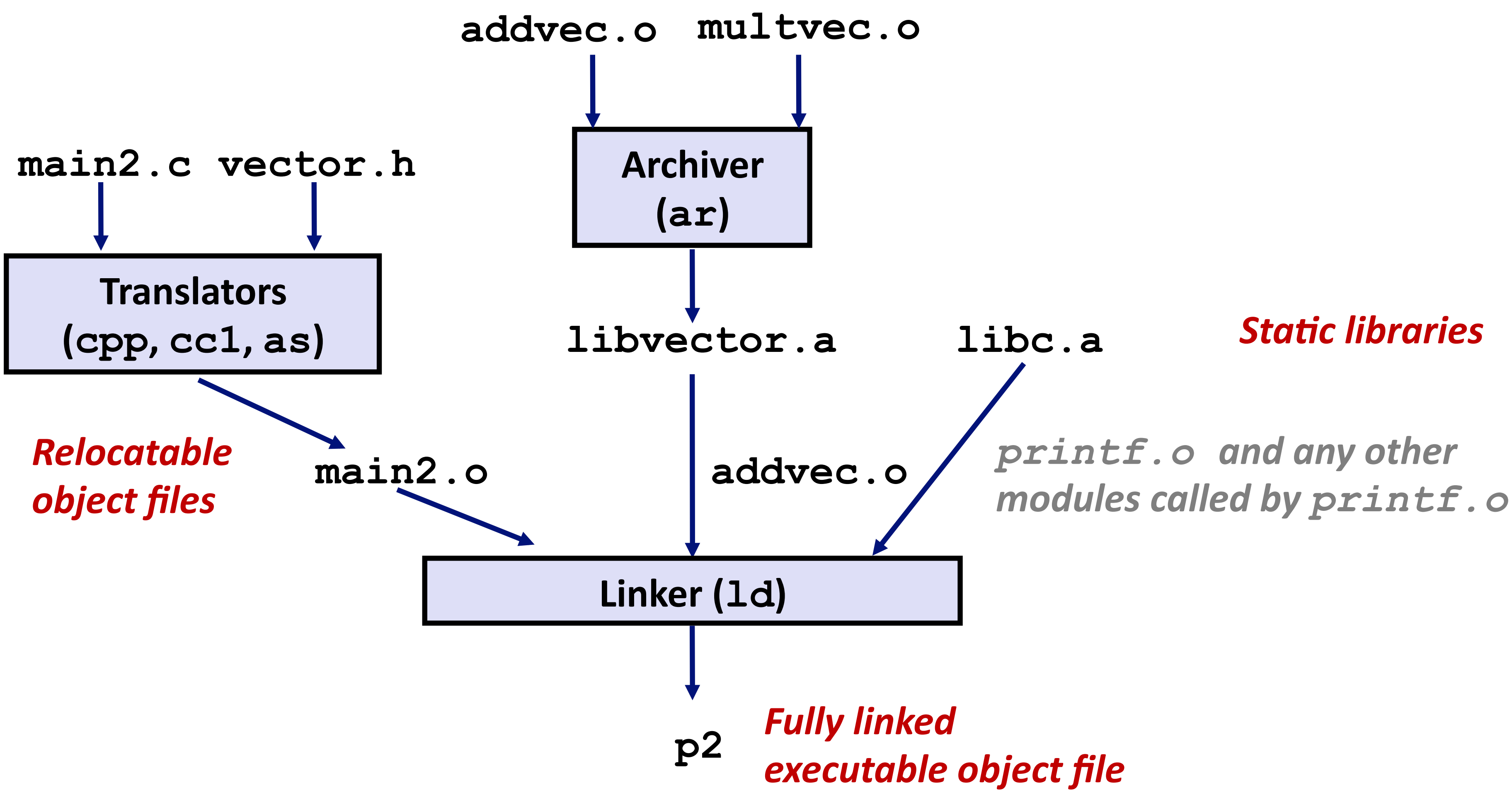
## `libm.a` (the C math library)

