



## Data Structures

"Every program depends on algorithms and data structures, but few programs depend on the invention of brand new ones."

-- Kernighan & Pike



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## Goals of this Lecture



Help you learn (or refresh your memory) about:

- Common data structures: linked lists and hash tables

Why? Deep motivation:

- Common data structures serve as "high level building blocks"
- A power programmer:
  - Rarely creates programs from scratch
  - Often creates programs using high level building blocks

Why? Shallow motivation:

- Provide background pertinent to Assignment 3
- ... esp. for those who have not taken COS 226

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## Symbol Table API



Goal: maintain a collection of key/value pairs

- For now, each key is a **string**; each value is an **int**
- Lookup by key, get value back
- Unknown number of key-value pairs

Examples

- (student name, grade)
  - ("john smith", 84), ("jane doe", 93), ("bill clinton", 81)
- (baseball player, number)
  - ("Ruth", 3), ("Gehrig", 4), ("Mantle", 7)
- (variable name, value)
  - ("maxLength", 2000), ("i", 7), ("j", -10)

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## Agenda



Linked lists

Hash tables

Hash table issues

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## Linked List Data Structure

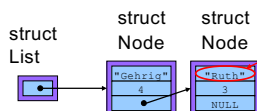


```
struct Node
{
  const char *key;
  int value;
  struct Node *next;
};

struct List
{
  struct Node *first;
};
```

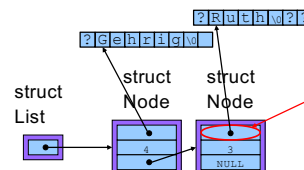
Your Assignment 3 data structures will be more elaborate

Really this is the address at which "Ruth" resides



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## Linked List Data Structure



Really this is the address at which "Ruth" resides

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## Linked List Algorithms

### Create

- Allocate `List` structure; set `first` to `NULL`
- Performance:  $O(1) \Rightarrow$  fast

### Add (no check for duplicate key required)

- Insert new node containing key/value pair at front of list
- Performance:  $O(1) \Rightarrow$  fast

### Add (check for duplicate key required)

- Traverse list to check for node with duplicate key
- Insert new node containing key/value pair into list
- Performance:  $O(n) \Rightarrow$  slow

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## Linked List Algorithms

### Search

- Traverse the list, looking for given key
- Stop when key found, or reach end
- Performance: ???

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## iClicker Question

Q: How fast is searching for a key in a linked list?

- A. Always fast –  $O(1)$
- B. Always slow –  $O(n)$
- C. On average, fast
- D. On average, slow

## Linked List Algorithms

### Search

- Traverse the list, looking for given key
- Stop when key found, or reach end
- Performance:  $O(n) \Rightarrow$  slow

### Free

- Free `Node` structures while traversing
- Free `List` structure
- Performance:  $O(n) \Rightarrow$  slow

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## Agenda

Linked lists

Hash tables

Hash table issues

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## Hash Table Data Structure

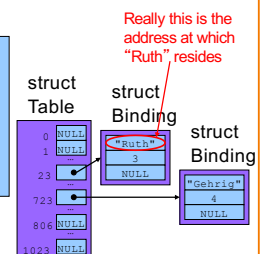
### Array of linked lists

```
enum {BUCKET_COUNT = 1024};

struct Binding
{
    const char *key;
    int value;
    struct Binding *next;
};

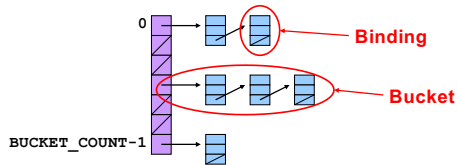
struct Table
{
    struct Binding *buckets[BUCKET_COUNT];
};
```

Your Assignment 3 data structures will be more elaborate



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## Hash Table Data Structure



Hash function maps given key to an integer  
Mod integer by `BUCKET_COUNT` to determine proper bucket

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## Hash Table Example

Example: `BUCKET_COUNT = 7`

Add (if not already present) bindings with these keys:

- the, cat, in, the, hat

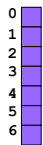
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## Hash Table Example (cont.)

