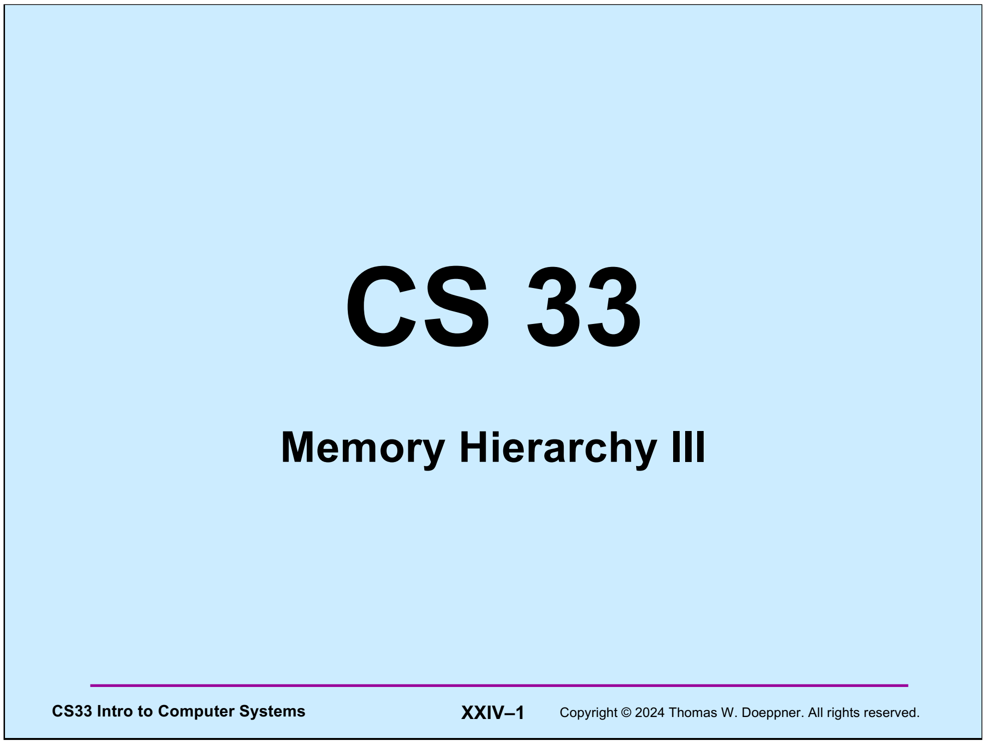


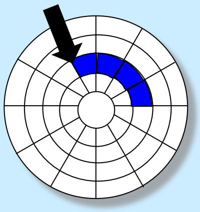
CS 33

Memory Hierarchy III

Most of the slides in this lecture are either from or adapted from slides provided by the authors of the textbook “Computer Systems: A Programmer’s Perspective,” 2nd Edition and are provided from the website of Carnegie-Mellon University, course 15-213, taught by Randy Bryant and David O’Hallaron in Fall 2010. These slides are indicated “Supplied by CMU” in the notes section of the slides.

Reading a File on a Rotating Disk

- Suppose the data of a file are stored on consecutive disk sectors on one track
  - this is the best possible scenario for reading data quickly
    - » single seek required
    - » single rotational delay
    - » all sectors read in a single scan



Quiz 1

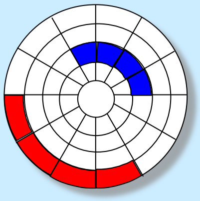
We have two files on the same (rotating) disk. The first file's data resides in consecutive sectors on one track, the second in consecutive sectors on another track. It takes a total of *t* seconds to read all of the first file then all of the second file.

Now suppose the files are read concurrently, perhaps a sector of the first, then a sector of the second, then the first, then the second, etc. Compared to reading them sequentially, this will take

a) less time

b) much more time

c) about the same amount of time (within a factor of 2)



Quiz 2

We have two files on the same solid-state disk. Each file's data resides in consecutive blocks. It takes a total of *t* seconds to read all of the first file then all of the second file.

Now suppose the files are read concurrently, perhaps a block of the first, then a block of the second, then the first, then the second, etc. Compared to reading them sequentially, this will take

a) less time

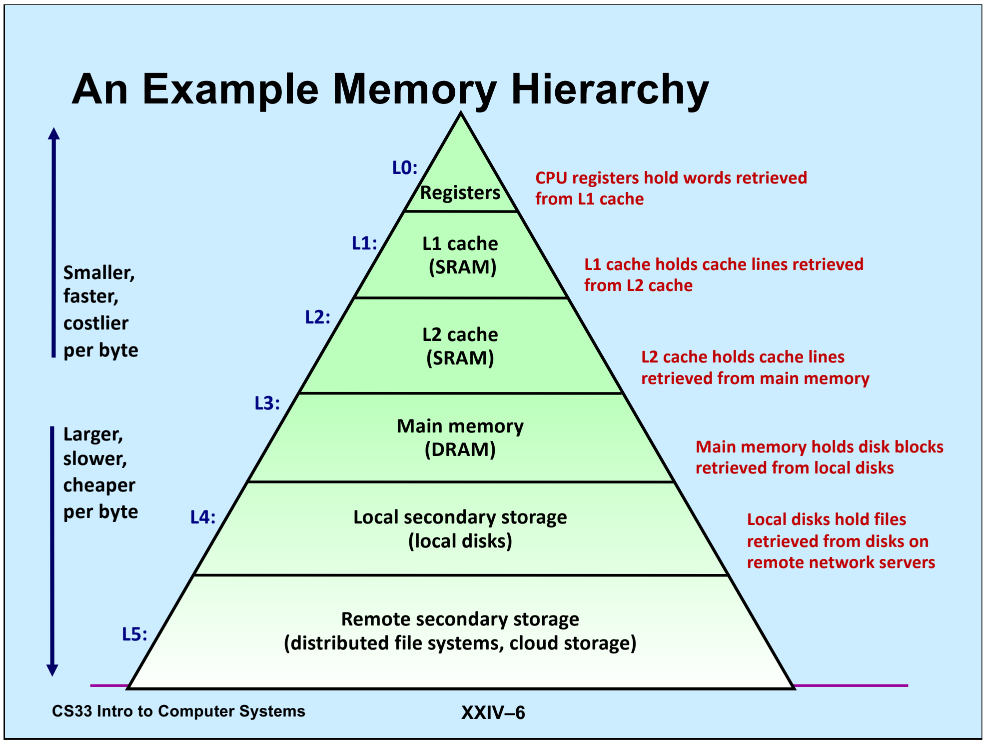
b) much more time

c) about the same amount of time
(within a factor of 2)

Memory Hierarchies

- Some fundamental and enduring properties of hardware and software:
  - fast storage technologies cost more per byte, have less capacity, and require more power (heat!)
  - the gap between CPU and main memory speed is widening
  - well written programs tend to exhibit good locality
- These fundamental properties complement each other beautifully
- They suggest an approach for organizing memory and storage systems known as a **memory hierarchy**

Supplied by CMU.



An Example Memory Hierarchy

Smaller,
faster,
costlier
per byte

Larger,
slower,
cheaper
per byte

L0: Registers

L1: L1 cache (SRAM)

L2: L2 cache (SRAM)

L3: Main memory (DRAM)

L4: Local secondary storage (local disks)

L5: Remote secondary storage (distributed file systems, cloud storage)

CPU registers hold words retrieved from L1 cache

L1 cache holds cache lines retrieved from L2 cache

L2 cache holds cache lines retrieved from main memory

Main memory holds disk blocks retrieved from local disks

Local disks hold files retrieved from disks on remote network servers

Supplied by CMU.

Putting Things Into Perspective ...

- Reading from:
  - ... the L1 cache is like grabbing a piece of paper from your desk (3 seconds)
  - ... the L2 cache is picking up a book from a nearby shelf (14 seconds)
  - ... main system memory (DRAM) is taking a 4-minute walk down the hall to talk to a friend
  - ... a hard drive is like leaving the building to roam the earth for one year and three months

This analogy is from http://duartes.org/gustavo/blog/post/what-your-computer-does-while-you-wait (definitely worth reading!).

Disks Are Still Important

- Cheap
  - – cost/byte less than SSDs
- (fairly) Reliable
  - – data written to a disk is likely to be there next year
- Sometimes fast
  - – data in consecutive sectors on a track can be read quickly
- Sometimes slow
  - – data in randomly scattered sectors takes a long time to read

Abstraction to the Rescue

- **Programs don't deal with sectors, tracks, and cylinders**
- **Programs deal with *files***
  - **maze.c rather than an ordered collection of sectors**
  - **OS provides the implementation**

Implementation Problems

- Speed
  - use the hierarchy
    - copy files into RAM, copy back when done
  - optimize layout
    - put sectors of a file in consecutive locations
  - use parallelism
    - spread file over multiple disks
    - read multiple sectors at once

Implementation Problems

- **Reliability**
  - – computer crashes
    - » what you thought was safely written to the file never made it to the disk — it's still in RAM, which is lost
    - » worse yet, some parts made it back to disk, some didn't
      - you don't know which is which
      - on-disk data structures might be totally trashed
  - – disk crashes
    - » you had backed it up … yesterday
  - – you screw up
    - » you accidentally delete the entire directory containing your shell 1 implementation

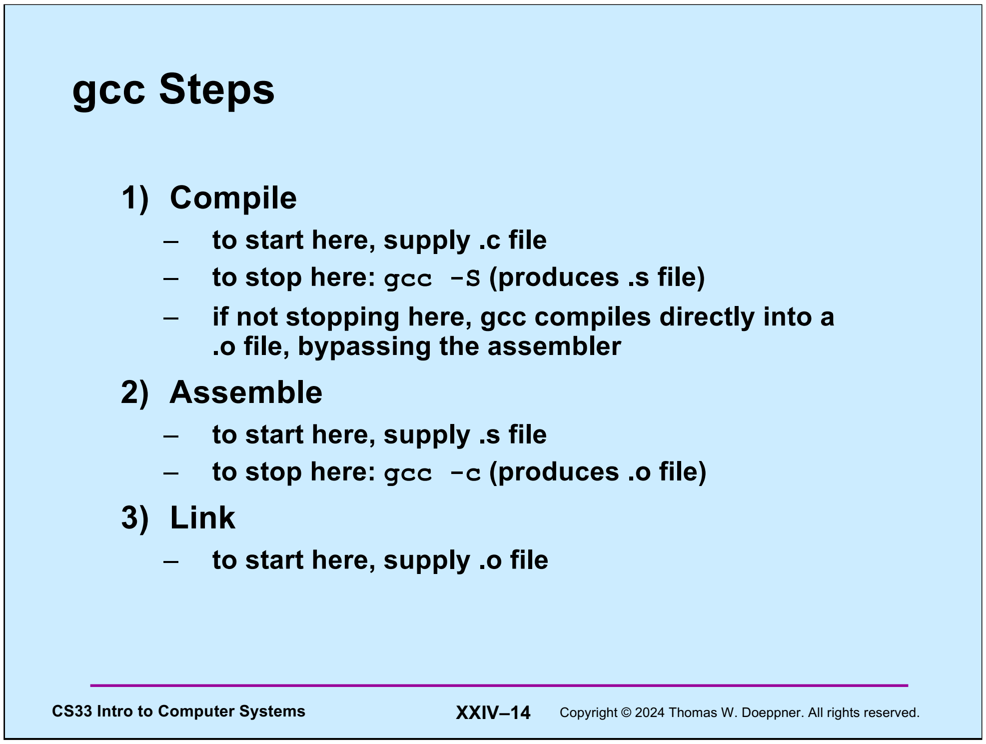
Implementation Problems

- Reliability solutions
  - computer crashes
    - transaction-oriented file systems
    - on-disk data structures always in well defined states
  - disk crashes
    - files stored redundantly on multiple disks
  - you screw up
    - file system automatically keeps "snapshots" of previous versions of files

All of this is covered in CSCI 1670.