- 1 MB archive of 226 object files.
- floating point math (sin, cos, tan, log, exp, sqrt, …)

```
% ar -t /usr/lib/libc.a | sort
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
…
```

```
% ar -t /usr/lib/libm.a | sort
…
e_acos.o
e_acosf.o
e_acosh.o
e_acoshf.o
e_acoshl.o
e_acosl.o
e_asin.o
e_asinf.o
e_asinl.o
…
```

# Linking with Static Libraries



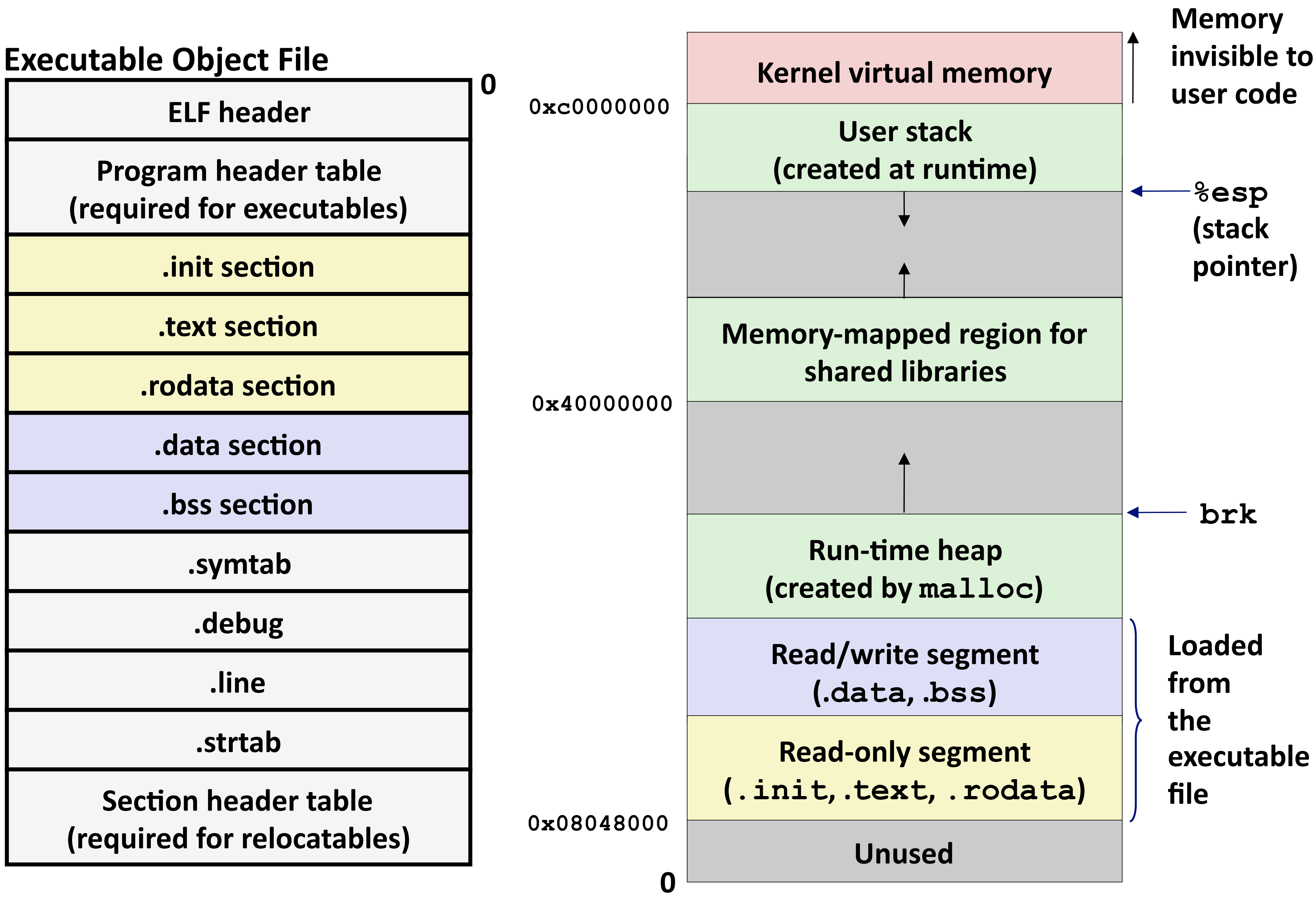
# Using Static Libraries

- **Linker's algorithm for resolving external references:**
  - Scan **`.o`** files and **`.a`** files in the command line order.
  - During the scan, keep a list of the current unresolved references.
  - As each new **`.o`** or **`.a`** file, *obj*, is encountered, try to resolve each unresolved reference in the list against the symbols defined in *obj*.
  - If any entries in the unresolved list at end of scan, then error.