First key: "the"

- $\text{hash}(\text{"the"}) = 965156977; 965156977 \% 7 = 1$

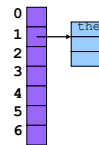
Search `buckets[1]` for binding with key "the"; not found



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## Hash Table Example (cont.)

Add binding with key "the" and its value to `buckets[1]`



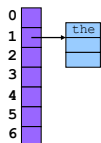
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## Hash Table Example (cont.)

Second key: "cat"

- $\text{hash}(\text{"cat"}) = 3895848756; 3895848756 \% 7 = 2$

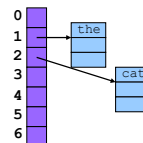
Search `buckets[2]` for binding with key "cat"; not found



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## Hash Table Example (cont.)

Add binding with key "cat" and its value to `buckets[2]`



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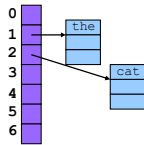
### Hash Table Example (cont.)



Third key: "in"

- $\text{hash}(\text{"in"}) = 6888005; 6888005 \% 7 = 5$

Search **buckets[5]** for binding with key "in"; not found

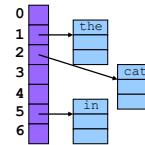


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### Hash Table Example (cont.)



Add binding with key "in" and its value to **buckets[5]**



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### Hash Table Example (cont.)

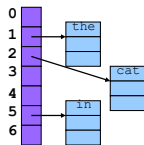


Fourth word: "the"

- $\text{hash}(\text{"the"}) = 965156977; 965156977 \% 7 = 1$

Search **buckets[1]** for binding with key "the"; found it!

- Don't change hash table



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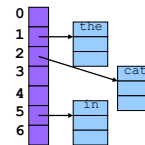
### Hash Table Example (cont.)



Fifth key: "hat"

- $\text{hash}(\text{"hat"}) = 865559739; 865559739 \% 7 = 2$

Search **buckets[2]** for binding with key "hat"; not found



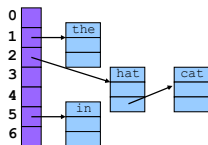
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### Hash Table Example (cont.)



Add binding with key "hat" and its value to **buckets[2]**

- At front or back? Doesn't matter
- Inserting at the front is easier, so add at the front



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### Hash Table Algorithms



#### Create

- Allocate **Table** structure; set each bucket to **NULL**
- Performance:  $O(1) \Rightarrow$  fast

#### Add

- Hash the given key
- Mod by **BUCKET\_COUNT** to determine proper bucket
- Traverse proper bucket to make sure no duplicate key
- Insert new binding containing key/value pair into proper bucket
- Performance: ???

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## iClicker Question

Q: How fast is adding a key to a hash table?

- A. Always fast
- B. Usually fast, but depends on how many keys are in the table
- C. Usually fast, but depends on how many keys hash to the same bucket
- D. Usually slow
- E. Always slow

## Hash Table Algorithms

### Search

- Hash the given key
- Mod by **BUCKET\_COUNT** to determine proper bucket
- Traverse proper bucket, looking for binding with given key
- Stop when key found, or reach end
- Performance: Usually  $O(1) \Rightarrow$  fast

### Free

- Traverse each bucket, freeing bindings
- Free **Table** structure
- Performance:  $O(n) \Rightarrow$  slow

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## Agenda

Linked lists

Hash tables

**Hash table issues**

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## How Many Buckets?

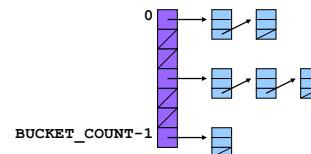
### Many!

