

COS 217: Introduction to Programming Systems

Data Structures

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

– Kernighan & Pike



PRINCETON UNIVERSITY



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 Data Structure

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

Symbol table key ownership

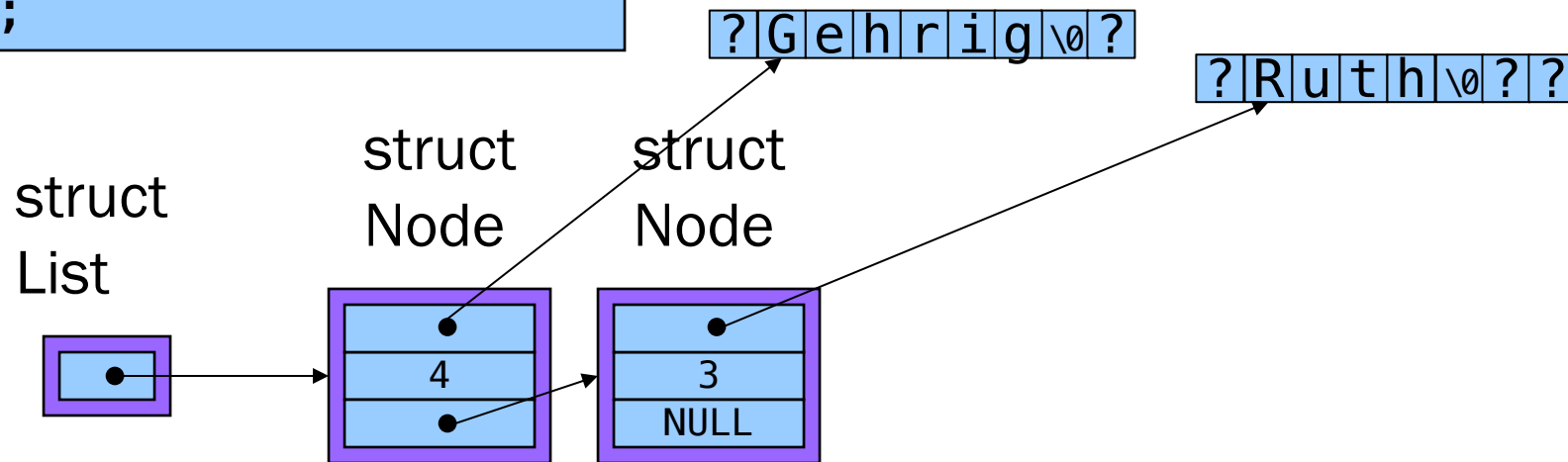


Linked List Data Structure (for a Symbol Table)

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

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

Your Assignment 3
data structures will
be more general and
perhaps more elaborate



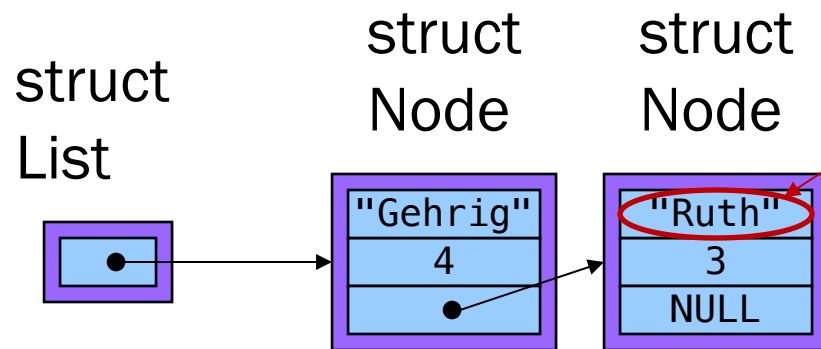


Linked List Data Structure

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

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

Your Assignment 3
data structures will
be more general and
perhaps more elaborate



Really this is the
address at which
a string with
contents "Ruth"
resides



Preview of A3/Lecture 12: Encapsulation (wrong!)