- **Problem:**
  - Command line order matters!
  - Moral: put libraries at the end of the command line.

```
unix> gcc -L. libtest.o -lmine
unix> gcc -L. -lmine libtest.o
libtest.o: In function `main':
libtest.o(.text+0x4): undefined reference to `libfun'
```

# Loading Executable Object Files



# Shared Libraries

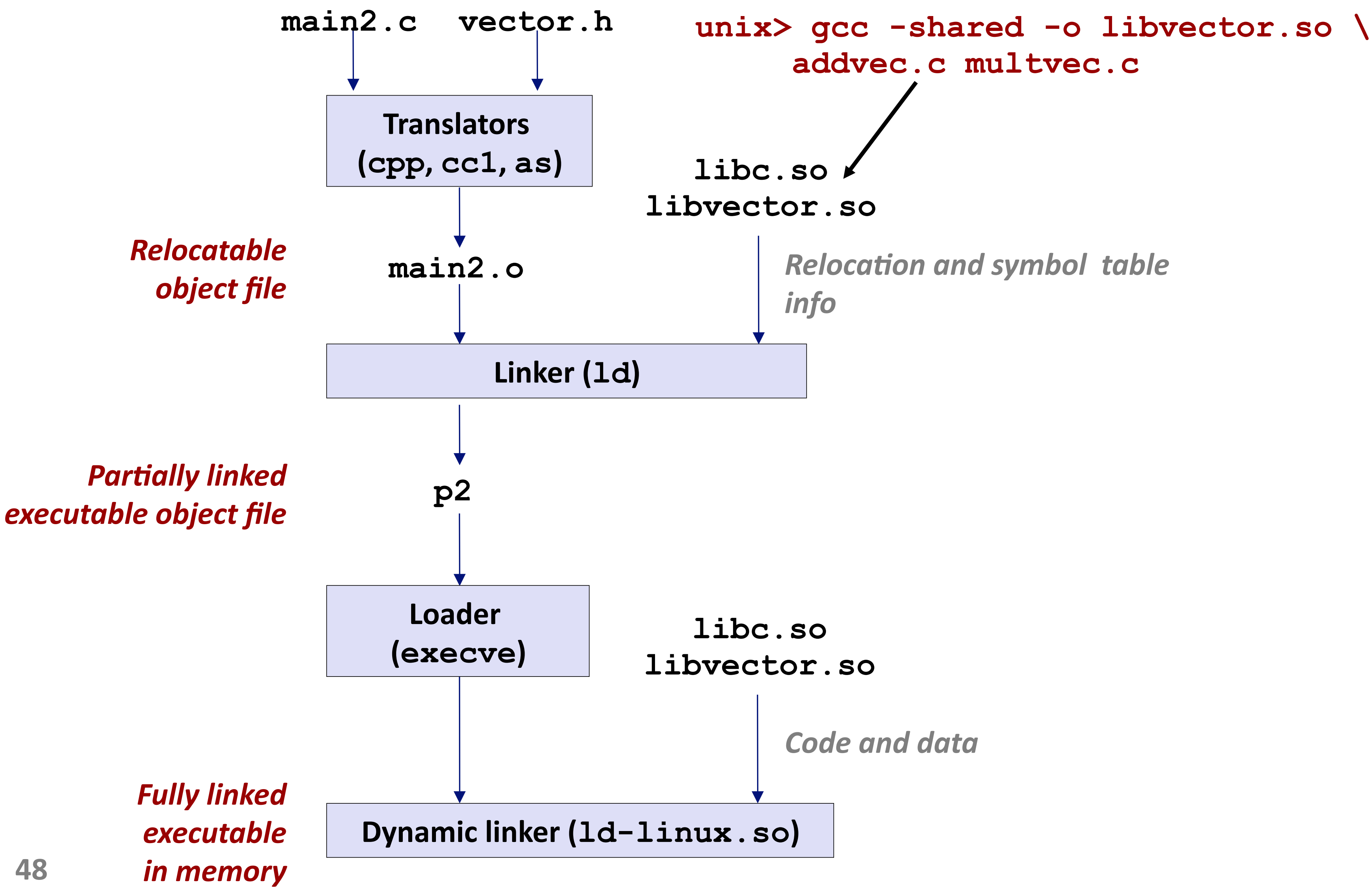
- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function need std libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink

