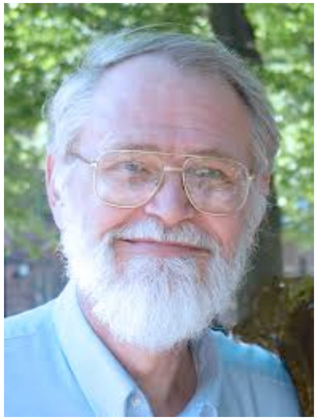
# Data Structures

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

-- Kernighan & Pike



# 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 mature programmer:
  - Rarely creates programs from scratch
  - Often creates programs using high level building blocks

Why? Shallow motivation:

- Provide background pertinent to Assignment 3
- … especially for those who haven’t taken COS 226
- … especially for those who skipped COS 126

# 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, class year)
  - ("Andrew Appel", 81), ("Jen Rexford", 91), ("JP Singh", 87)
- (baseball player, number)
  - ("Ruth", 3), ("Gehrig", 4), ("Mantle", 7)
- (variable name, value)
  - ("maxLength", 2000), ("i", 7), ("j", -10)

# Agenda

**Linked lists**

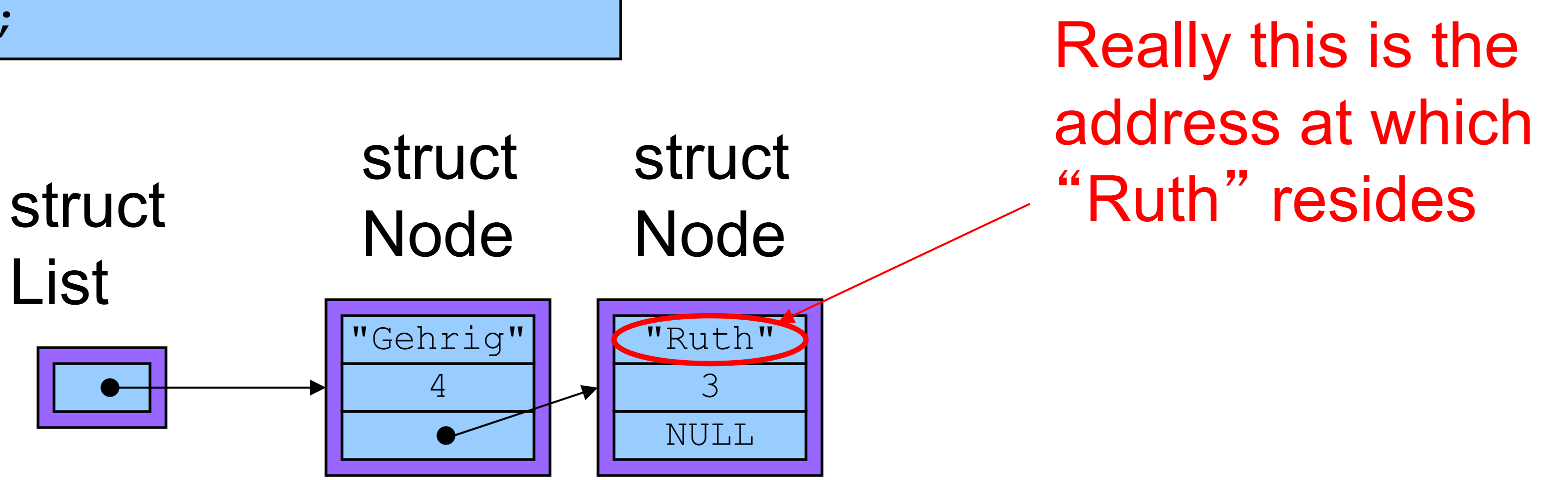
Hash tables

Hash table issues

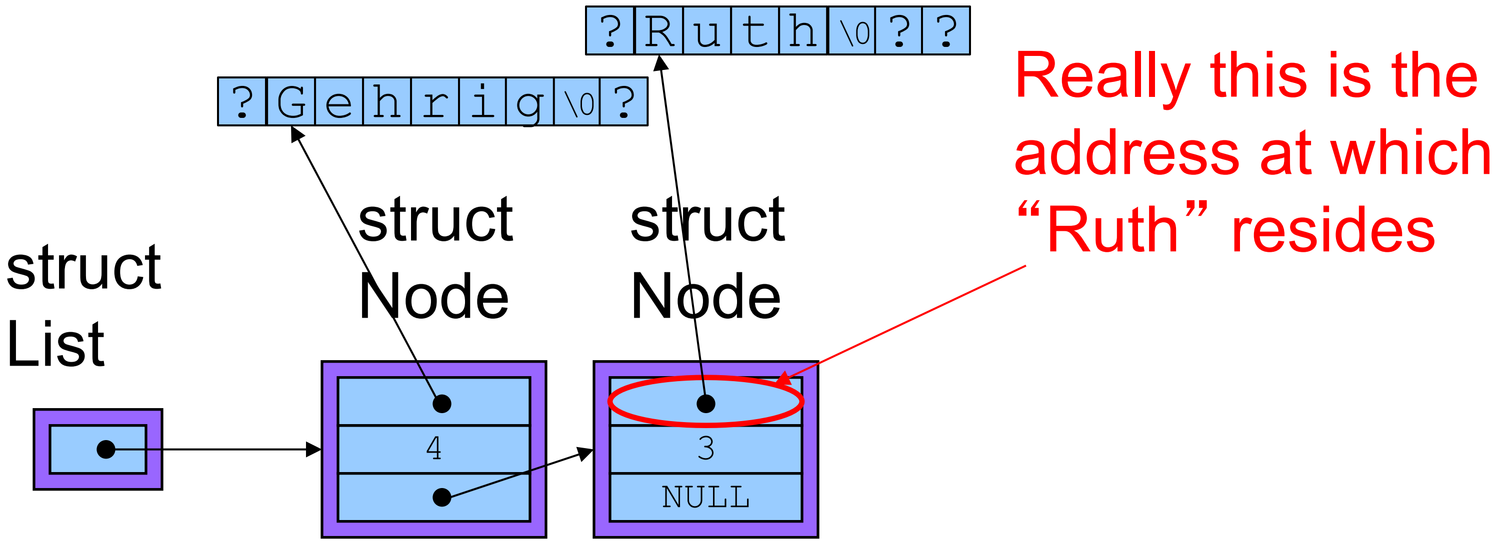