list.h

```
struct Node {const char* key; int value; struct Node *next;};  
struct List {struct Node *first;};  
  
struct List *new();  
void insert(struct List *p, const char* key, int value);  
void concat(struct List *p,  
            struct List *q);  
int nth_value(struct List *p, int n);
```

Nothing stops a client from doing this!

```
p->first = NULL;
```

If you put the representation here, then it's not an **abstract** data type, it's just a data type.

client.c

```
#include "list.h"  
  
int f(void) {  
    struct List *p, *q;  
    p = new();  
    q = new();  
    insert(p,"six",6);  
    insert(p,"sept",7);  
    insert(q,"cinq",5);  
    concat(p,q);  
    concat(q,p);  
    return nth_value(q,1);  
}
```

list_linked.c

```
#include "list.h"  
  
struct List *new()  
{  
    struct List *p;  
    p = calloc(1, sizeof(*p));  
    if(p == NULL) { cry(); return NULL; }  
    return p;  
}  
  
void insert(struct List *p, const char* key, int value) {...}  
  
void concat(struct List *p, struct List *q) { ... }  
  
int nth_value(struct List *p, int n) { ... }
```



Preview of A3/Lecture 12: Encapsulation (right!)

list.h

```

struct List;
typedef struct List *List_T;

List_T new();
void insert(List_T p, const char* key, int value);
void concat(List_T p,
            List_T q);
int nth_value(List_T p, int n);

```

Including only the declaration in header file **enforces** the abstraction: it keeps clients from accessing fields of the struct, allowing implementation to change

Now this code won't compile!

```
p->first = NULL;
```

client.c

```

#include "list.h"

int f(void) {
    List_T p, q;
    p = new();
    q = new();
    insert(p,"six",6);
    insert(p,"sept",7);
    insert(q,"cinq",5);
    concat(p,q);
    concat(q,p);
    return nth_value(q,1);
}

```

list_linked.c

```

#include "list.h"

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

struct List *new()
{
    struct List *p;
    p = calloc(1, sizeof(*p));
    if(p == NULL) {cry(); return NULL;}
    return p;
}

void insert(struct List *p, const char* key, int value) {...}
void concat(struct List *p, struct List *q) { ... }
int nth_value(struct List *p, int n) { ... }