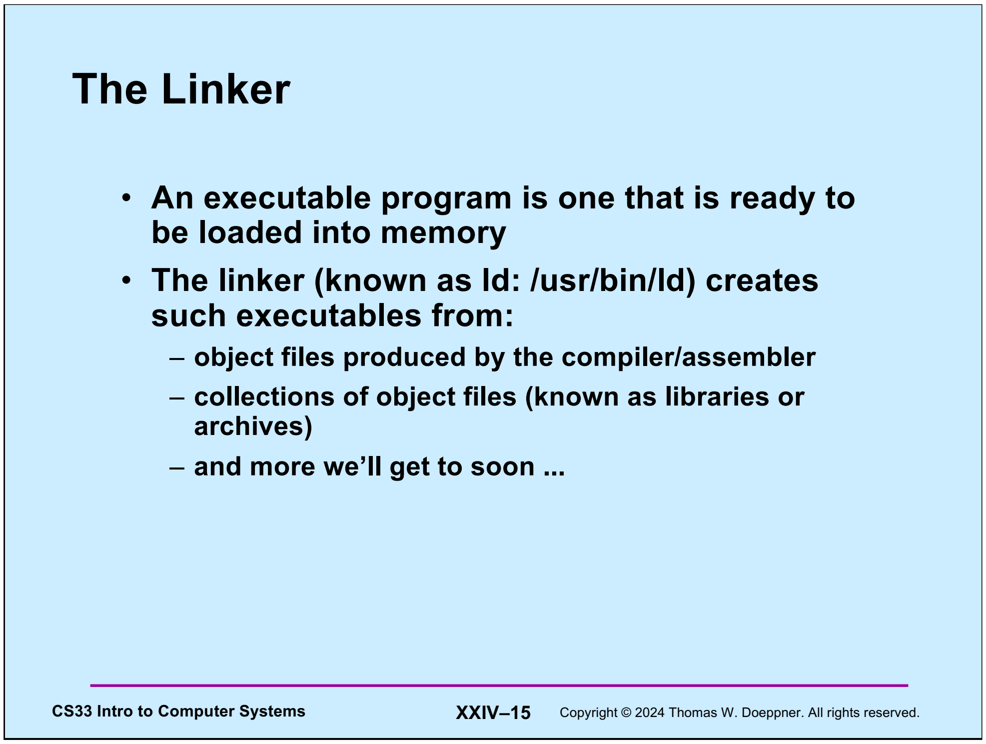
CS 33

Linkers



gcc Steps

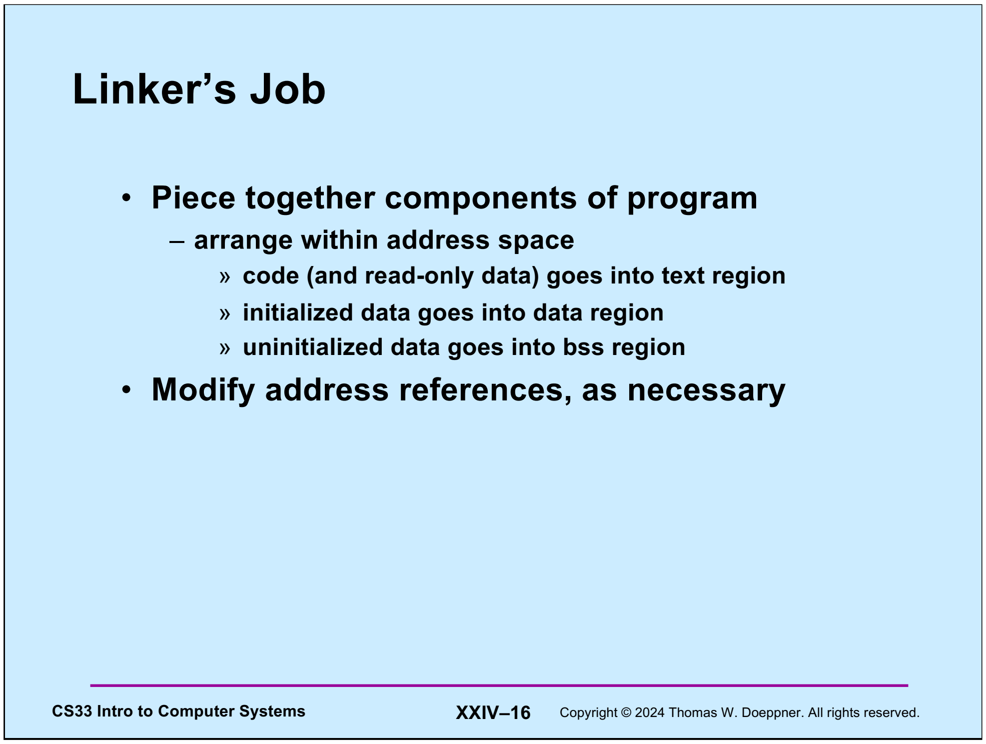
1) Compile
   - to start here, supply .c file
   - to stop here: `gcc -S` (produces .s file)
   - if not stopping here, gcc compiles directly into a .o file, bypassing the assembler
2) Assemble
   - to start here, supply .s file
   - to stop here: `gcc -c` (produces .o file)
3) Link
   - to start here, supply .o file



The Linker

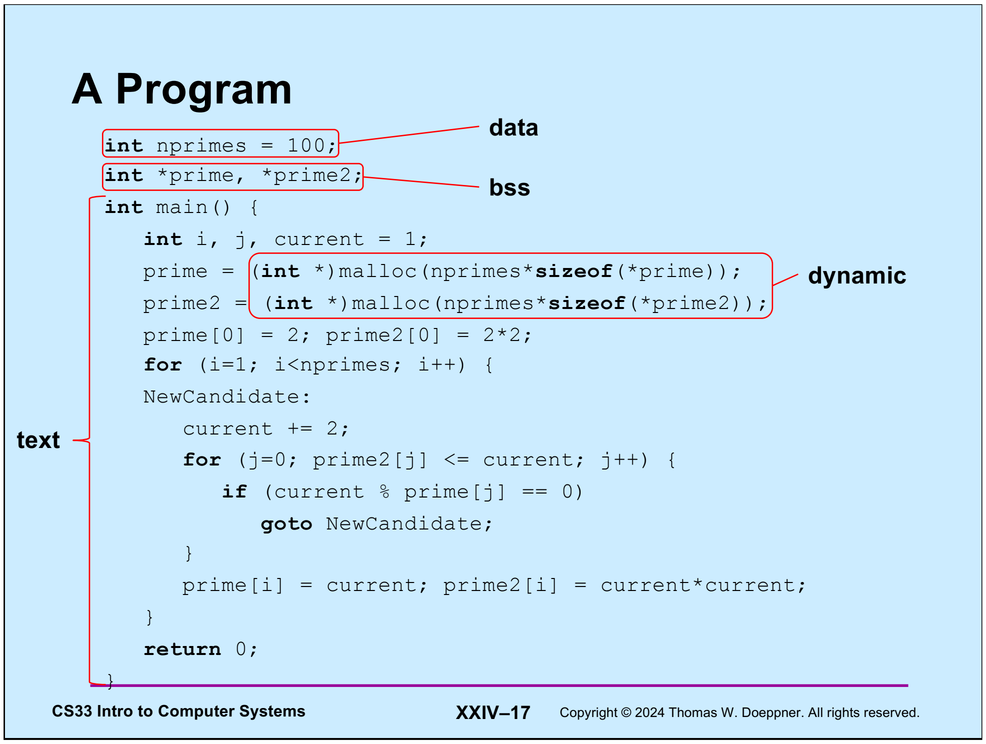
- An executable program is one that is ready to be loaded into memory
- The linker (known as ld: /usr/bin/ld) creates such executables from:
  - object files produced by the compiler/assembler
  - collections of object files (known as libraries or archives)
  - and more we’ll get to soon ...

The technology described here is current as of around 1990 and is known as static linking. We discuss static linking first, then move on to dynamic linking (in a few weeks), which is commonplace today.