# Linked List Data Structure

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

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

Your Assignment 3 data structures will be more elaborate



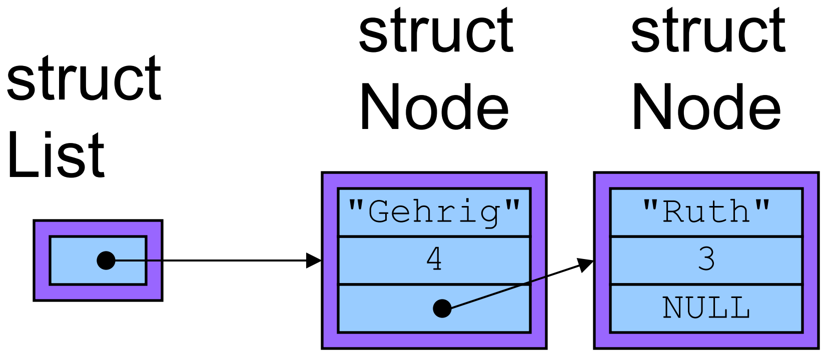
# Linked List Data Structure



# Accessing a Linked List

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

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

```
struct List lineup;
struct Node g;
struct Node* r = malloc(…);
g.key = "Gehrig";
lineup.first = &g;
(*lineup.first).value = 4;
lineup.first->value = 4;
(*lineup.first).next = r;
lineup.first->next = r;
```



# Linked List Algorithms

## Create

- Allocate **`List`** structure; set **`first`** to **`NULL`**
- Performance: O(1) ⇒ fast

## Add (no check for duplicate key required)

- Insert new node containing key/value pair at front of list
- Performance: O(1) ⇒ 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) ⇒ slow

