



# Data Structures

# “Programming in the Large” Steps



## Design & Implement

- Program & programming style (done)
- Common data structures and algorithms <-- we are here
- Modularity
- Building techniques & tools (done)

## Debug

- Debugging techniques & tools (done)

## Test

- Testing techniques (done)

## Maintain

- Performance improvement techniques & tools



# 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

# Common Task



## Maintain a collection of key/value pairs

- Each key is a **string**; each value is an **int**
- 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)

# Agenda



**Linked lists**

Hash tables

Hash table issues



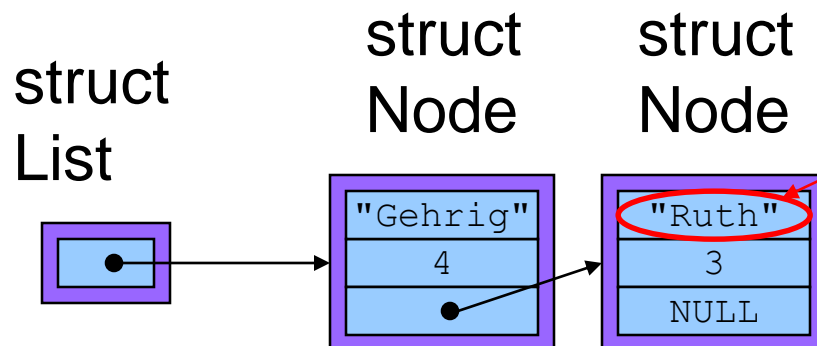
# Linked List Data Structure

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