Linker’s Job

- Piece together components of program
  - arrange within address space
    - code (and read-only data) goes into text region
    - initialized data goes into data region
    - uninitialized data goes into bss region
- Modify address references, as necessary

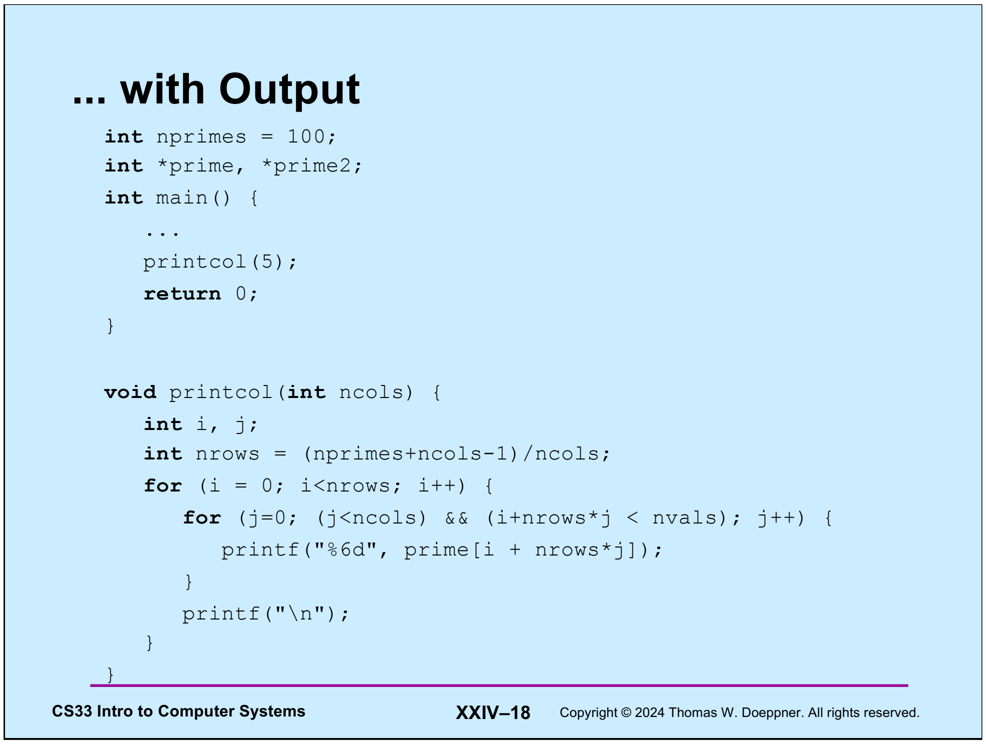


A Program

```
int nprimes = 100;
int *prime, *prime2;
int main() {
   int i, j, current = 1;
   prime = (int *)malloc(nprimes*sizeof(*prime));
   prime2 = (int *)malloc(nprimes*sizeof(*prime2));
   prime[0] = 2; prime2[0] = 2*2;
   for (i=1; i<nprimes; i++) {
   NewCandidate:
      current += 2;
      for (j=0; prime2[j] <= current; j++) {
         if (current % prime[j] == 0)
            goto NewCandidate;
      }
      prime[i] = current; prime2[i] = current*current;
   }
   return 0;
}
```

The code is an implementation of the “sieve of Eratosthenes”, an early (~200 BCE) algorithm for enumerating prime numbers. The idea is to iterate through the positive integers. 2 is the first prime number. 3 is prime, since it’s not divisible by 2. 4 is not prime, since it is divisible by 2. 5 is not prime, since it’s not divisible by any of the primes discovered so far (5 is less than the largest’s square). This continues ad infinitum.

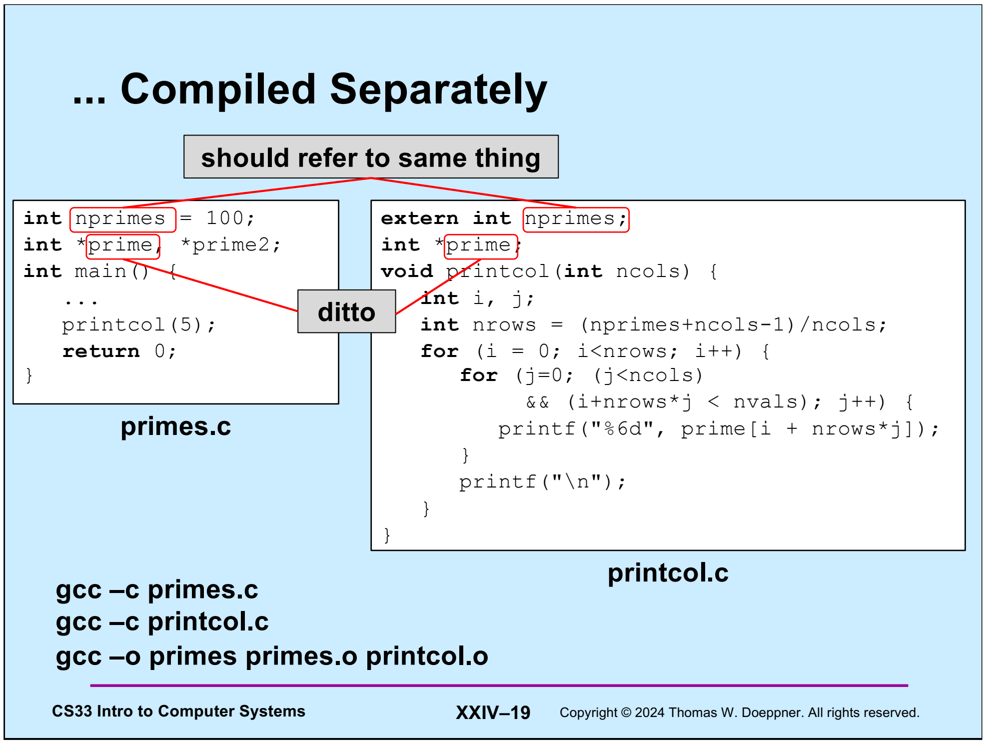
The **malloc** function allocates storage within the dynamic region. We discuss it in detail in an upcoming lecture.



... with Output

```
int nprimes = 100;
int *prime, *prime2;
int main() {
   ...
   printcol(5);
   return 0;
}

void printcol(int ncols) {
   int i, j;
   int nrows = (nprimes+ncols-1)/ncols;
   for (i = 0; i<nrows; i++) {
      for (j=0; (j<ncols) && (i+nrows*j < nvals); j++) {
         printf("%6d", prime[i + nrows*j]);
      }
      printf("\n");
   }
}
```

What this program actually does isn't all that important for our discussion. However, it prints out the vector of prime numbers in multiple columns.



... Compiled Separately

should refer to same thing

ditto

```
int nprimes = 100;
int *prime, *prime2;
int main() {
   ...
   printcol(5);
   return 0;
}
```

primes.c

```
extern int nprimes;
int *prime;
void printcol(int ncols) {
   int i, j;
   int nrows = (nprimes+ncols-1)/ncols;
   for (i = 0; i<nrows; i++) {
      for (j=0; (j<ncols)
           && (i+nrows*j < nvals); j++) {
         printf("%6d", prime[i + nrows*j]);
      }
      printf("\n");
   }
}
```

printcol.c

```
gcc –c primes.c
gcc –c printcol.c
gcc –o primes primes.o printcol.o
```

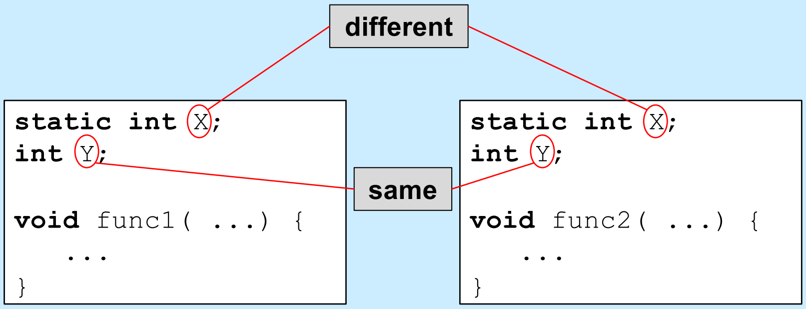
In the first two invocations of gcc, the “-c” flag tells it to compile the C code and produce an object (“.o”) file, but not to go any further (and thus not to produce an executable program). In the third invocation, gcc invokes the ld (linker) program to combine the two object files into an executable program. As we discuss soon, it will also bring in code (such as printf) from libraries.

Global Variables

- **Initialized vs. uninitialized**
  - **initialized allocated in *data* section**
  - **uninitialized allocated in *bss* section**
    - **implicitly initialized to zero**
- **File scope vs. program scope**
  - ***static* global variables known only within file that declares them**
    - **two of same name in different files are different**
    - **e.g., `static int X;`**
  - **non-static global variables potentially shared across all files**
    - **two of same name in different files are same**
    - **e.g., `int X;`**

BSS is a mnemonic from an ancient assembler (not as ancient as Eratosthenes) and stands for “block started by symbol”, a rather meaningless phrase. The BSS section of the address space is where all uninitialized global and static local variables are placed. When the program starts up, this entire section is filled with zeroes.

Scope



```
static int X;
int Y;

void func1( ...) {
   ...
}
```

file1.c

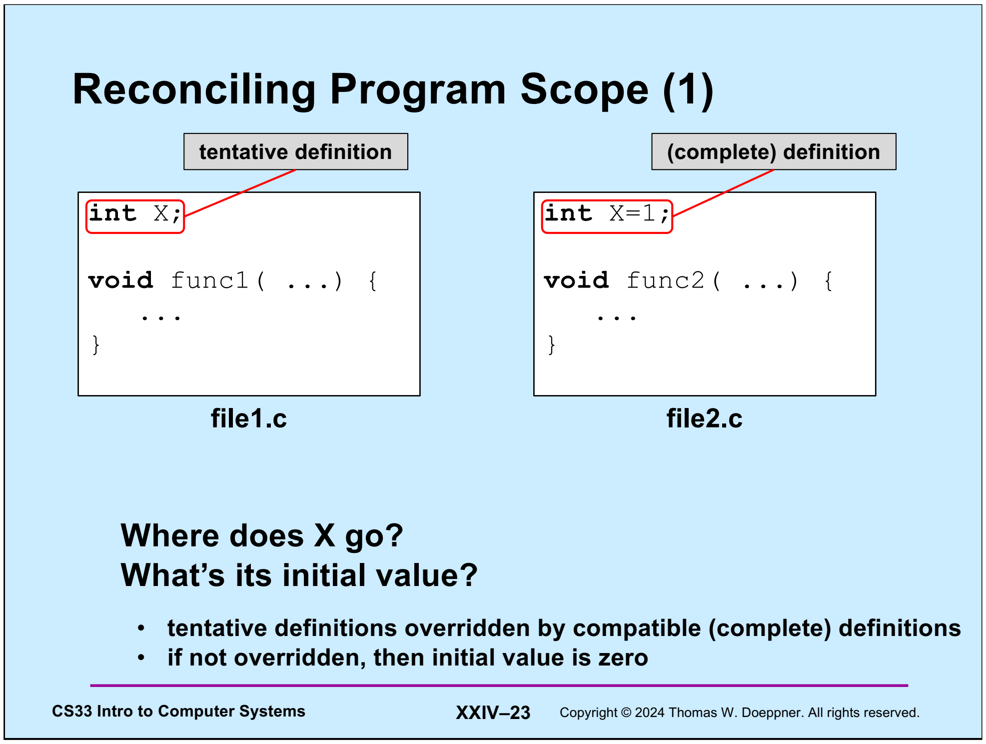
```
static int X;
int Y;

void func2( ...) {
   ...
}
```

file2.c

Static Local Variables

```
int *sub1() {                       int *sub2() {
  int var = 1;                        static int var = 1;
  …                                   …
  return &var;                        return &var;
  /* amazingly illegal */             /* (amazingly) legal */
}                                   }
```

Static local variables have the same scope as other local variables, but their values are retained across calls to the procedures they are declared in. Like global variables, uninitialized static local variables are stored in the BSS section of the address space (and implicitly initialized to zero), initialized static local variables are stored in the data section of the address space.