- **Modern Solution: Shared Libraries**
  - Object files that contain code and data that are loaded and linked into an application *dynamically,* at either *load-time* or *run-time*
  - Also called: dynamic link libraries, DLLs, .so files

# Shared Libraries (cont.)

- **Dynamic linking can occur when executable is first loaded and run (load-time linking).**
  - Common case for Linux, handled automatically by the dynamic linker (**`ld-linux.so`**).
  - Standard C library (**`libc.so`**) usually dynamically linked.
- **Dynamic linking can also occur after program has begun (run-time linking).**
  - In Unix, this is done by calls to the **`dlopen()`** interface.
    - High-performance web servers.
    - Runtime library interpositioning
- **Shared library routines can be shared by multiple processes.**
  - More on this when we learn about virtual memory

# Dynamic Linking at Load-time



# Dynamic Linking at Runtime

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

int x[2] = {1, 2};
int y[2] = {3, 4};
int z[2];

int main()
{
    void *handle;
    void (*addvec)(int *, int *, int *, int);
    char *error;

    /* dynamically load the shared lib that contains addvec() */
    handle = dlopen("./libvector.so", RTLD_LAZY);
    if (!handle) {
            fprintf(stderr, "%s\n", dlerror());
            exit(1);
    }
```

# Dynamic Linking at Run-time

```
    ...

    /* get a pointer to the addvec() function we just loaded */
    addvec = dlsym(handle, "addvec");
    if ((error = dlerror()) != NULL) {
            fprintf(stderr, "%s\n", error);
            exit(1);
    }

    /* Now we can call addvec() it just like any other function */
    addvec(x, y, z, 2);
    printf("z = [%d %d]\n", z[0], z[1]);

    /* unload the shared library */
    if (dlclose(handle) < 0) {
            fprintf(stderr, "%s\n", dlerror());
            exit(1);
    }
    return 0;
}
```

# Case Study: Library Interpositioning

**Library interpositioning is a powerful linking technique that allows programmers to intercept calls to arbitrary functions**

**Interpositioning can occur at:**

- compile time
  - When the source code is compiled
- link time
  - When the relocatable object files are linked to form an executable object file
- load/run time
  - When an executable object file is loaded into memory, dynamically linked, and then executed.

See Lectures page for real examples of using all three interpositioning techniques to generate malloc traces.

# Some Interpositioning Applications

## Security

- Confinement (sandboxing)
  - Interpose calls to libc functions.
- Behind the scenes encryption
  - Automatically encrypt otherwise unencrypted network connections.

## Monitoring and Profiling

- Count number of calls to functions
- Characterize call sites and arguments to functions
- Malloc tracing
  - Detecting memory leaks
  - Generating malloc traces

# Example: `malloc()` Statistics

## Count how much memory is allocated by a function

```
void *malloc(size_t size){
    static void *(*fp)(size_t) = 0;
    void *mp;
    char *errorstr;

    /* Get a pointer to the real malloc() */
    if (!fp) {
        fp = dlsym(RTLD_NEXT, "malloc");
        if ((errorstr = dlerror()) != NULL) {
            fprintf(stderr, "%s(): %s\n", fname, errorstr);
            exit(1);
        }
    }

    /* Call the real malloc function */
    mp = fp(size);

    mem_used += size;

    return mp;
}
```