# Linked List Algorithms

## Search

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

# 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) ⇒ slow

## Free

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

# Agenda

Linked lists

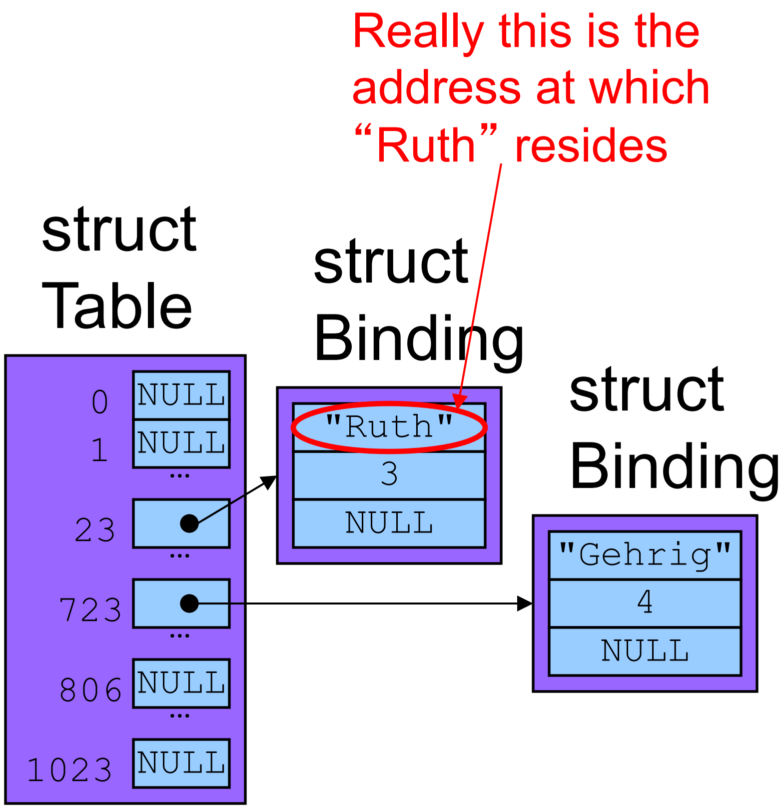
**Hash tables**

Hash table issues

# Hash Table Data Structure

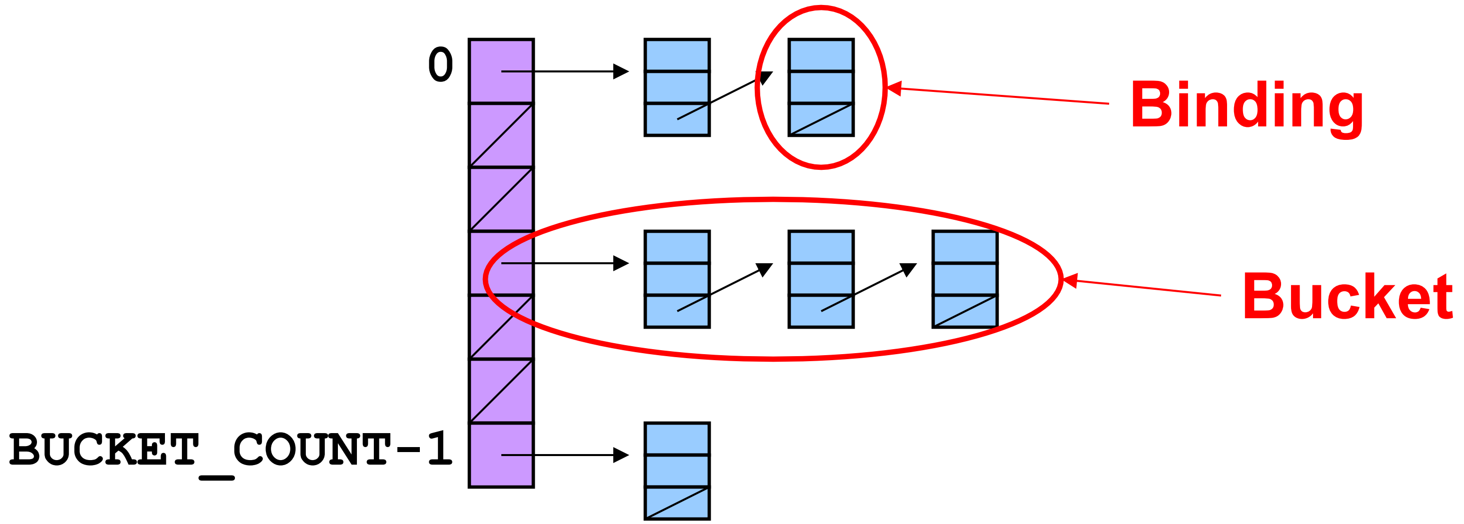
## Array of linked lists

```
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

# Hash Table Data Structure




**Hash function** maps given key to an integer

Mod integer by **`BUCKET_COUNT`** to determine proper bucket

# Hash Table Example

Example: **`BUCKET_COUNT`** = 7

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

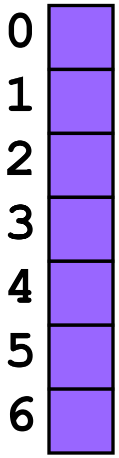
- the, cat, in, the, hat

# Hash Table Example (cont.)

First key: "the"