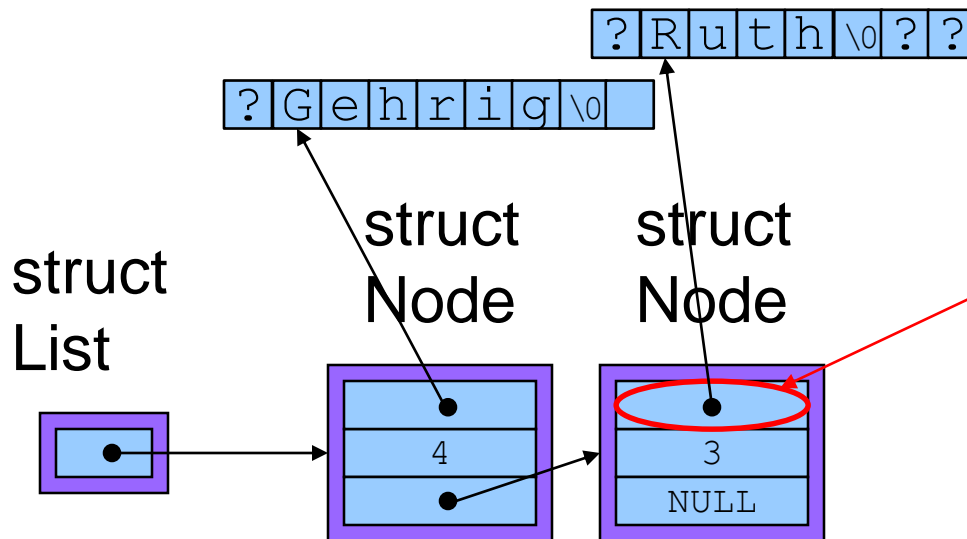
struct List
{  struct Node *first;
};
```

Your Assignment 3 data structures will be more elaborate

Really this is the address at which "Ruth" resides



# Linked List Data Structure



Really this is the address at which "Ruth" resides



# 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





# 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

Would it be better to keep the nodes sorted by key?

# Agenda



Linked lists

**Hash tables**

Hash table issues

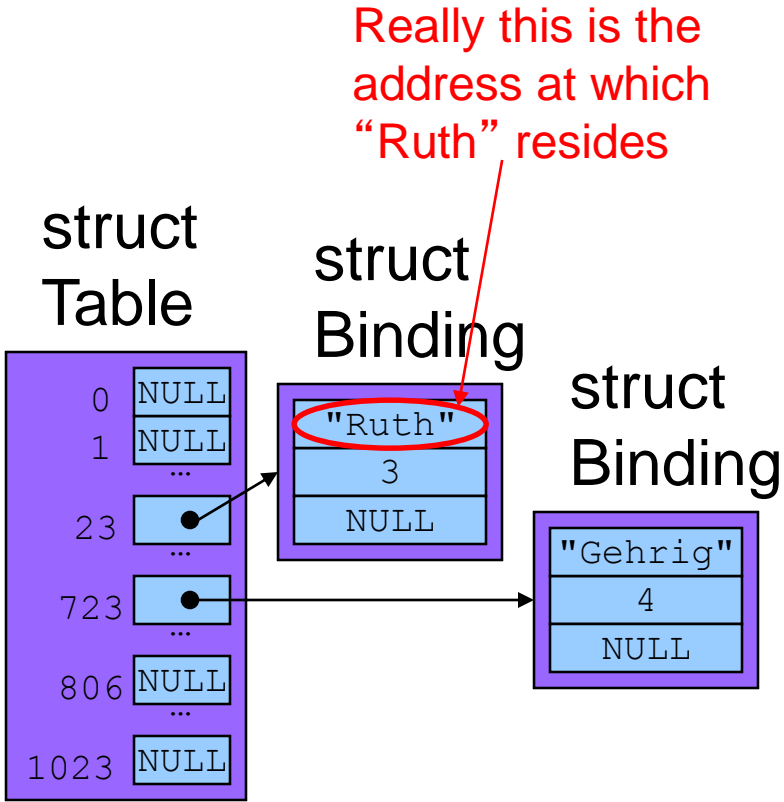


# Hash Table Data Structure

## Array of linked lists

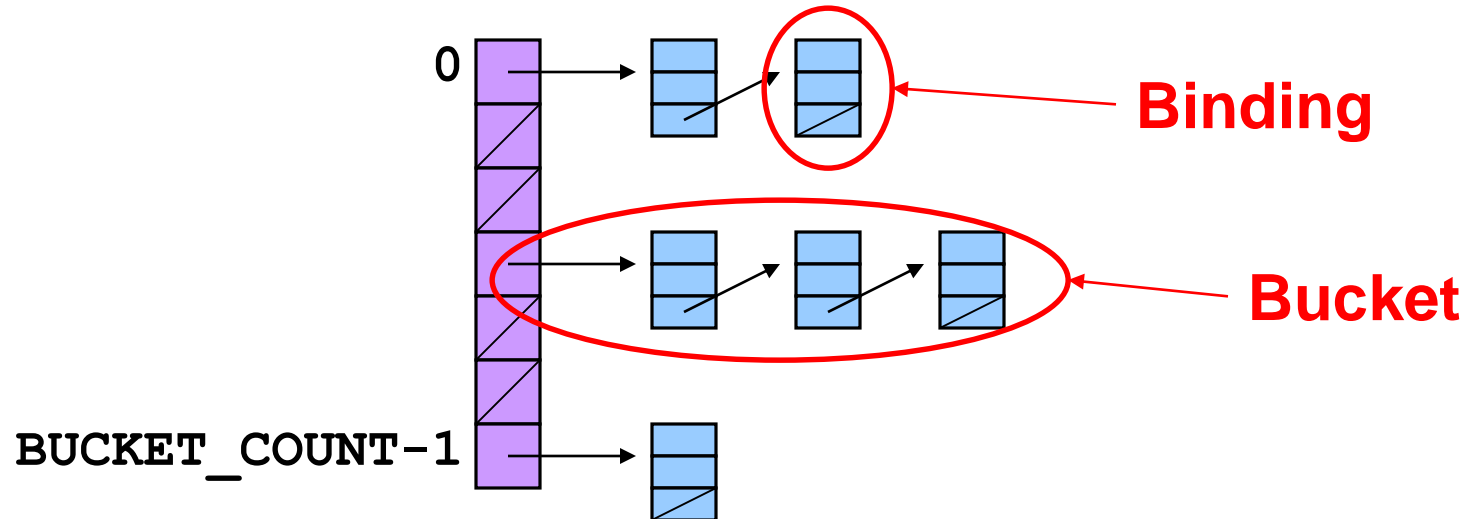
```
enum {BUCKET_COUNT = 1024};  
  
struct Binding  
{  const char *key;  
   int value;  
   struct Binding *next;  
};  
  