- Too few  $\Rightarrow$  large buckets  $\Rightarrow$  slow add, slow search

### But not too many!

- Too many  $\Rightarrow$  memory is wasted

### This is OK:



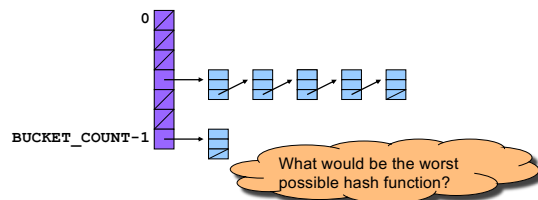
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## What Hash Function?

Should distribute bindings across the buckets well

- Distribute bindings over the range  $0, 1, \dots, \text{BUCKET\_COUNT}-1$
- Distribute bindings *evenly* to avoid very long buckets

This is not so good:



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## How to Hash Strings?

### Simple hash schemes don't distribute the keys evenly

- Number of characters, mod **BUCKET\_COUNT**
- Sum the numeric codes of all characters, mod **BUCKET\_COUNT**
- ...

### A reasonably good hash function:

- Weighted sum of characters  $s_i$  in the string  $s$ 
  - $(\sum a^i s_i) \bmod \text{BUCKET\_COUNT}$
- Best if  $a$  and **BUCKET\_COUNT** are relatively prime
  - E.g.,  $a = 65599, \text{BUCKET\_COUNT} = 1024$

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## How to Hash Strings?

A bit of math, and translation to code, yields:

```
size_t hash(const char *s, size_t bucketCount)
{
    size_t i;
    size_t h = 0;
    for (i=0; s[i]!='\0'; i++)
        h = h * 65599 + (size_t)s[i];
    return h % bucketCount;
}
```

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## How to Protect Keys?

Suppose `Table_add()` function contains this code:

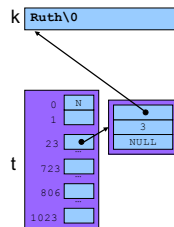
```
void Table_add(struct Table *t, const char *key, int value)
{
    ...
    struct Binding *p =
        (struct Binding*)malloc(sizeof(struct Binding));
    p->key = key;
    ...
}
```

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## How to Protect Keys?

Problem: Consider this calling code:

```
struct Table *t;
char k[100] = "Ruth";
...
Table_add(t, k, 3);
```

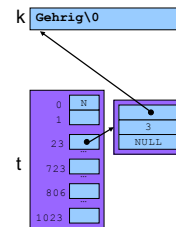


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## How to Protect Keys?

Problem: Consider this calling code:

```
struct Table *t;
char k[100] = "Ruth";
...
Table_add(t, k, 3);
strcpy(k, "Gehrig");
```



What happens if the client searches t for "Ruth"? For Gehrig?

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## How to Protect Keys?

Solution: `Table_add()` saves a **defensive copy** of the given key

```
void Table_add(struct Table *t, const char *key, int value)
{
    ...
    struct Binding *p =
        (struct Binding*)malloc(sizeof(struct Binding));
    p->key = (const char*)malloc(strlen(key) + 1);
    strcpy((char*)p->key, key);
    ...
}
```

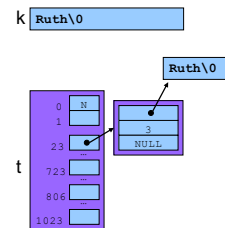
Why add 1?

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## How to Protect Keys?

Now consider same calling code:

```
struct Table *t;
char k[100] = "Ruth";
...
Table_add(t, k, 3);
```



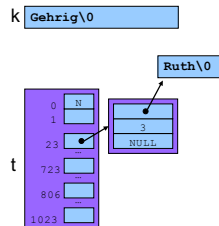
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## How to Protect Keys?

Now consider same calling code:

```
struct Table *t;
char k[100] = "Ruth";
...
Table_add(t, k, 3);
strcpy(k, "Gehrig");
```

Hash table is  
not corrupted



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## Who Owns the Keys?