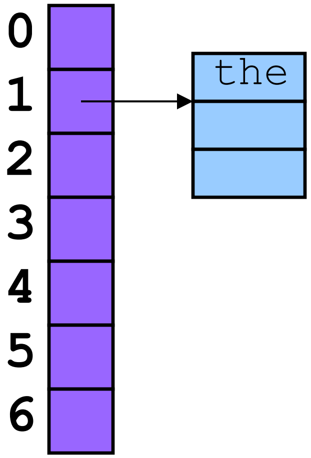
- hash("the") = 965156977; 965156977 % 7 = 1

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



# Hash Table Example (cont.)

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

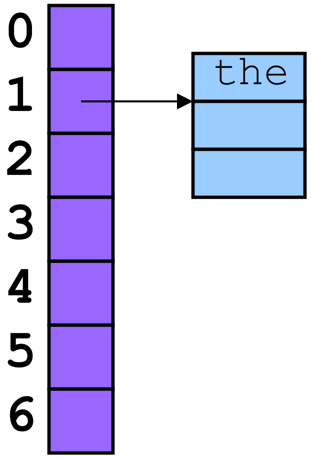


# Hash Table Example (cont.)

Second key: "cat"

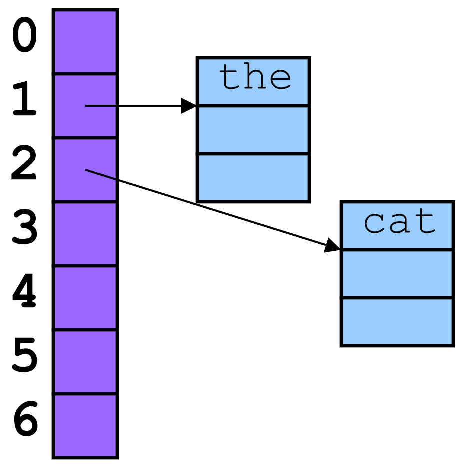
- hash("cat") = 3895848756; 3895848756 % 7 = 2

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



# Hash Table Example (cont.)

Add binding with key “cat” and its value to **`buckets[2]`**

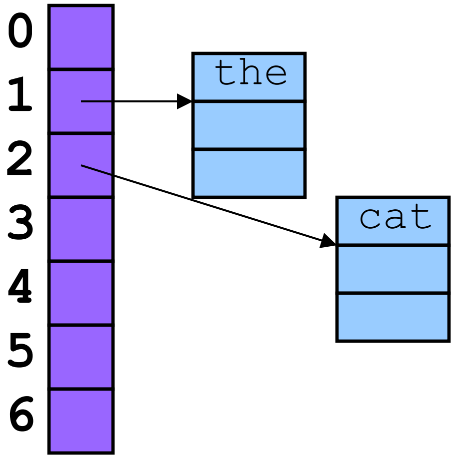


# Hash Table Example (cont.)

Third key: "in"

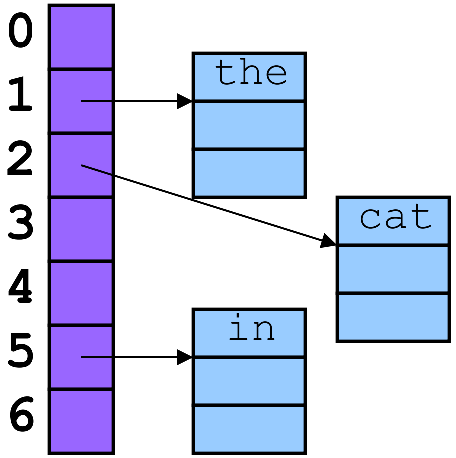
- hash("in") = 6888005; 6888005% 7 = 5

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



# Hash Table Example (cont.)

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