struct Table  
{  struct Binding *buckets[BUCKET_COUNT];  
};
```

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

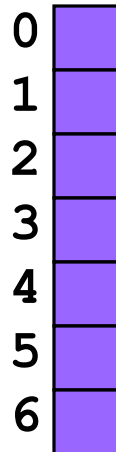


# Hash Table Example (cont.)

First key: “the”

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

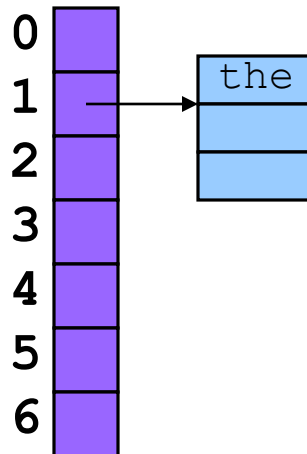
Search **buckets [1]** for binding with key “the”; not found



# Hash Table Example (cont.)



Add binding with key “the” and its value to **buckets [1]**



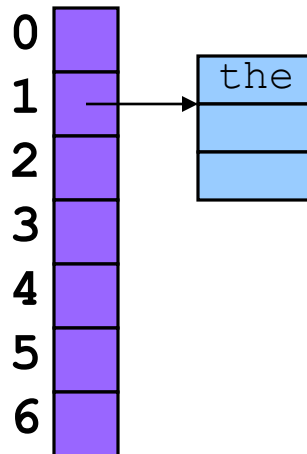


# Hash Table Example (cont.)

Second key: “cat”

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

Search **buckets [2]** for binding with key “cat”; not found

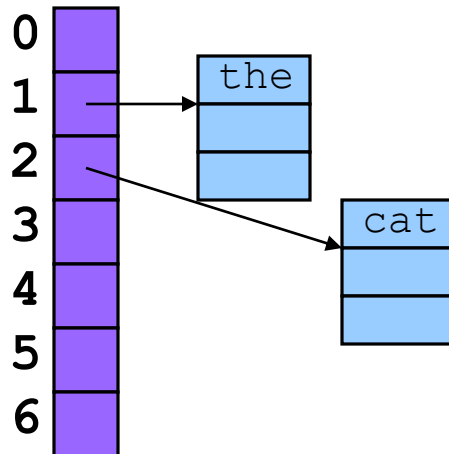




# Hash Table Example (cont.)



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



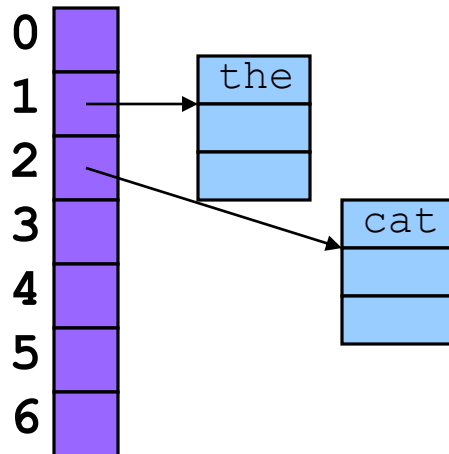


# Hash Table Example (cont.)

Third key: “in”

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

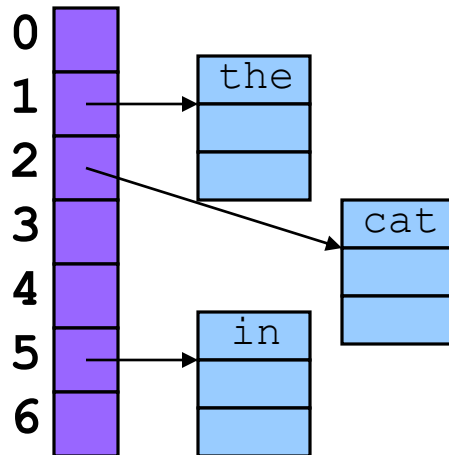
Search **buckets [5]** for binding with key “in”; not found





# Hash Table Example (cont.)

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





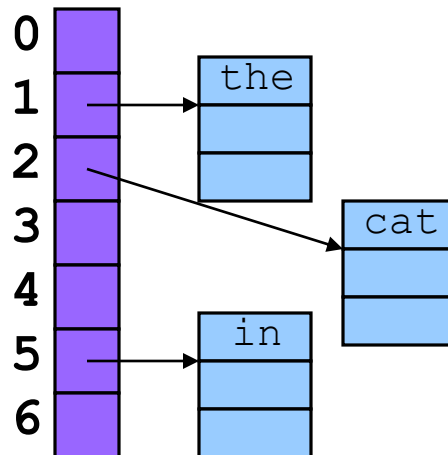
# Hash Table Example (cont.)

Fourth word: “the”

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

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

- Don't change hash table



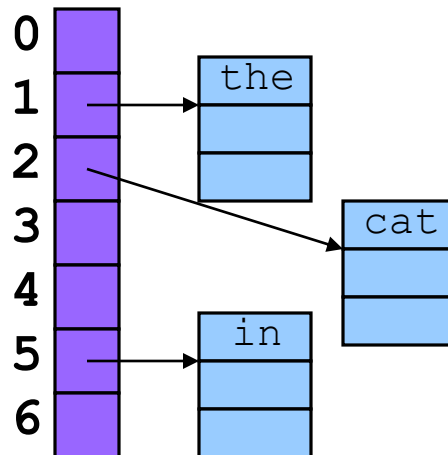


# Hash Table Example (cont.)

Fifth key: “hat”

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

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

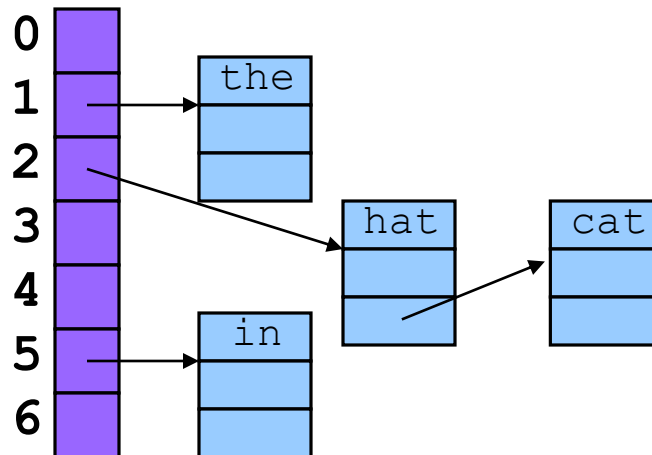




# Hash Table Example (cont.)

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