```

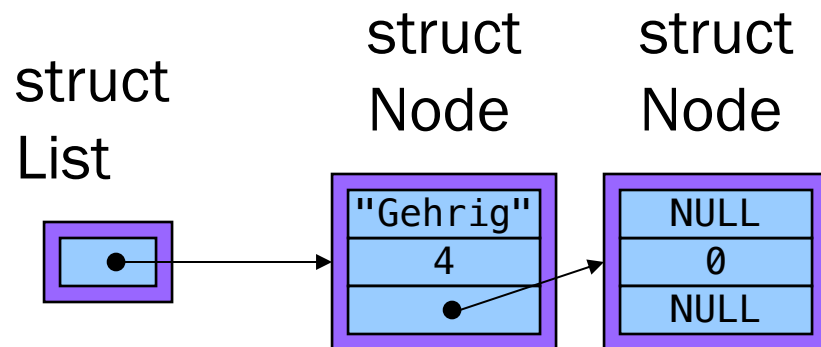



Accessing a Linked List

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

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

```
struct List lineup;
struct Node g;
struct Node* r =
    calloc(1, sizeof(struct Node));
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: $O(1) \Rightarrow$ 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: ???



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

Not well specified:

Depends on order of inserts, queries, etc.

Best answer is D.



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

Agenda



Linked lists

Hash tables

Hash table issues

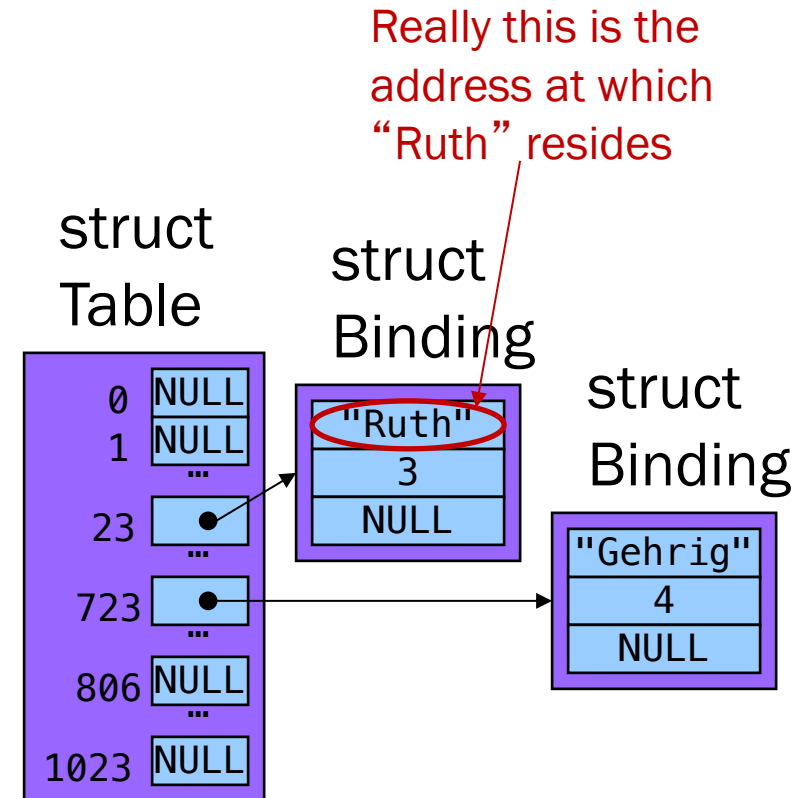
Symbol table key ownership



Hash Table Data Structure (For COS 226 nerds – hashing with separate chaining)

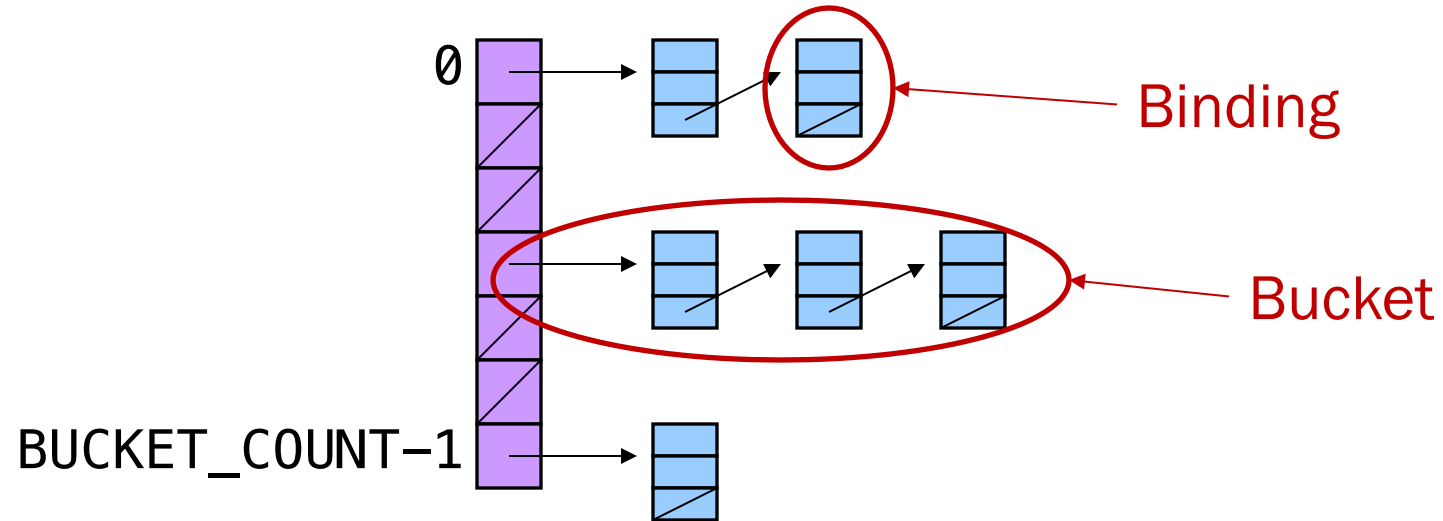