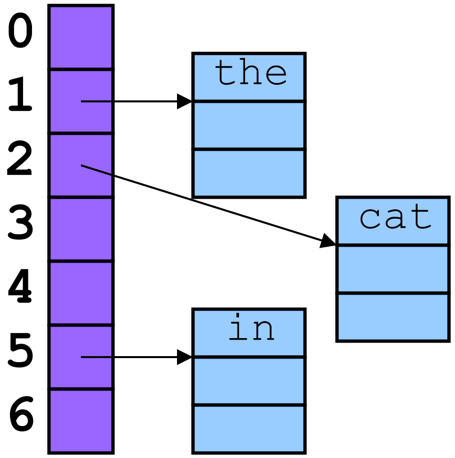
# Hash Table Example (cont.)

Fourth word: “the”

- hash(“the”) = 965156977; 965156977 % 7 = 1

Search **`buckets[1]`** for binding with key “the”; found it!

- Don’t change hash table

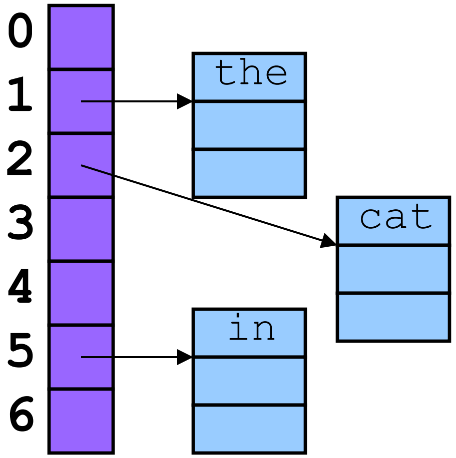


# Hash Table Example (cont.)

Fifth key: "hat"

- hash("hat") = 865559739; 865559739 % 7 = 2

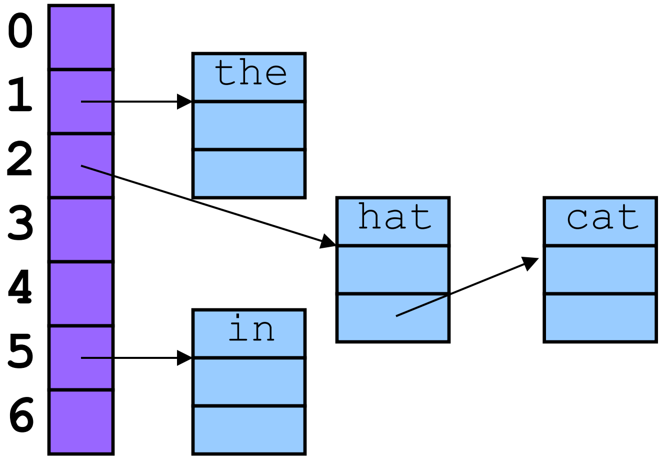
Search **`buckets[2]`** for binding with key "hat"; not found



# Hash Table Example (cont.)

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

- At front or back?



# Hash Table Algorithms

## Create

- Allocate **`Table`** structure; set each bucket to **`NULL`**
- Performance: O(1) ⇒ 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: ???

# 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) ⇒ fast

Free

- Traverse each bucket, freeing bindings