Then the hash table **owns** its keys

- That is, the hash table owns the memory in which its keys reside
- `Hash_free()` function must free the memory in which the key resides

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## Summary

Common data structures and associated algorithms

- Linked list
  - (Maybe) fast add
  - Slow search
- Hash table
  - (Potentially) fast add
  - (Potentially) fast search
  - Very common

Hash table issues

- Hashing algorithms
- Defensive copies
- Key ownership

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## Princeton University

Computer Science 217: Introduction to Programming Systems

## Debugging (Part 2)



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## Agenda

- (9) Look for common DMM bugs
- (10) Diagnose seg faults using gdb
- (11) Manually inspect malloc calls
- (12) Hard-code malloc calls
- (13) Comment-out free calls
- (14) Use Meminfo
- (15) Use Valgrind

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## Look for Common DMM Bugs

Some of our favorites:

```
int *p; /* value of p undefined */
...
*p = somevalue;
```

```
char *p; /* value of p undefined */
...
fgets(p, 1024, stdin);
```

```
int *p;
...
p = (int*)malloc(sizeof(int));
...
*p = 5;
...
free(p);
...
*p = 6;
```

What are  
the errors?

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## Look for Common DMM Bugs

Some of our favorites:

```
int *p;
...
p = (int*)malloc(sizeof(int));
...
*p = 5;
...
p = (int*)malloc(sizeof(int));
```

```
int *p;
...
p = (int*)malloc(sizeof(int));
...
*p = 5;
...
free(p);
...
free(p);
```

What are the errors?

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## Agenda

- (9) Look for common DMM bugs
- (10) Diagnose seg faults using gdb**
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## Diagnose Seg Faults Using GDB

Segmentation fault => make it happen in gdb

- Then issue the gdb `where` command
- Output will lead you to the line that caused the fault
  - But that line may not be where the error resides!

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## Agenda

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- (15) Use Valgrind

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## Manually Inspect Malloc Calls

Manually inspect each call of `malloc()`

- Make sure it allocates enough memory

Do the same for `calloc()` and `realloc()`

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## Manually Inspect Malloc Calls

Some of our favorites:

```
char *s1 = "hello, world";
char *s2;
s2 = (char*)malloc(strlen(s1));
strcpy(s2, s1);
```

```
char *s1 = "Hello";
char *s2;
s2 = (char*)malloc(sizeof(s1));
strcpy(s2, s1);
```

```
long double *p;
p = (long double*)malloc(sizeof(long double*));
```

```
long double *p;
p = (long double*)malloc(sizeof(p));
```

What are the errors?

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## Agenda



- (9) Look for common DMM bugs
- (10) Diagnose seg faults using gdb
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- (12) Hard-code malloc calls**
- (13) Comment-out free calls
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- (15) Use Valgrind

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## Hard-Code Malloc Calls



Temporarily change each call of `malloc()` to request a large number of bytes

- Say, 10000 bytes
- If the error disappears, then at least one of your calls is requesting too few bytes

Then incrementally restore each call of `malloc()` to its previous form

- When the error reappears, you might have found the culprit

Do the same for `calloc()` and `realloc()`

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## Agenda



- (9) Look for common DMM bugs
- (10) Diagnose seg faults using gdb
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- (12) Hard-code malloc calls
- (13) Comment-out free calls**
- (14) Use Meminfo
- (15) Use Valgrind

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## Comment-Out Free Calls



Temporarily comment-out every call of `free()`

- If the error disappears, then program is
  - Freeing memory too soon, or
  - Freeing memory that already has been freed, or
  - Freeing memory that should not be freed,
  - Etc.