Array of linked lists

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





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

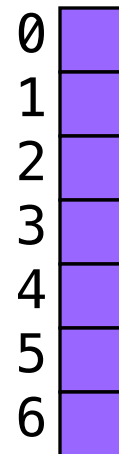


Hash Table Example (cont.)

First key: “the”

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

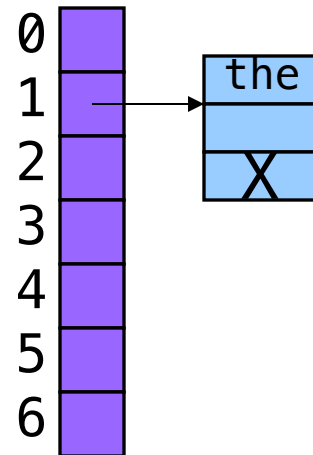
Search buckets [1] for binding with key “the”; not found





Hash Table Example (cont.)

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



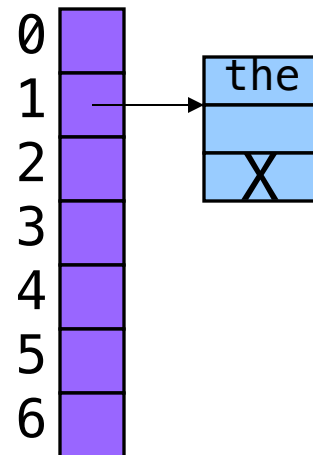


Hash Table Example (cont.)

Second key: “cat”

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

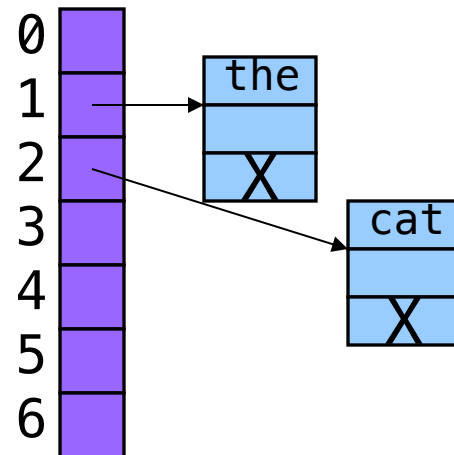
Search buckets [2] for binding with key “cat”; not found





Hash Table Example (cont.)

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



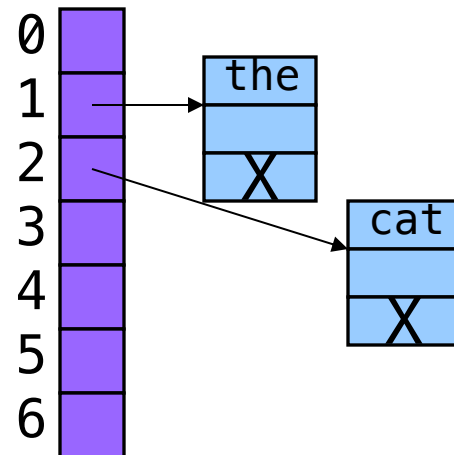