- Free **`Table`** structure
- Performance: O(n) ⇒ slow

# Agenda

Linked lists

Hash tables

**Hash table issues**

# How Many Buckets?

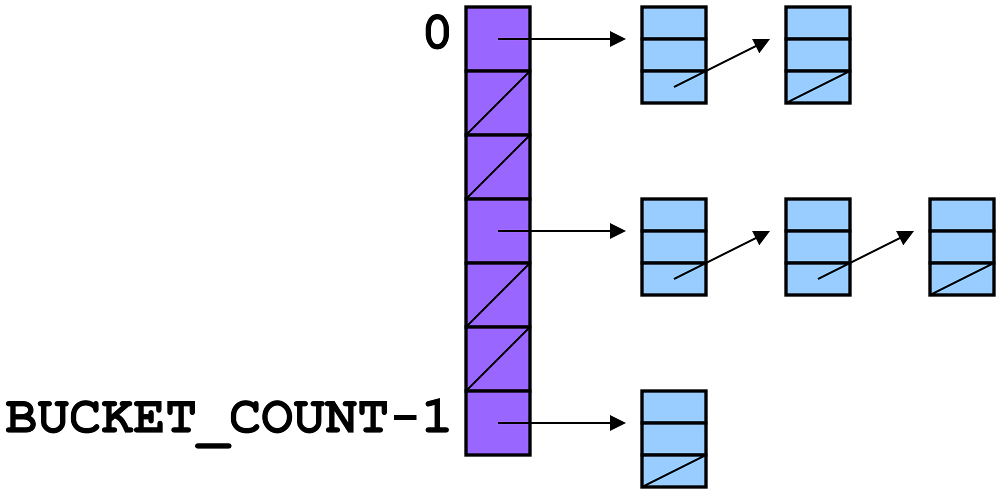
Many!

- Too few ⇒ large buckets ⇒ slow add, slow search

But not too many!

- Too many ⇒ memory is wasted

This is OK:

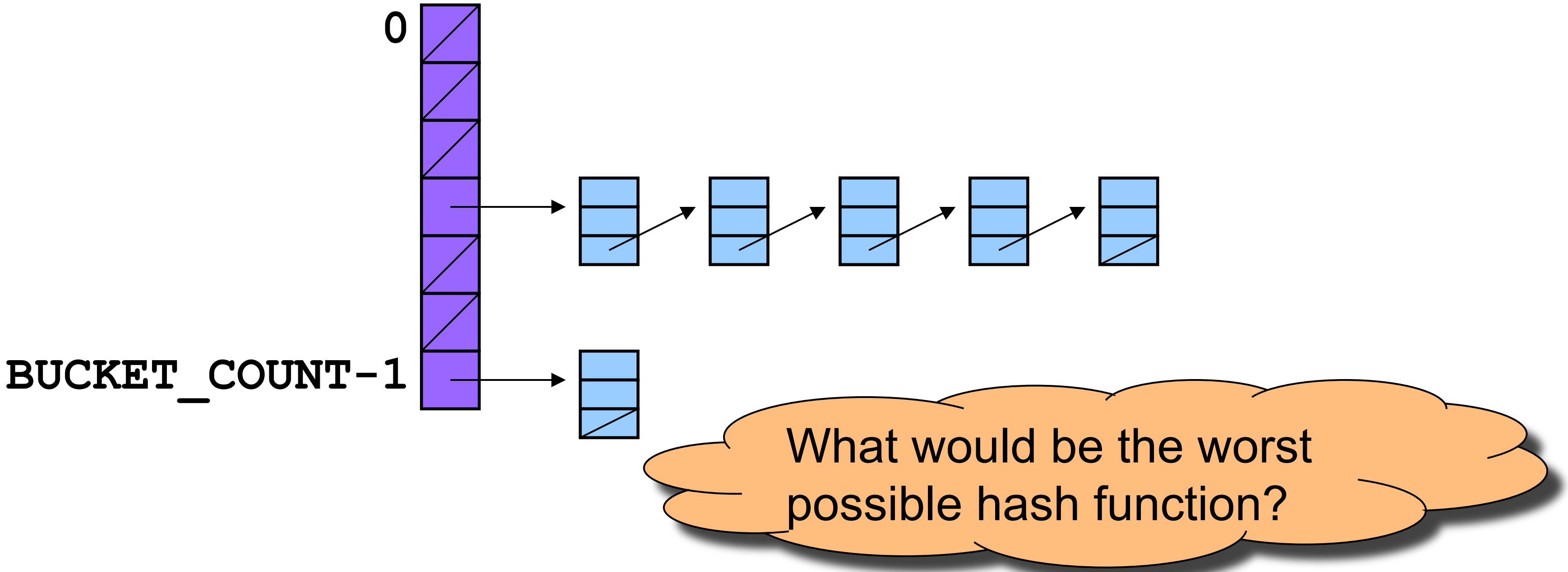


# What Hash Function?

Should distribute bindings across the buckets well

- Distribute bindings over the range `0, 1, …, BUCKET_COUNT-1`
- Distribute bindings *evenly* to avoid very long buckets

This is not so good:



# 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**
  - $(\Sigma\ a^i s_i)$ **mod BUCKET_COUNT**
- Best if **a** and **BUCKET_COUNT** are relatively prime
  - E.g., **a** = 65599, **BUCKET_COUNT** = 1024

# 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;
}
```