Reconciling Program Scope (1)

file1.c

```
int X;

void func1( ...) {
    ...
}
```

file2.c

```
int X=1;

void func2( ...) {
    ...
}
```

Where does X go?
What’s its initial value?

- tentative definitions overridden by compatible (complete) definitions
- if not overridden, then initial value is zero

X goes in the data section and has an initial value of 1. If file2.c did not exist, then X would go in the bss section and have an initial value of 0. Note that the textbook calls tentative definitions “weak definitions” and complete definitions “strong definitions”. This is non-standard terminology and conflicts with the standard use of the term “weak definition,” which we discuss shortly.

Reconciling Program Scope (2)

```
int X=2;

void func1( ...) {
   ...
}
```

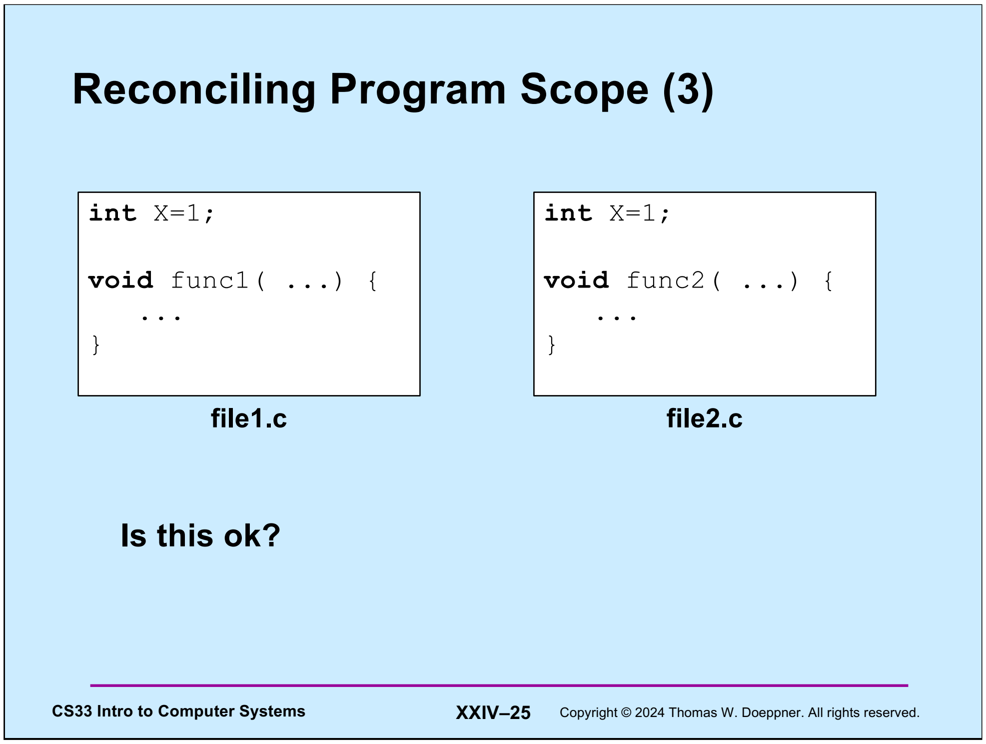
file1.c

```
int X=1;

void func2( ...) {
   ...
}
```

file2.c

What happens here?

In this case we have conflicting definitions of X — this will be flagged (by the ld program) as an error.



Reconciling Program Scope (3)

```
int X=1;

void func1( ...) {
   ...
}
```

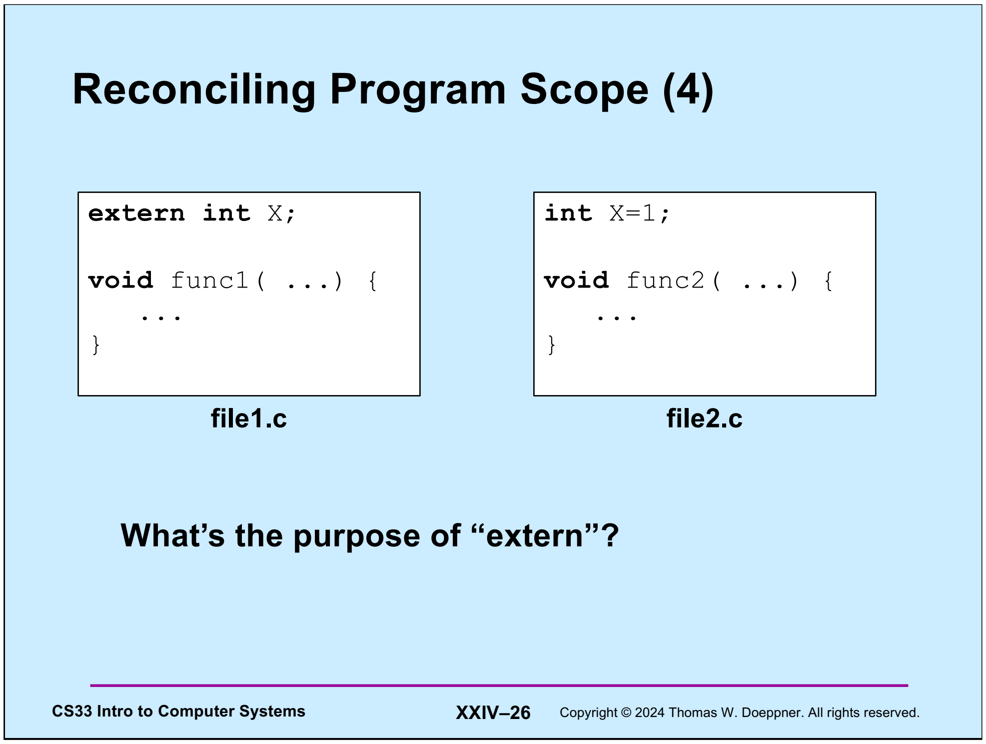
file1.c

```
int X=1;

void func2( ...) {
   ...
}
```

file2.c

Is this ok?

No; it is flagged as an error: only one file may supply an initial value.



Reconciling Program Scope (4)

```
extern int X;

void func1( ...) {
   ...
}
```

file1.c

```
int X=1;

void func2( ...) {
   ...
}
```

file2.c

What’s the purpose of “extern”?

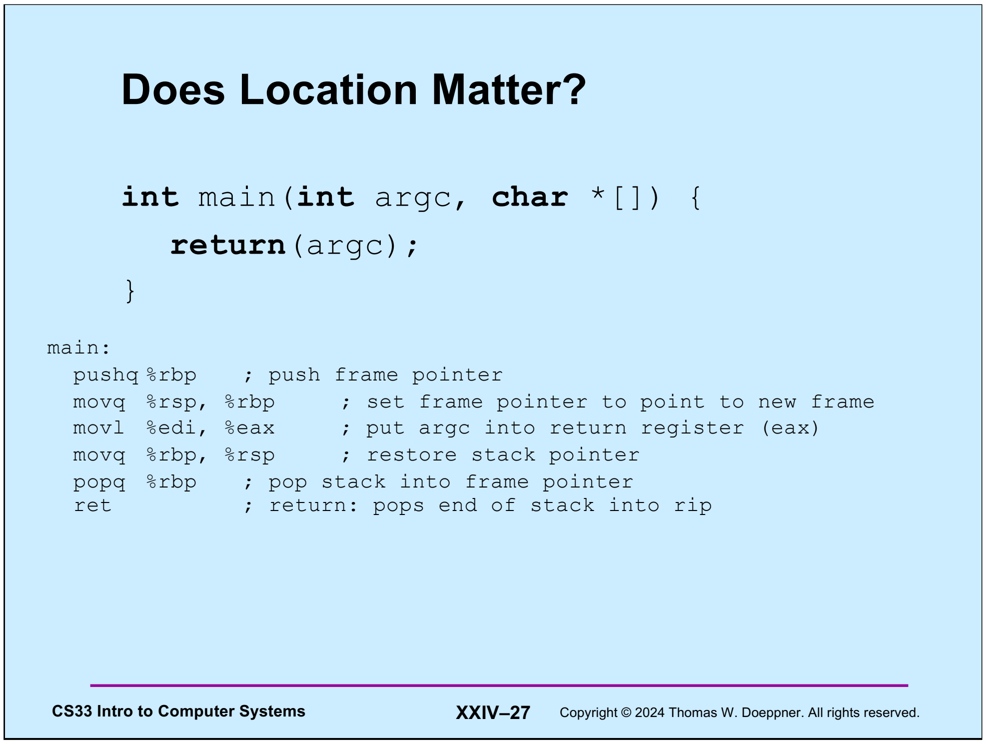
The “extern” means that this file will be using X, but it depends on some other file to provide a definition for it, either initialized of uninitialized. If no other file provides a definition, then ld flags an error.

If the “extern” were not there, i.e., if X were declared simply as an “int” in file1.c, then it wouldn’t matter if no other file provided a definition for X — X would be allocated in bss with an implicit initial value of 0.

Note: this description of extern is how it is implemented by gcc. The official C99 standard doesn’t require this behavior, but merely permits it. It also permits “extern” to be essentially superfluous: its presence may mean the same thing as its absence.

The C11 standard more-or-less agrees with the C99 standard. Moreover, it explicitly allows a declaration of the form “extern int X=1;” (i.e., initialization), which is not allowed by gcc.