Then incrementally "comment-in" each call of `free()`

- When the error reappears, you might have found the culprit

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## Agenda



- (9) Look for common DMM bugs
- (10) Diagnose seg faults using gdb
- (11) Manually inspect malloc calls
- (12) Hard-code malloc calls
- (13) Comment-out free calls
- (14) Use Meminfo**
- (15) Use Valgrind

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## Use Meminfo



Use the **Meminfo** tool

- Simple tool
- Initial version written by Dondero
- Current version written by COS 217 alumnus RJ Lijestrom
- Reports errors **after** program execution
  - Memory leaks
  - Some memory corruption
- User-friendly output

Appendix 1 provides example buggy programs

Appendix 2 provides Meminfo analyses

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## Agenda

- (9) Look for common DMM bugs
- (10) Diagnose seg faults using gdb
- (11) Manually inspect malloc calls
- (12) Hard-code malloc calls
- (13) Comment-out free calls
- (14) Use Meminfo
- (15) Use Valgrind

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## Use Valgrind

### Use the Valgrind tool

- Complex tool
- Written by multiple developers, worldwide
  - See [www.valgrind.org](http://www.valgrind.org)
- Reports errors **during** program execution
  - Memory leaks
  - Multiple frees
  - Dereferences of dangling pointers
  - Memory corruption
- Comprehensive output
  - But not always user-friendly

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## Use Valgrind

Appendix 1 provides example buggy programs  
Appendix 3 provides Valgrind analyses

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## Summary

Strategies and tools for debugging the DMM aspects of your code:

- Look for common DMM bugs
- Diagnose seg faults using gdb
- Manually inspect malloc calls
- Hard-code malloc calls
- Comment-out free calls
- Use Meminfo
- Use Valgrind

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## Appendix 1: Buggy Programs

leak.c

```
1. #include <stdio.h>
2. #include <stdlib.h>
3. int main(void)
4. { int *pi;
5.   pi = (int*)malloc(sizeof(int));
6.   *pi = 5;
7.   printf("%d\n", *pi);
8.   pi = (int*)malloc(sizeof(int));
9.   *pi = 6;
10.  printf("%d\n", *pi);
11.  free(pi);
12.  return 0;
13. }
```

Memory leak:  
Memory allocated at line 5 is leaked

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## Appendix 1: Buggy Programs

doublefree.c

```
1. #include <stdio.h>
2. #include <stdlib.h>
3. int main(void)
4. { int *pi;
5.   pi = (int*)malloc(sizeof(int));
6.   *pi = 5;
7.   printf("%d\n", *pi);
8.   free(pi);
9.   free(pi);
10.  return 0;
11. }
```

Multiple free:  
Memory allocated at line 5 is freed twice

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## Appendix 1: Buggy Programs

danglingptr.c

```
1. #include <stdio.h>
2. #include <stdlib.h>
3. int main(void)
4. { int *pi;
5.   pi = (int*)malloc(sizeof(int));
6.   *pi = 5;
7.   printf("%d\n", *pi);
8.   free(pi);
9.   printf("%d\n", *pi);
10.  return 0;
11. }
```

Dereference of dangling pointer:  
Memory accessed at line 9 already was freed

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## Appendix 1: Buggy Programs

toosmall.c

```
1. #include <stdio.h>
2. #include <stdlib.h>
3. int main(void)
4. { int *pi;
5.   pi = (int*)malloc(1);
6.   *pi = 5;
7.   printf("%d\n", *pi);
8.   free(pi);
9.   return 0;
10. }
```

Memory corruption:  
Too little memory is allocated at line 5  
Line 6 corrupts memory

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## Appendix 2: Meminfo

Meminfo can detect memory leaks:

```
$ gcc217m leak.c -o leak
$ ./leak
5
6
$ ls
.. leak.c leak meminfo30462.out
$ meminfo report meminfo30462.out
Errors:
** 4 un-freed bytes (1 block) allocated at leak.c:5
Summary Statistics:
Maximum bytes allocated at once: 8
Total number of allocated bytes: 8
Statistics by Line:
      Bytes Location
-4 leak.c:11
4 leak.c:5
4 leak.c:8
4 TOTAL
Statistics by Compilation Unit:
4 leak.c
4 TOTAL
```