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





# 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:  $O(1) \Rightarrow$  fast

Is the add performance always fast?



# 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:  $O(1) \Rightarrow$  fast

## Free

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

Is the search performance always fast?



# Agenda



Linked lists

Hash tables

**Hash table issues**



# How Many Buckets?

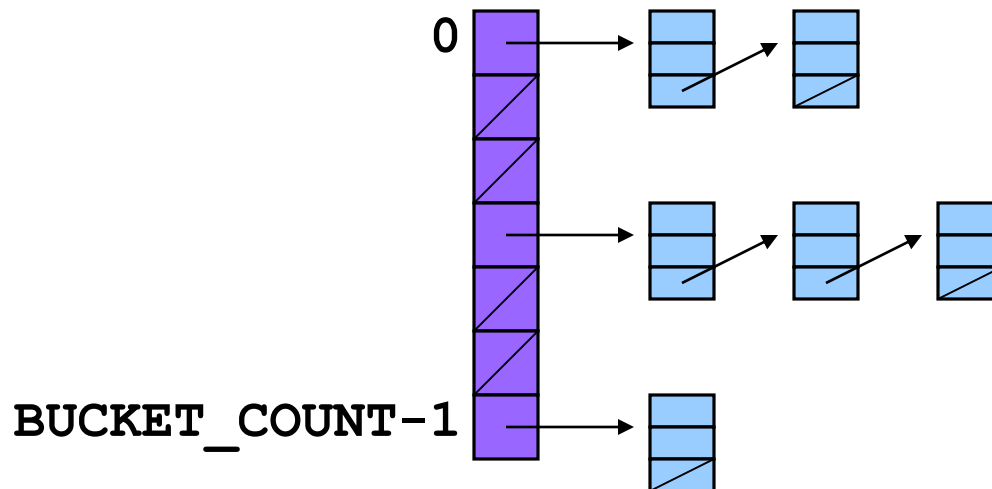
Many!

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

But not too many!

- Too many  $\Rightarrow$  memory is wasted

This is OK:

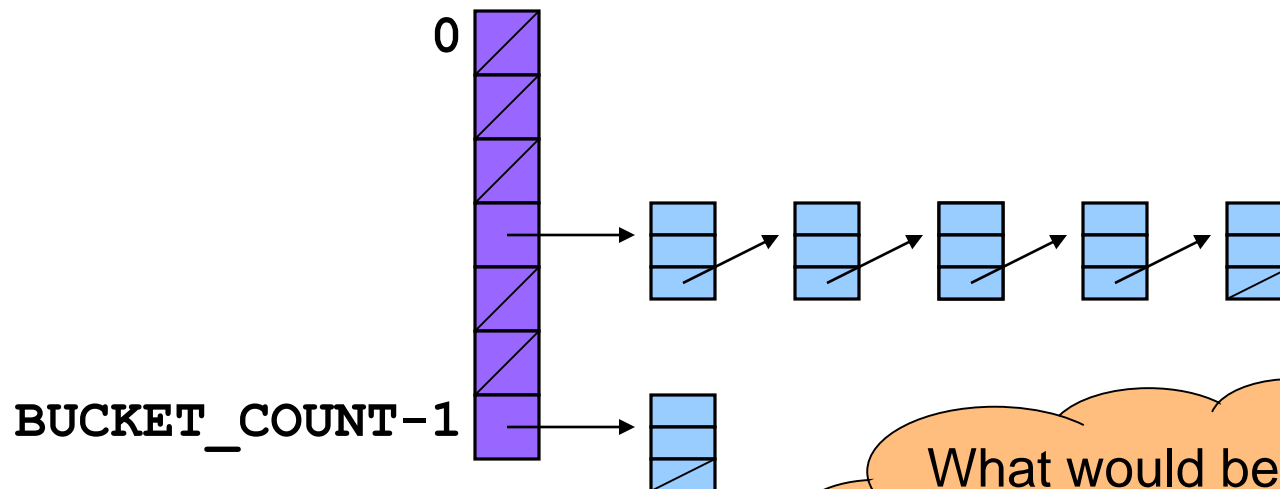


# What Hash Function?

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:



What would be the worst possible hash function?



# How to Hash Strings?

Simple hash schemes don't distribute the keys evenly enough

- 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.,  $a = 65599$ , **BUCKET\_COUNT** = 1024

Why?



# How to Hash Strings?

Potentially expensive to compute  $\sum a^i s_i$

So let's do some algebra ("Horner's rule")

- (by example, for string  $s$  of length 5,  $a=65599$ ):

$$h = \sum 65599^i * s_i$$

$$h = 65599^0 * s_0 + 65599^1 * s_1 + 65599^2 * s_2 + 65599^3 * s_3 + 65599^4 * s_4$$

Direction of traversal of  $s$  doesn't matter, so...

$$h = 65599^0 * s_4 + 65599^1 * s_3 + 65599^2 * s_2 + 65599^3 * s_1 + 65599^4 * s_0$$

$$h = 65599^4 * s_0 + 65599^3 * s_1 + 65599^2 * s_2 + 65599^1 * s_3 + 65599^0 * s_4$$

$$h = (((((s_0) * 65599 + s_1) * 65599 + s_2) * 65599 + s_3) * 65599) + s_4$$

# How to Hash Strings?



Yielding this function