Hash Table Example (cont.)

Third key: “in”

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

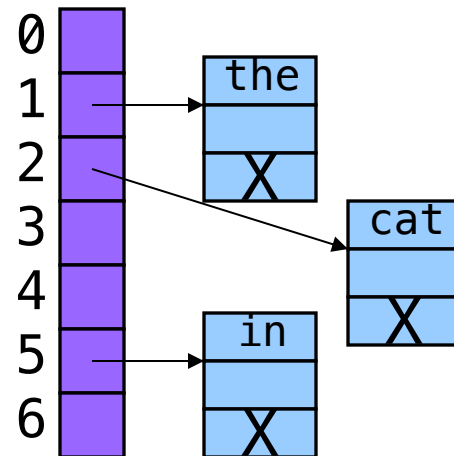
Search buckets [5] for binding with key “in”; not found





Hash Table Example (cont.)

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





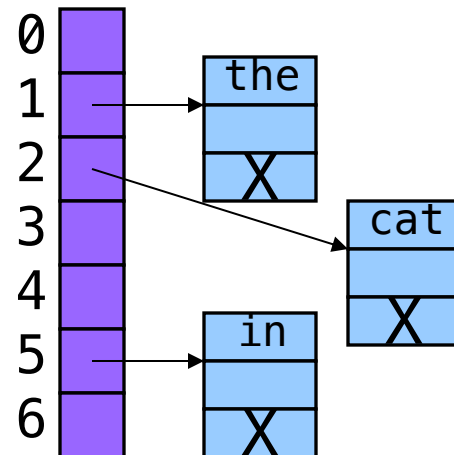
Hash Table Example (cont.)

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



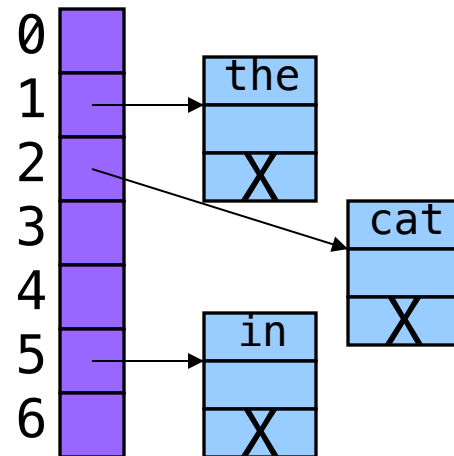


Hash Table Example (cont.)

Fifth key: “hat”

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

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

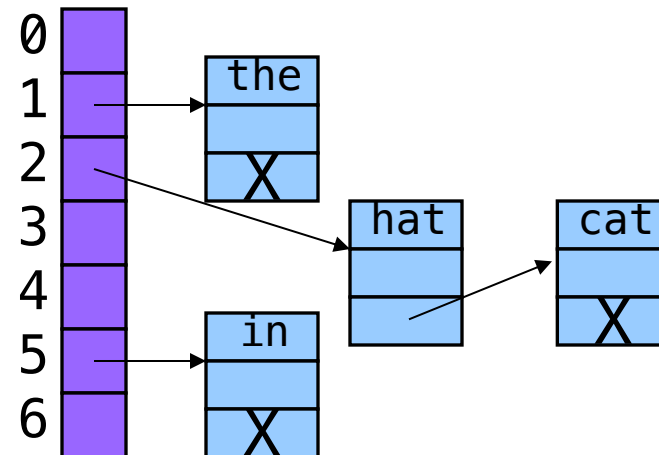




Hash Table Example (cont.)

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

- At front or back?





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: ???