# How to Protect Keys?

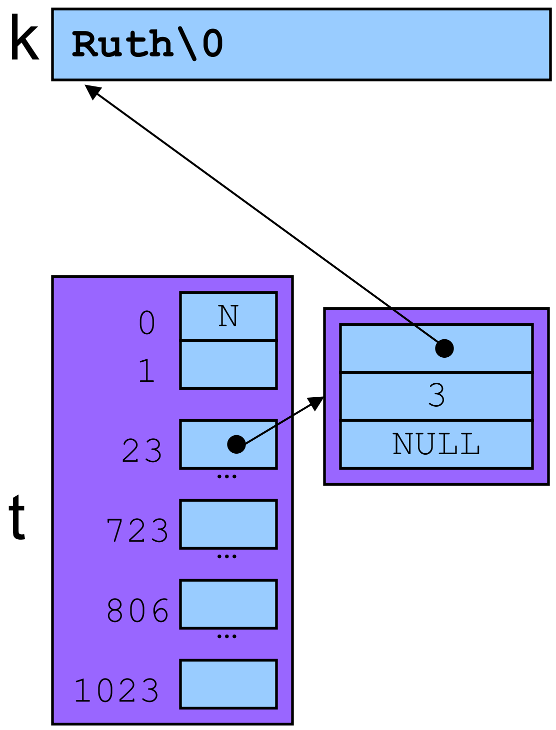
Suppose **`Table_add()`** function contains this code:

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

# How to Protect Keys?

Problem: Consider this calling code:

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



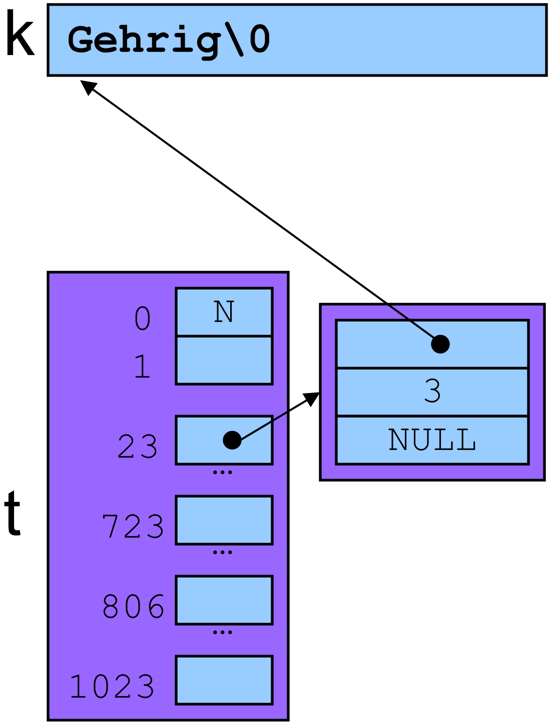
# How to Protect Keys?

Problem: Consider this calling code:

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

k is REALLY &k[0]!

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



# How to Protect Keys?

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

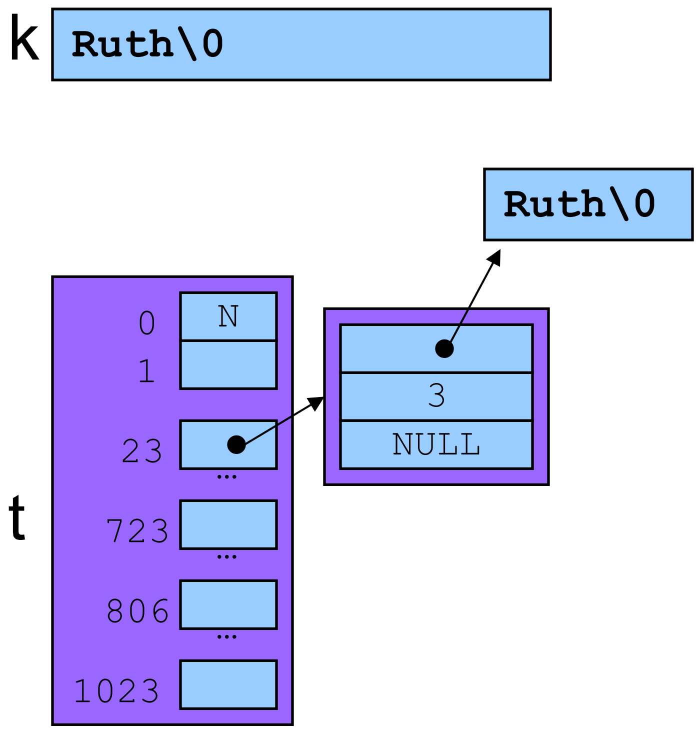
```
void Table_add(struct Table *t, const char *key, int value)
{   …
    struct Binding *p =
        (struct Binding*)malloc(sizeof(struct Binding));
    p->key = (const char*)malloc(strlen(key) + 1);
    strcpy((char*)p->key, key);
    …
}
```