```
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:

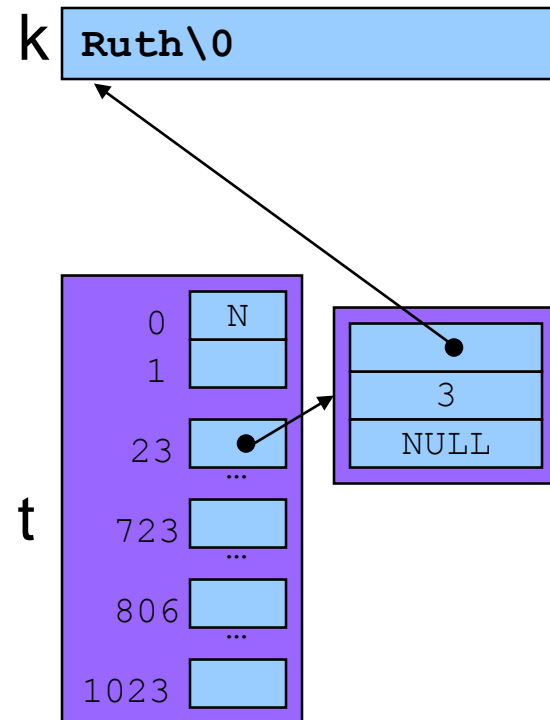
```
void Table_add(struct Table *t, const char *key, int value)
{
    ...
    struct Binding *p =
        (struct Binding*)malloc(sizeof(struct Binding));
    p->key = key;
    ...
}
```



# How to Protect Keys?

Problem: Consider this calling code:

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





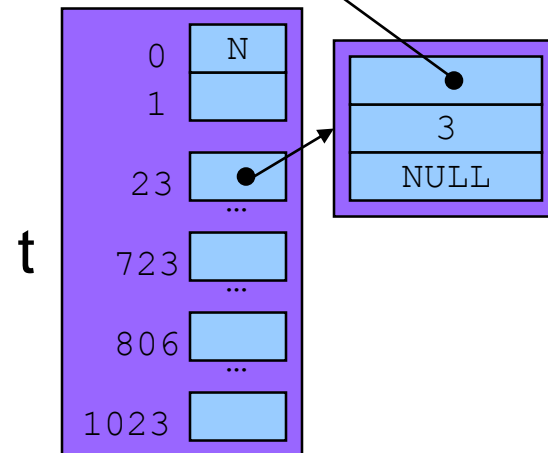


# How to Protect Keys?

Problem: Consider this calling code:

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

k Gehrig\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?