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

C

If bindings are spread across buckets, this is fast (though B is a concern).

Worst case: everything hashes to the same bucket – $O(n)$



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

Agenda



Linked lists

Hash tables

Hash table issues

Symbol table key ownership



How Many Buckets?

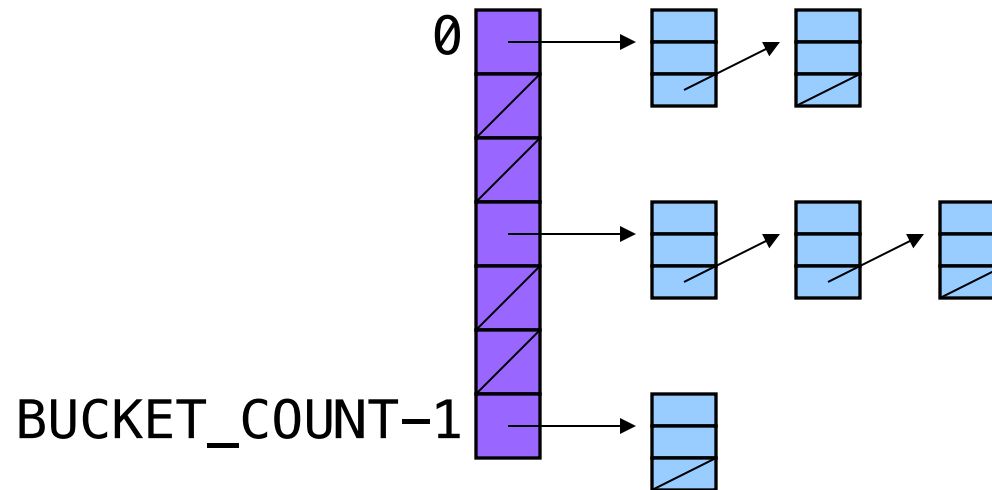
Many!

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

But not too many!

- Too many \Rightarrow memory is wasted

This is OK:



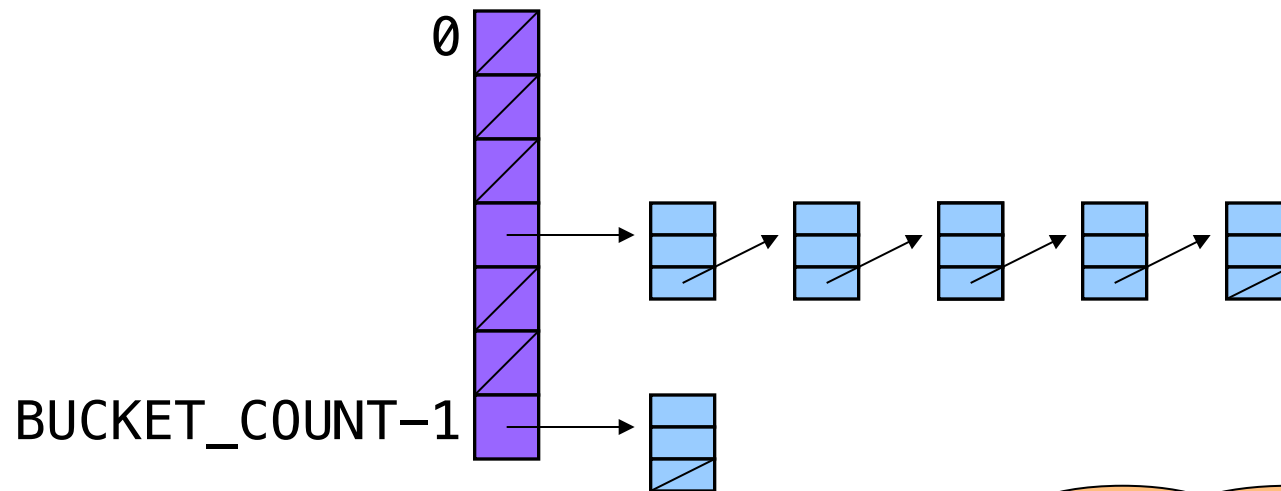


What Hash Function?

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

- 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



How to Hash Strings?

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

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

Agenda