For most practical purposes, whatever gcc says is the law …

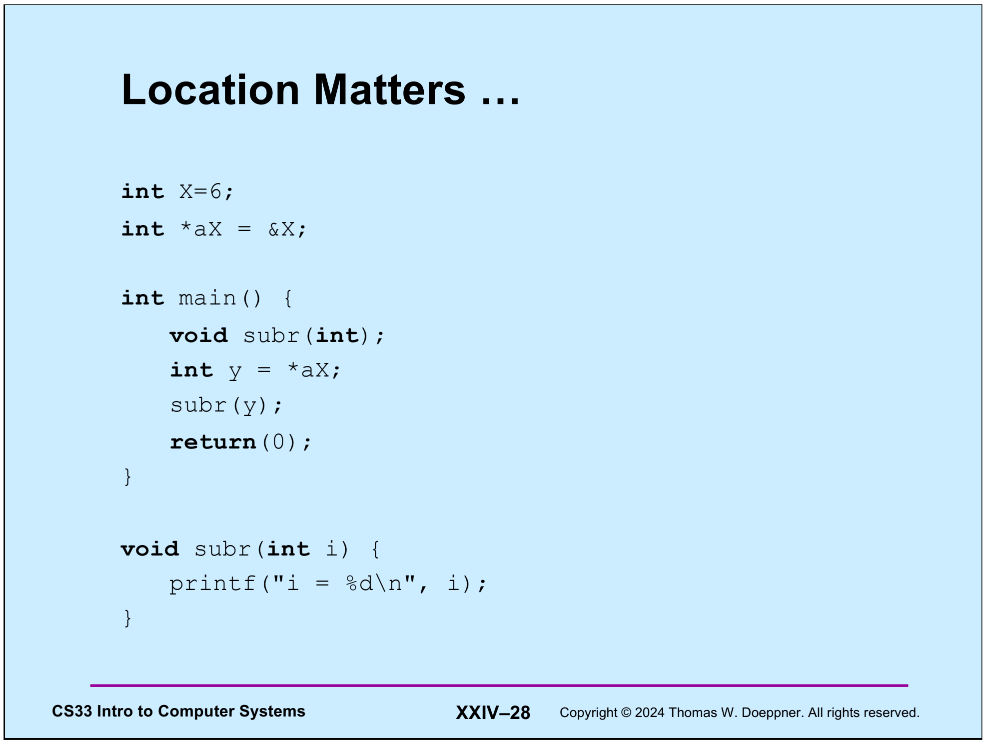


Does Location Matter?

```
int main(int argc, char *[]) {
   return(argc);
}
```

```
main:
  pushq %rbp    ; push frame pointer
  movq  %rsp, %rbp     ; set frame pointer to point to new frame
  movl  %edi, %eax     ; put argc into return register (eax)
  movq  %rbp, %rsp     ; restore stack pointer
  popq  %rbp    ; pop stack into frame pointer
  ret           ; return: pops end of stack into rip
```

This rather trivial program references memory via only rsp and rip (rbp is set from rsp). Its code contains no explicit references to memory, i.e., it contains no explicit addresses.



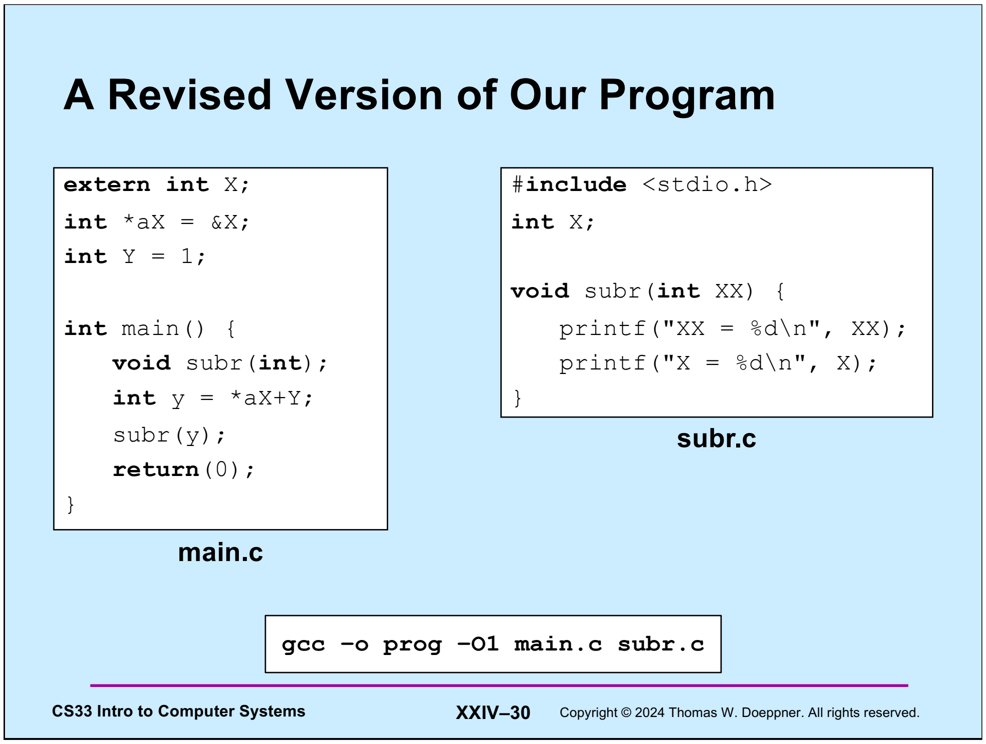
Location Matters …

```
int X=6;
int *aX = &X;

int main() {
   void subr(int);
   int y = *aX;
   subr(y);
   return(0);
}

void subr(int i) {
   printf("i = %d\n", i);
}
```

We don’t need to look at the assembler code to see what’s different about this program: the machine code produced for it can’t simply be copied to an arbitrary location in our computer’s memory and executed. The location identified by the name **aX** should contain the address of the location containing **X**. But since the address of **X** will not be known until the program is copied into memory, neither the compiler nor the assembler can initialize **aX** correctly. Similarly, the addresses of **subr** and **printf** are not known until the program is copied into memory — again, neither the compiler nor the assembler would know what addresses to use.

Coping

- Relocation
  - modify internal references according to where module is loaded in memory
  - modules needing relocation are said to be *relocatable*
    - which means they *require* relocation
  - the compiler/assembler provides instructions to the linker on how to do this



A Revised Version of Our Program

```
extern int X;
int *aX = &X;
int Y = 1;

int main() {
   void subr(int);
   int y = *aX+Y;
   subr(y);
   return(0);
}
```

main.c

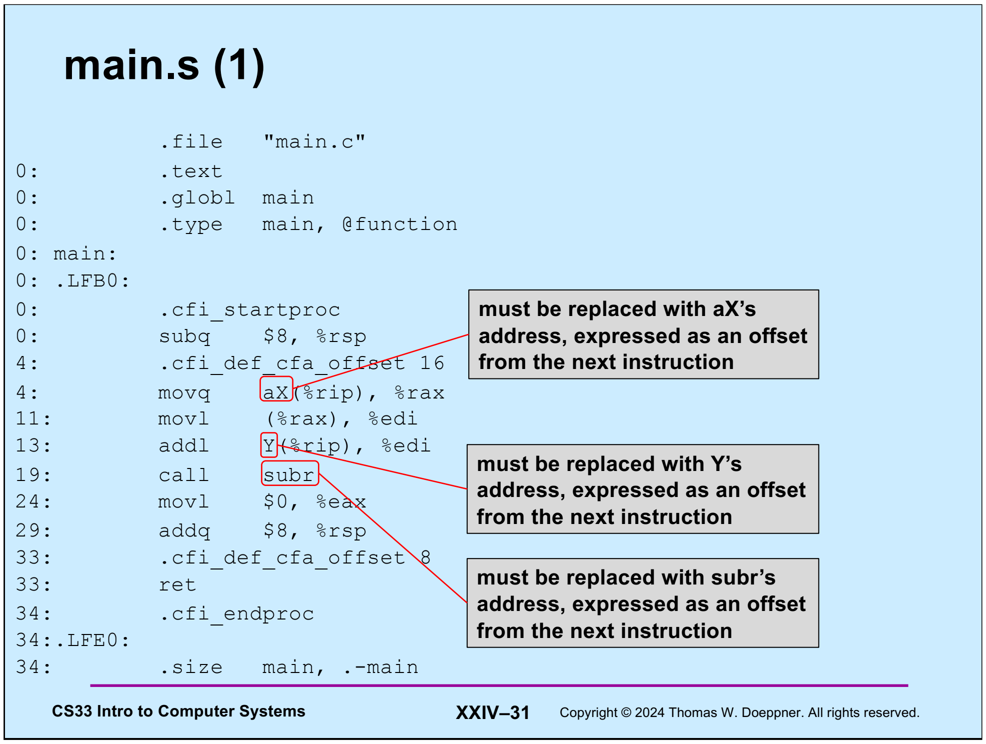
```
#include <stdio.h>
int X;

void subr(int XX) {
   printf("XX = %d\n", XX);
   printf("X = %d\n", X);
}
```

subr.c

```
gcc –o prog –O1 main.c subr.c
```

Note that what we did, in order to obtain what's in the next few slides, was:

```
gcc –S –O1 main.c subr.c
gcc –c main.s subr.s
gcc –o prog main.o subr.o
```



main.s (1)

```
          .file   "main.c"
0:        .text
0:        .globl  main
0:        .type   main, @function
0: main:
0: .LFB0:
0:        .cfi_startproc
0:        subq    $8, %rsp
4:        .cfi_def_cfa_offset 16
4:        movq    aX(%rip), %rax
11:       movl    (%rax), %edi
13:       addl    Y(%rip), %edi
19:       call    subr
24:       movl    $0, %eax
29:       addq    $8, %rsp
33:       .cfi_def_cfa_offset 8
33:       ret
34:       .cfi_endproc
34:.LFE0:
34:       .size   main, .-main
```

must be replaced with aX's address, expressed as an offset from the next instruction

must be replaced with Y's address, expressed as an offset from the next instruction

must be replaced with subr's address, expressed as an offset from the next instruction

Note that a symbol's value is the location of what it refers to. The compiler/assembler knows what the values (i.e., locations) of **aX** and **Y** are relative to the beginning of this module's data section (next slide), but has no idea what **subr**'s value is. It is the linker's job to provide final values for these symbols, which will be the addresses of the corresponding C constructs when the program is loaded into memory. The linker will adjust these values to obtain the locations of what they refer to relative to the value of register rip when the referencing instructions are executed.

One might ask why these locations are referred to using offsets from the instruction pointer (also known as the program counter), rather than simply using their addresses. The reason is to save space: the addresses would be 64 bits long, but the offsets are only 32 bits long.