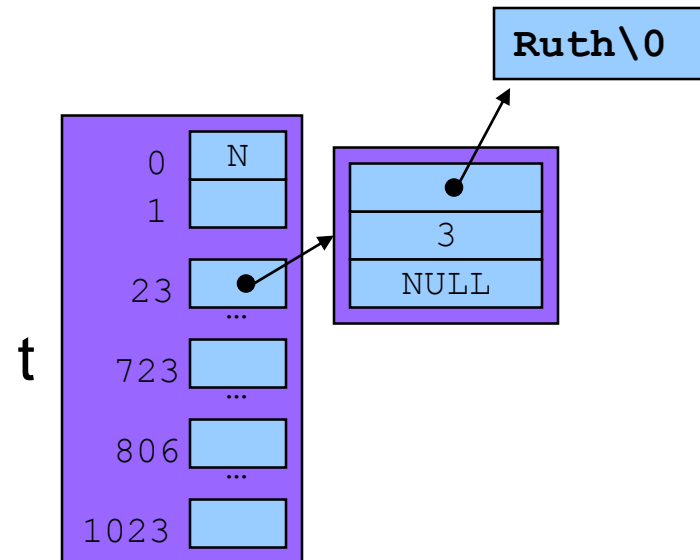


# How to Protect Keys?

Now consider same calling code:

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

k Ruth\0



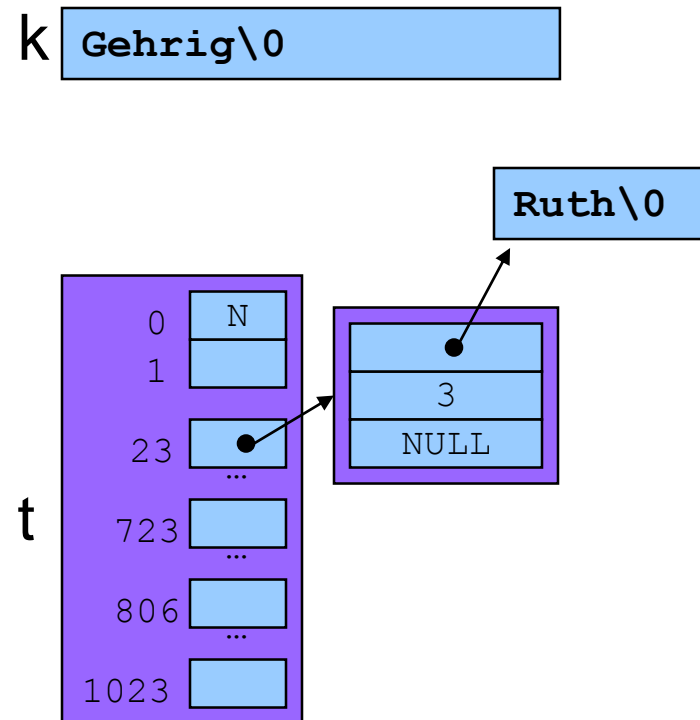


# How to Protect Keys?

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)



# “Programming in the Large” Steps



## Design & Implement

- Program & programming style (done)
- Common data structures and algorithms
- Modularity
- Building techniques & tools (done)

## Test

- Testing techniques (done)

## Debug

- Debugging techniques & tools <-- we are still here

## Maintain

- Performance improvement techniques & tools





# Goals of this Lecture

## Help you learn about:

- Debugging strategies & tools related to **dynamic memory management (DMM)** \*

## Why?

- Many bugs occur in code that does DMM
- DMM errors can be difficult to find
  - DMM error in one area can manifest itself in a distant area
- A power programmer knows a wide variety of DMM debugging **strategies**
- A power programmer knows about **tools** that facilitate DMM debugging

\* Management of heap memory via **malloc()**, **calloc()**, **realloc()**, and **free()**

# 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**

(11) Manually inspect malloc calls

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(14) Use Meminfo

(15) Use Valgrind

# Diagnose Seg Faults Using GDB



Segmentation fault  $\Rightarrow$  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
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- (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](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

# 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