Why add 1?

# How to Protect Keys?

Now consider same calling code:

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

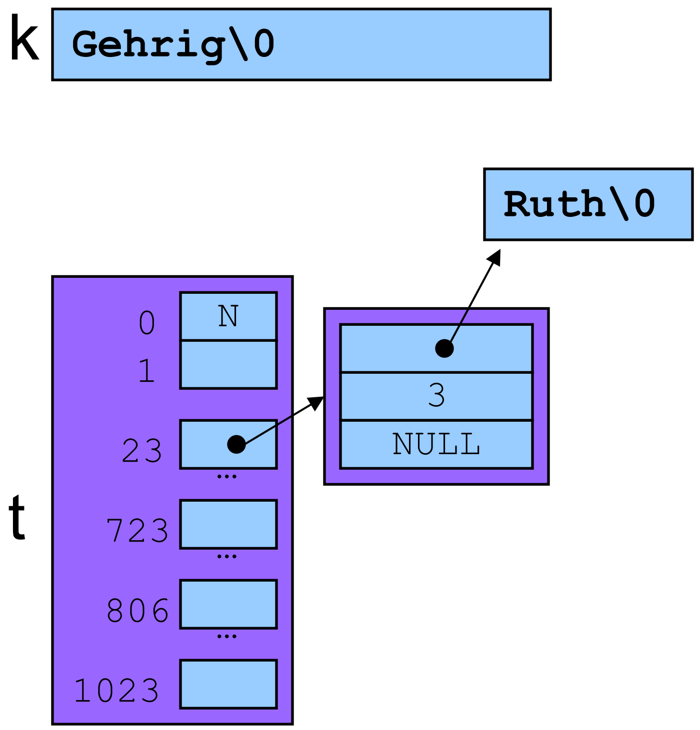


# How to Protect Keys?

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



# 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

# 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

# Debugging (Part 2)

# 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

# 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?

# 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?

# 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!

# 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

# Manually Inspect Malloc Calls

Manually inspect each call of `malloc()`

- Make sure it allocates enough memory

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

# 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?

# 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

# 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()`**

# 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

# 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

# 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

# Use Meminfo

Use the **Meminfo** tool

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

Appendix 1 provides example buggy programs

Appendix 2 provides Meminfo analyses

# 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**

# Use Valgrind

## Use the **Valgrind** tool

- Complex tool
- Written by multiple developers, worldwide
  - See 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

# Use Valgrind

Appendix 1 provides example buggy programs

Appendix 3 provides Valgrind analyses

# 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

# 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

# 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

# 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

# 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

# Appendix 2: Meminfo

Meminfo can detect memory leaks:

```
$ gcc217m leak.c -o leak
$ ./leak
5
6
$ ls
.  ..  leak.c  leak  meminfo30462.out
$ meminforeport 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
```

# Appendix 2: Meminfo

## Meminfo can detect memory corruption:

```
$ gcc217m toosmall.c -o toosmall
$ ./toosmall
5
$ ls
.  ..  toosmall.c  toosmall  meminfo31891.out
$ meminforeport 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
```

# 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

# 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)
```

# 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)
```

# 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==
==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)
```

# 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==
5
==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)
```

# Appendix 3: Valgrind

## Valgrind can detect memory corruption:

```
$ gcc217 toosmall.c -o toosmall
$ valgrind ./toosmall
==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: toosmall
==436==
==436== Invalid write of size 4
==436==    at 0x40056E: main (toosmall.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 (toosmall.c:5)
==436==
==436== Invalid read of size 4
==436==    at 0x400578: main (toosmall.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 (toosmall.c:5)
==436==
5
```

Continued on next slide

# 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)
```

# 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