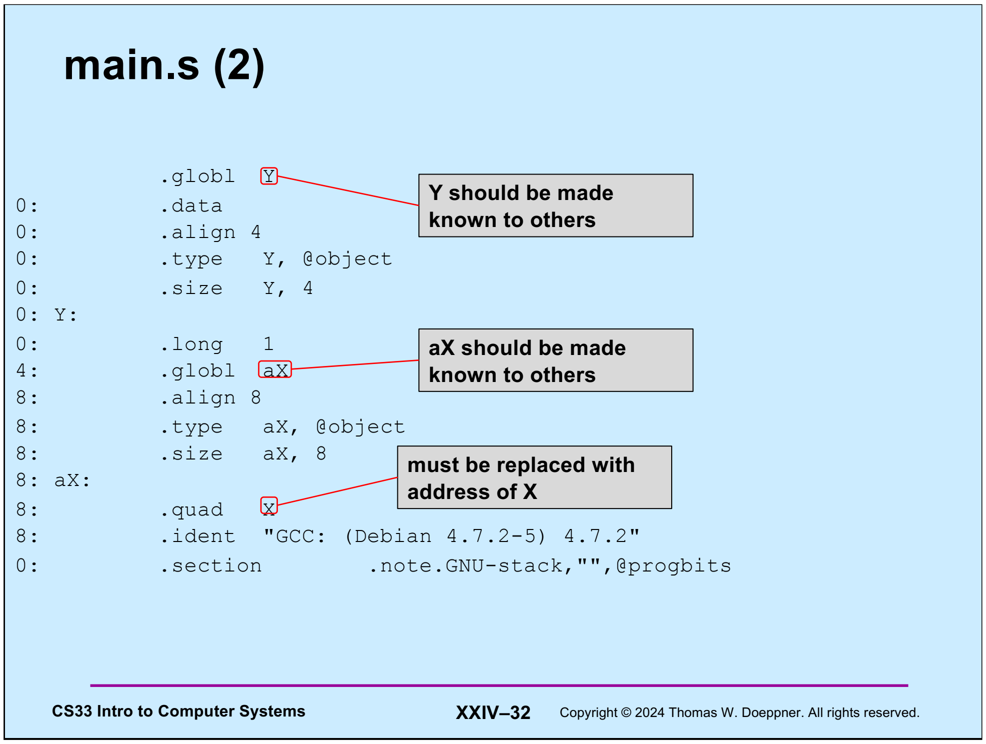
The ".file" directive supplies information to be placed in the object file and the executable of use to debuggers — it tells them what the source-code file is.

The ".globl" directive indicates that the symbol, defined here, will be used by other modules, and thus should be made known to the linker.

The ".type" directive indicates how the symbol is used. Two possibilities are function and object (meaning a data object).

The " .size" directive indicates the size that should be associated with the given symbol.

The directives starting with ".cfi_" are there for the sake of the debugger. They generate auxiliary information stored in the object file (but not executed) that describes the relation between the stack pointer (%rsp) and the beginning of the stack frame. Thus they compensate for the lack of a standard frame-pointer register (%esp for IA32). In particular, they emit data going into a table that is used by a debugger (such as gdb) to determine, based on the value of the instruction pointer (%rip) and the stack pointer, where the beginning of the current stack frame is.



main.s (2)

```
                .globl  Y
0:              .data
0:              .align 4
0:              .type   Y, @object
0:              .size   Y, 4
0:  Y:
0:              .long   1
4:              .globl  aX
8:              .align 8
8:              .type   aX, @object
8:              .size   aX, 8
8:  aX:
8:              .quad   X
8:              .ident  "GCC: (Debian 4.7.2-5) 4.7.2"
0:              .section        .note.GNU-stack,"",@progbits
```

Y should be made known to others

aX should be made known to others

must be replaced with address of X

The symbol **X**’s value is, at this point, unknown.

The “.data” directive indicates that what follows goes in the data section.

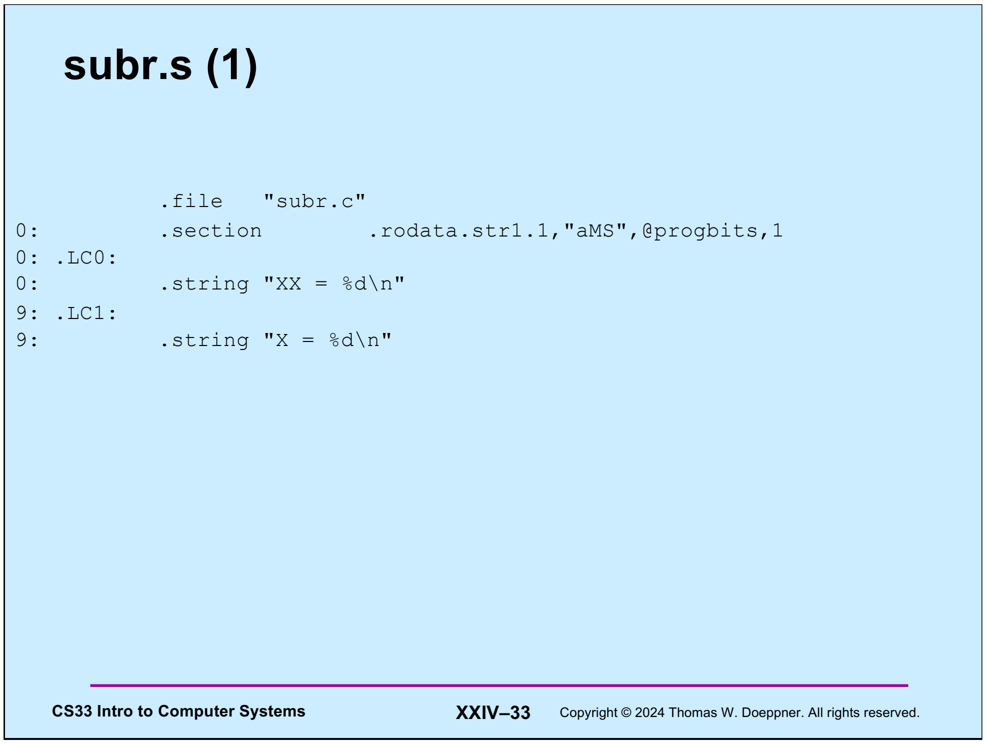
The “.long” directive indicates that storage should be allocated for a long word.

The “.quad” directive indicates that storage should be allocated for a quad word.

The “.align” directive indicates that the storage associated with the symbol should be aligned, in the cases here, on 4-byte and 8-byte boundaries (i.e., the least-significant two bits and three bits of their addresses should be zeroes).

The “.ident” directive indicates the software used to produce the file and its version.

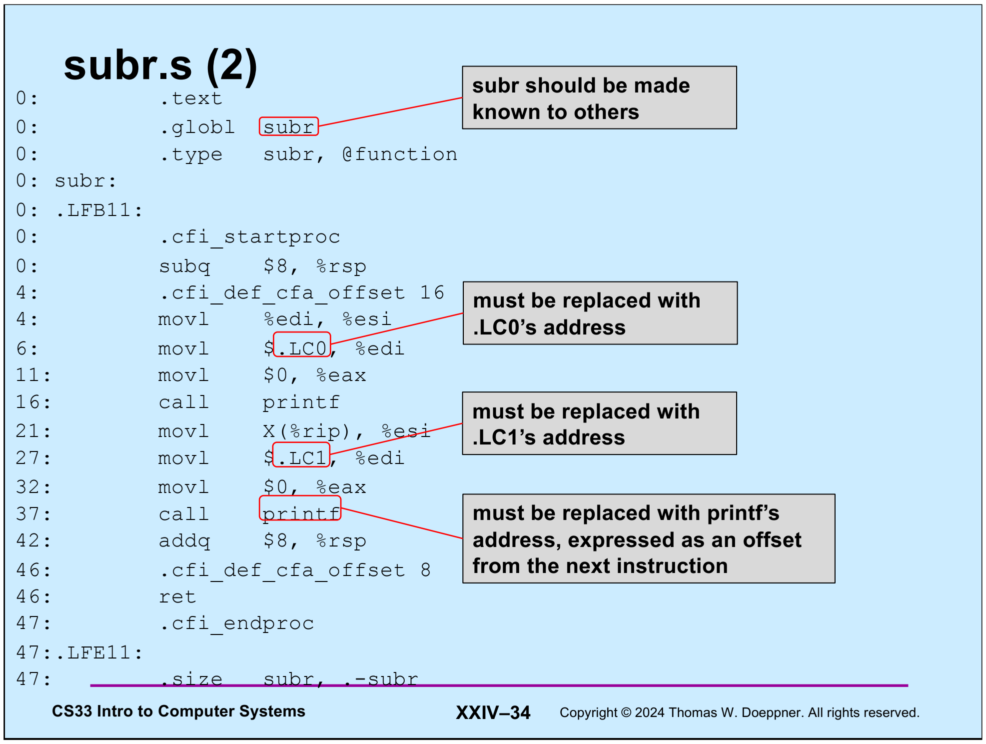
The “.section” directive used here is supplied by gcc by default and indicates that the program should have a non-executable stack (this is important for security purposes).



subr.s (1)

```
          .file   "subr.c"
0:        .section        .rodata.str1.1,"aMS",@progbits,1
0: .LC0:
0:        .string "XX = %d\n"
9: .LC1:
9:        .string "X = %d\n"
```

The ".section" directive here indicates that what follows should be placed in read-only storage (and will be included in the text section). Furthermore, what follows are strings with a one-byte-per-character encoding that require one-byte (i.e., unrestricted) alignment. This information will ultimately be used by the linker to reduce storage by identifying strings that are suffices of others.



subr.s (2)

```
0:           .text
0:           .globl  subr
0:           .type   subr, @function
0:  subr:
0:  .LFB11:
0:           .cfi_startproc
0:           subq    $8, %rsp
4:           .cfi_def_cfa_offset 16
4:           movl    %edi, %esi
6:           movl    $.LC0, %edi
11:          movl    $0, %eax
16:          call    printf
21:          movl    X(%rip), %esi
27:          movl    $.LC1, %edi
32:          movl    $0, %eax
37:          call    printf
42:          addq    $8, %rsp
46:          .cfi_def_cfa_offset 8
46:          ret
47:          .cfi_endproc
47:.LFE11:
47:          .size   subr, .-subr
```