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## Appendix 2: Meminfo

Meminfo can detect memory corruption:

```
$ gcc217m toosmall.c -o toosmall
$ ./toosmall
5
6
$ ls
.. toosmall.c toosmall meminfo31891.out
$ meminfo report meminfo31891.out
Errors:
** Underflow detected at toosmall.c:8 for memory allocated at toosmall.c:5
Summary Statistics:
Maximum bytes allocated at once: 1
Total number of allocated bytes: 1
Statistics by Line:
      Bytes Location
1 toosmall.c:5
-1 toosmall.c:8
0 TOTAL
Statistics by Compilation Unit:
0 toosmall.c
0 TOTAL
```

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## Appendix 2: Meminfo

Meminfo caveats:

- Don't mix .o files built with gcc217 and gcc217m
- meminfo\*.out files can be large
  - Should delete frequently
- Programs built with gcc217m run slower than those built with gcc217
  - Don't build with gcc217m when doing timing tests

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## Appendix 3: Valgrind

Valgrind can detect memory leaks:

```
$ gcc217 leak.c -o leak
$ valgrind ./leak
==31921== Memcheck, a memory error detector
==31921== Copyright (C) 2002-2012, and GNU GPL'd, by Julian Seward et al.
==31921== Using Valgrind-3.8.1 and LibVEX; rerun with -h for copyright info
==31921== Command: leak
==31921==
5
6
==31921==
==31921== HEAP SUMMARY:
==31921==   in use at exit: 4 bytes in 1 blocks
==31921==   total heap usage: 2 allocs, 1 frees, 8 bytes allocated
==31921==
==31921== LEAK SUMMARY:
==31921==   definitely lost: 4 bytes in 1 blocks
==31921==   indirectly lost: 0 bytes in 0 blocks
==31921==   possibly lost: 0 bytes in 0 blocks
==31921==   still reachable: 0 bytes in 0 blocks
==31921==   suppressed: 0 bytes in 0 blocks
==31921== Rerun with --leak-check=full to see details of leaked memory
==31921==
==31921== For counts of detected and suppressed errors, rerun with: -v
==31921== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 6 from 6)
```

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## Appendix 3: Valgrind

Valgrind can detect memory leaks:

```
$ valgrind --leak-check=full ./leak
==476== Memcheck, a memory error detector
==476== Copyright (C) 2002-2012, and GNU GPL'd, by Julian Seward et al.
==476== Using Valgrind-3.8.1 and LibVEX; rerun with -h for copyright info
==476== Command: leak
==476==
5
6
==476==
==476== HEAP SUMMARY:
==476==   in use at exit: 4 bytes in 1 blocks
==476==   total heap usage: 2 allocs, 1 frees, 8 bytes allocated
==476==
==476== 4 bytes in 1 blocks are definitely lost in loss record 1 of 1
==476==   at 0x4A069EE: malloc (vg_replace_malloc.c:270)
==476==   by 0x400565: main (leak.c:5)
==476==
==476== LEAK SUMMARY:
==476==   definitely lost: 4 bytes in 1 blocks
==476==   indirectly lost: 0 bytes in 0 blocks
==476==   possibly lost: 0 bytes in 0 blocks
==476==   still reachable: 0 bytes in 0 blocks
==476==   suppressed: 0 bytes in 0 blocks
==476==
==476== For counts of detected and suppressed errors, rerun with: -v
==476== ERROR SUMMARY: 1 errors from 1 contexts (suppressed: 6 from 6)
```

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## Appendix 3: Valgrind

Valgrind can detect multiple frees:

```
$ gcc217 doublefree.c -o doublefree
$ valgrind ./doublefree
==31951== Memcheck, a memory error detector
==31951== Copyright (C) 2002-2012, and GNU GPL'd, by Julian Seward et al.
==31951== Using Valgrind-3.8.1 and LibVEX; rerun with -h for copyright info
==31951== Command: doublefree
==31951==
5
==31951== Invalid free() / delete / delete[] / realloc()
==31951==   at 0x4A063F0: free (vg_replace_malloc.c:446)
==31951==   by 0x4005A5: main (doublefree.c:9)
==31951== Address 0x4c2a040 is 0 bytes inside a block of size 4 free'd
==31951==   at 0x4A063F0: free (vg_replace_malloc.c:446)
==31951==   by 0x400599: main (doublefree.c:8)
==31951==
==31951== HEAP SUMMARY:
==31951==   in use at exit: 0 bytes in 0 blocks
==31951==   total heap usage: 1 allocs, 2 frees, 4 bytes allocated
==31951==
==31951== All heap blocks were freed -- no leaks are possible
==31951==
==31951== For counts of detected and suppressed errors, rerun with: -v
==31951== ERROR SUMMARY: 1 errors from 1 contexts (suppressed: 6 from 6)
```

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## Appendix 3: Valgrind

Valgrind can detect dereferences of dangling pointers:

```
$ gcc217 danglingptr.c -o danglingptr
$ valgrind ./danglingptr
==336== Memcheck, a memory error detector
==336== Copyright (C) 2002-2012, and GNU GPL'd, by Julian Seward et al.
==336== Using Valgrind-3.8.1 and LibVEX; rerun with -h for copyright info
==336== Command: danglingptr
==336==
5
==336== Invalid read of size 4
==336==   at 0x40059E: main (danglingptr.c:9)
==336== Address 0x4c2a040 is 0 bytes inside a block of size 4 free'd
==336==   at 0x4A063F0: free (vg_replace_malloc.c:446)
==336==   by 0x400599: main (danglingptr.c:8)
==336==
==336==
==336== HEAP SUMMARY:
==336==   in use at exit: 0 bytes in 0 blocks
==336==   total heap usage: 1 allocs, 1 frees, 4 bytes allocated
==336==
==336== All heap blocks were freed -- no leaks are possible
==336==
==336== For counts of detected and suppressed errors, rerun with: -v
==336== ERROR SUMMARY: 1 errors from 1 contexts (suppressed: 6 from 6)
```

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## Appendix 3: Valgrind

Valgrind can detect memory corruption:

```
$ gcc217 toomall.c -o toomall
$ valgrind ./toomall
==436== Memcheck, a memory error detector
==436== Copyright (C) 2002-2012, and GNU GPL'd, by Julian Seward et al.
==436== Using Valgrind-3.8.1 and LibVEX; rerun with -h for copyright info
==436== Command: toomall
==436==
==436== Invalid write of size 4
==436==   at 0x40056E: main (toomall.c:6)
==436== Address 0x4c2a040 is 0 bytes inside a block of size 1 alloc'd
==436==   at 0x4A069EE: malloc (vg_replace_malloc.c:270)
==436==   by 0x400565: main (toomall.c:5)
==436==
==436== Invalid read of size 4
==436==   at 0x400578: main (toomall.c:7)
==436== Address 0x4c2a040 is 0 bytes inside a block of size 1 alloc'd
==436==   at 0x4A069EE: malloc (vg_replace_malloc.c:270)
==436==   by 0x400565: main (toomall.c:5)
==436==
5
```

Continued on next slide

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## Appendix 3: Valgrind

Valgrind can detect memory corruption (cont.):

Continued from previous slide

```
==436==
==436== HEAP SUMMARY:
==436==   in use at exit: 0 bytes in 0 blocks
==436==   total heap usage: 1 allocs, 1 frees, 1 bytes allocated
==436==
==436== All heap blocks were freed -- no leaks are possible
==436==
==436== For counts of detected and suppressed errors, rerun with: -v
==436== ERROR SUMMARY: 2 errors from 2 contexts (suppressed: 6 from 6)
```

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## Appendix 3: Valgrind

Valgrind caveats:

- Not intended for programmers who are new to C
  - Messages may be cryptic
- Suggestion:
  - Observe line numbers referenced by messages
  - Study code at those lines
  - Infer meanings of messages

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