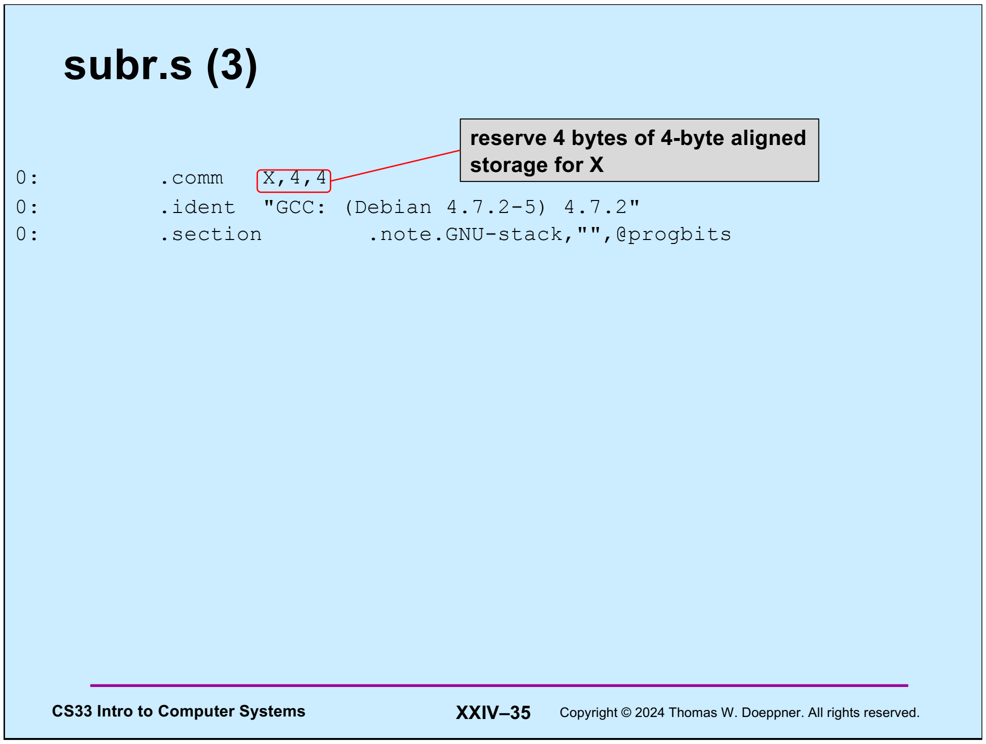
subr should be made known to others

must be replaced with .LC0's address

must be replaced with .LC1's address

must be replaced with printf's address, expressed as an offset from the next instruction

Note that the compiler has generated **movl** instructions (copying 32 bits) for copying the addresses of .LC0 and .LC1: it's assuming that both addresses will fit in 32 bits (in other words, that the text section of the program will be less than 2^{32} bytes long — probably a reasonable assumption.



subr.s (3)

```
0:         .comm   X,4,4
0:         .ident  "GCC: (Debian 4.7.2-5) 4.7.2"
0:         .section        .note.GNU-stack,"",@progbits
```

reserve 4 bytes of 4-byte aligned storage for X

The “.comm” directive indicates here that four bytes of four-byte aligned storage are required for X in BSS. “comm” stands for “common”, which is what the Fortran language uses to mean the same thing as BSS. Since Fortran predates pretty much everything (except for Eratosthenes), its terminology wins (at least here).

Quiz 3

```
int X;
int func(int arg) {
  static int Y;
  int Z;

  ...

}
```

Which of *X*, *Y*, *Z*, and *arg* would the compiler know the addresses of at compile time?

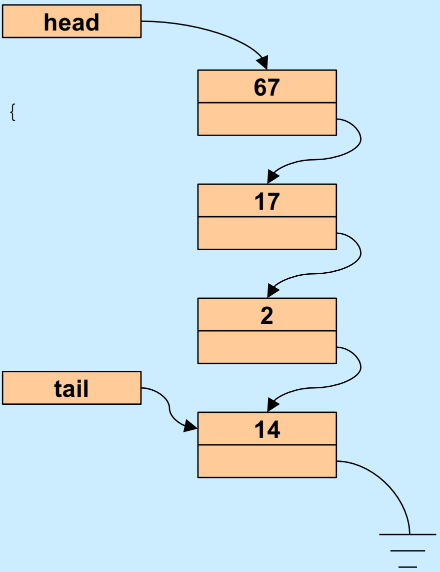
- **a) none**
- **b) just *X* and *Y***
- **c) just *arg* and *Z***
- **d) all**

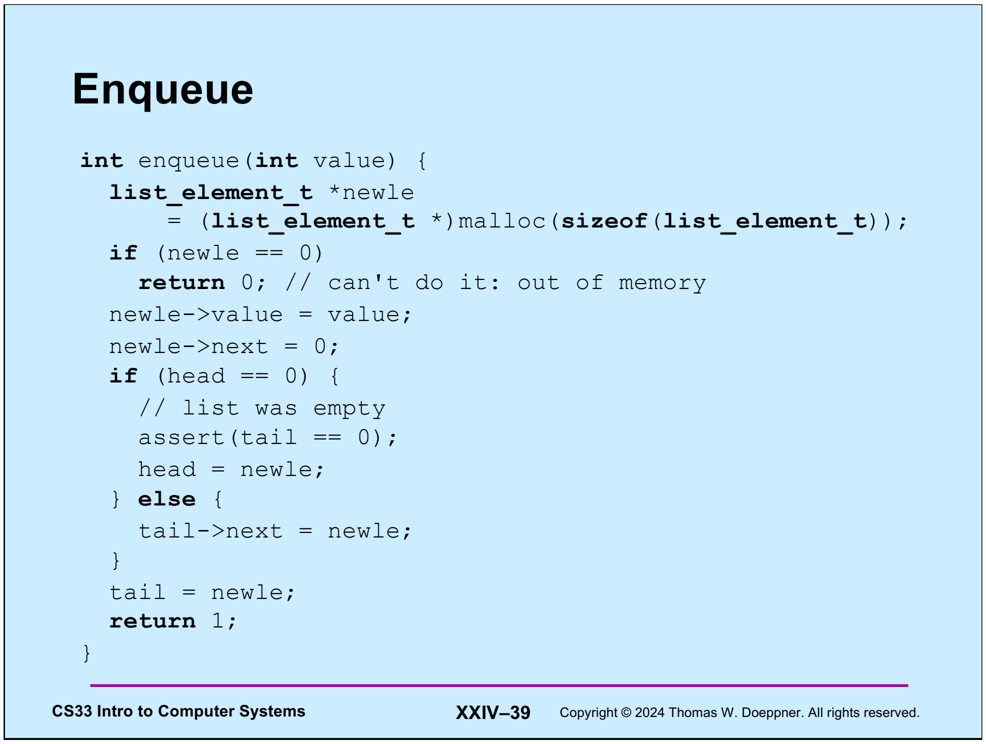
CS 33

Intro to Storage Allocation

A Queue

```
typedef struct list_element {
  int value;
  struct list_element *next;
} list_element_t;

list_element_t *head, *tail;
```





Enqueue

```
int enqueue(int value) {
  list_element_t *newle
      = (list_element_t *)malloc(sizeof(list_element_t));
  if (newle == 0)
    return 0; // can't do it: out of memory
  newle->value = value;
  newle->next = 0;
  if (head == 0) {
    // list was empty
    assert(tail == 0);
    head = newle;
  } else {
    tail->next = newle;
  }
  tail = newle;
  return 1;
}
```

Note that **malloc** allocates storage to hold a new instance of **list_element_t**.

Dequeue

```
int dequeue(int *value) {
  list_element_t *first;
  if (head == 0) {
    // list is empty
    return 0;
  }
  *value = head->value;
  first = head;
  head = head->next;
  if (tail == first) {
    assert(head == 0);
    tail = 0;
  }
  return 1;
}
```

What’s wrong with this code???

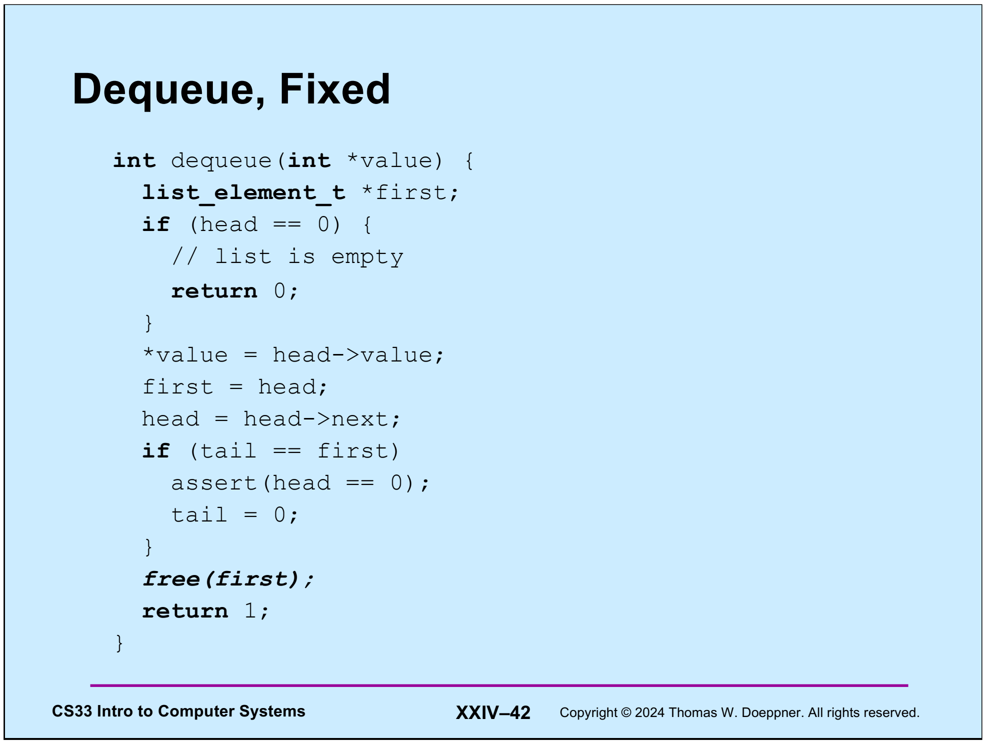
The problem with this code, which removes the first item in the queue, is that the list element being removed is lost – its storage is not returned to the pool of free memory.

Storage Leaks

```
int main() {
  while(1)
    if (malloc(sizeof(list_element_t)) == 0)
      break;
  return 1;
}
```

For how long will this program run before terminating?

Answer: around 18 seconds on a SunLab machine.



Dequeue, Fixed

```
int dequeue(int *value) {
  list_element_t *first;
  if (head == 0) {
    // list is empty
    return 0;
  }
  *value = head->value;
  first = head;
  head = head->next;
  if (tail == first)
    assert(head == 0);
    tail = 0;
  }
  free(first);
  return 1;
}
```

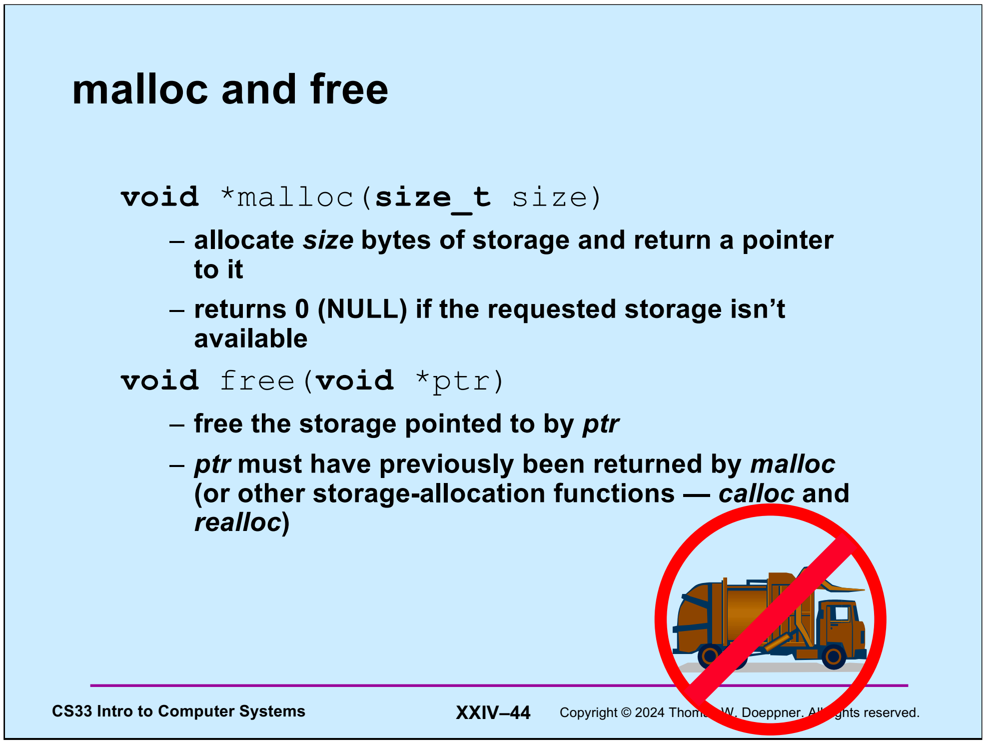
Here after removing the list element from the list, we return it to the pool of free memory by calling *free*.

Quiz 4

```
int enqueue(int value) {
  list_element_t *newle
      = (list_element_t *)malloc(sizeof(list_element_t));
  if (newle == 0)
    return 0;
  newle->value = value;
  newle->next = 0;
  if (head == 0) {
    // list was empty
    assert(tail == 0);
    head = newle;
  } else {
    tail->next = newle;
  }
  tail = newle;
  free(newle); // saves us the bother of freeing it later
  return 1;
}
```

This version of enqueue makes unnecessary the call to free in dequeue.

- **a) It works well.**
- **b) It fails occasionally.**
- **c) It hardly ever works.**
- **d) It never works.**



malloc and free

`void *malloc(size_t size)`

- allocate *size* bytes of storage and return a pointer to it
- returns 0 (NULL) if the requested storage isn't available

`void free(void *ptr)`

- free the storage pointed to by *ptr*
- *ptr* must have previously been returned by *malloc* (or other storage-allocation functions — *calloc* and *realloc*)

When something is malloc'd, the system must keep track of its size. Thus, when it's freed, the system will know how much storage is being freed.

realloc

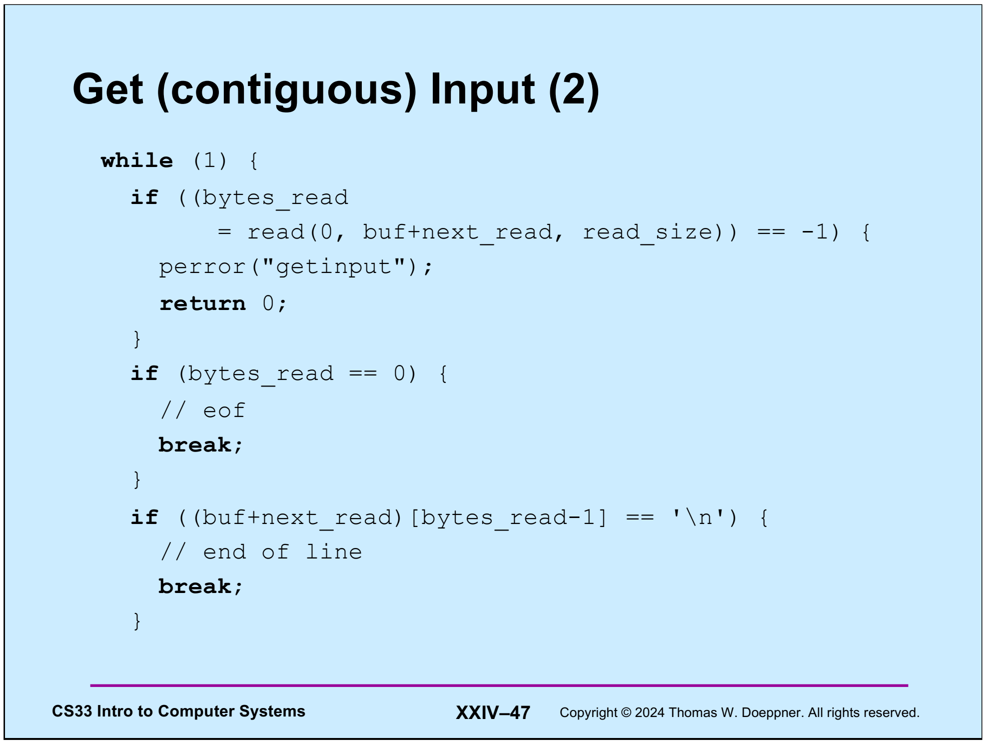
`void *realloc(void *ptr, size_t size)`

- change the size of the storage pointed to by *ptr*
- the contents, up to the minimum of the old size and new size, will not be changed
- *ptr* must have been returned by a previous call to *malloc*, *realloc*, or *calloc*
- it may be necessary to allocate a completely new area and copy from the old to the new
  - thus the return value may be different from *ptr*
  - if copying is done the old area is freed
- returns 0 if the operation cannot be done

Get (contiguous) Input (1)

```
char *getinput() {
  int alloc_size = 4;  // start small
  int read_size = 4;   // max number of bytes to read
  int next_read = 0;   // index in buf of next read
  int bytes_read;      // number of bytes read
  char *buf = (char *)malloc(alloc_size);
  char *newbuf;

  if (buf == 0) {
    // no memory
    return 0;
  }
```

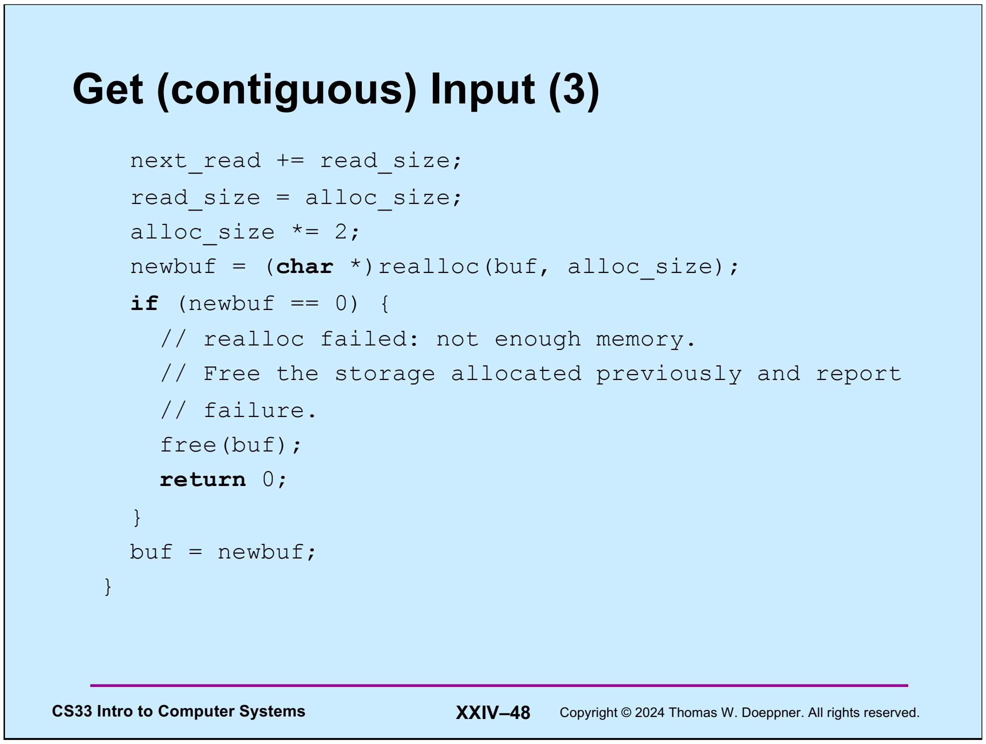
In this example, we're to read a line of input, where a line is delineated by a newline character. However, we have no upper bound on its length. So, we start by allocating four bytes of storage for the line. If that's not enough (the four bytes read in don't end with a '\n'), we then double our allocation and read in more up to the end of the new allocation, if that's not enough, we double the allocation again, and so forth. When we're finished, we reduce the allocation, giving back to the system that portion we didn't need.



Get (contiguous) Input (2)

```
while (1) {
  if ((bytes_read
        = read(0, buf+next_read, read_size)) == -1) {
    perror("getinput");
    return 0;
  }
  if (bytes_read == 0) {
    // eof
    break;
  }
  if ((buf+next_read)[bytes_read-1] == '\n') {
    // end of line
    break;
  }
```

We assume that if read returns neither -1 nor 0, then either it has filled the buffer or that the last character read in was '\n'.



Get (contiguous) Input (3)

```
    next_read += read_size;
    read_size = alloc_size;
    alloc_size *= 2;
    newbuf = (char *)realloc(buf, alloc_size);
    if (newbuf == 0) {
      // realloc failed: not enough memory.
      // Free the storage allocated previously and report
      // failure.
      free(buf);
      return 0;
    }
    buf = newbuf;
  }
```

If we get here, then it's the case that the buffer wasn't big enough. So, let's try to get a larger buffer. If we can't get a larger buffer (e.g., the system is out of memory), we free up everything and report failure (probably not a great way to handle this, but it's convenient for the slide).

Get (contiguous) Input (4)

```
  // reduce buffer size to the minimum necessary
  newbuf = (char *)realloc(buf,
      alloc_size - (read_size - bytes_read));
  if (newbuf == 0) {
    // couldn't allocate smaller buf
    return buf;
  }
  return newbuf;
}
```