Linked lists

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How to Protect Keys?

Suppose a hash table function `Table_add()` contains this code:

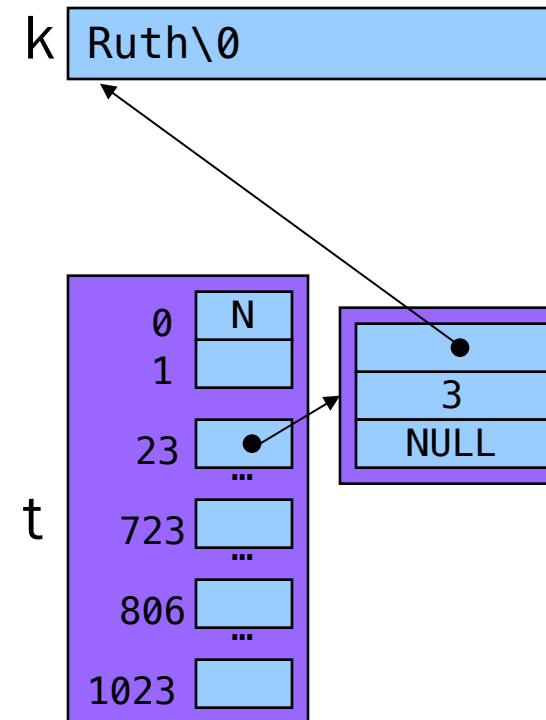
```
void Table_add(struct Table *t, const char *key, int value)
{
    ...
    struct Binding *p =
        (struct Binding*)malloc(sizeof(struct Binding));
    p->key = key;
    ...
}
```



How to Protect Keys?

Problem: Consider this calling code:

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





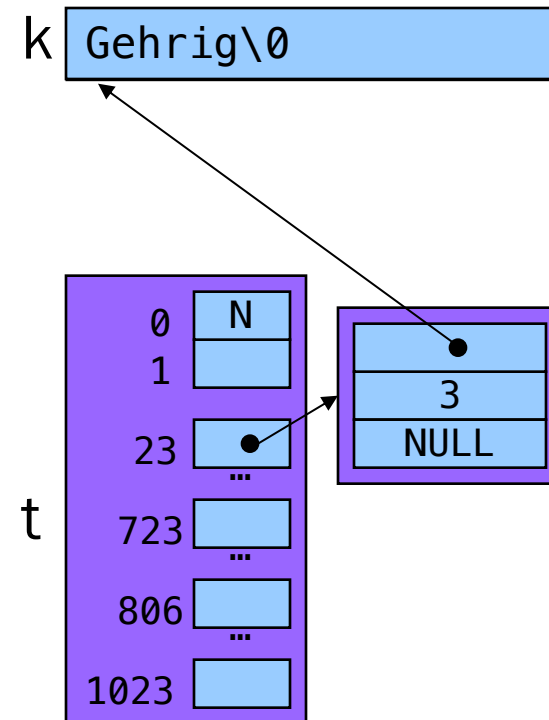
How to Protect Keys?

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?

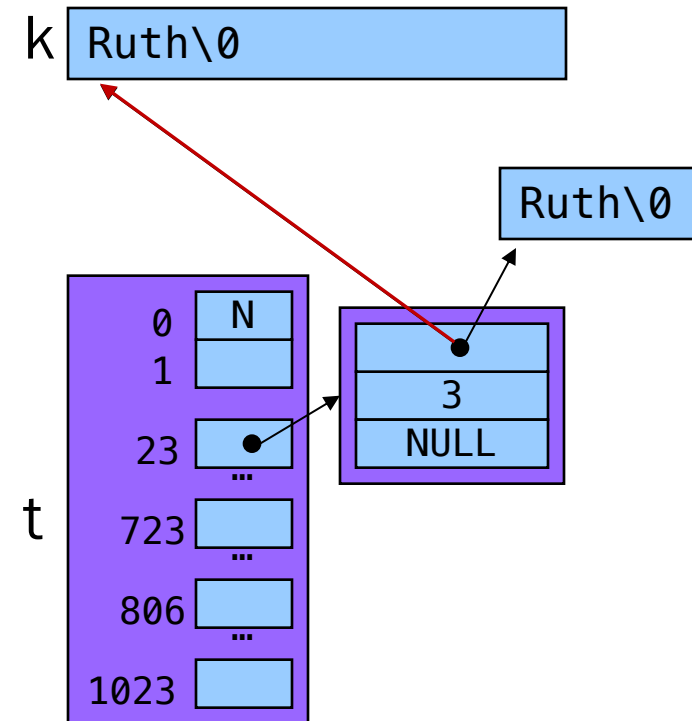
What is missing from this code that you should have in yours?



How to Protect Keys?

Now consider same calling code:

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



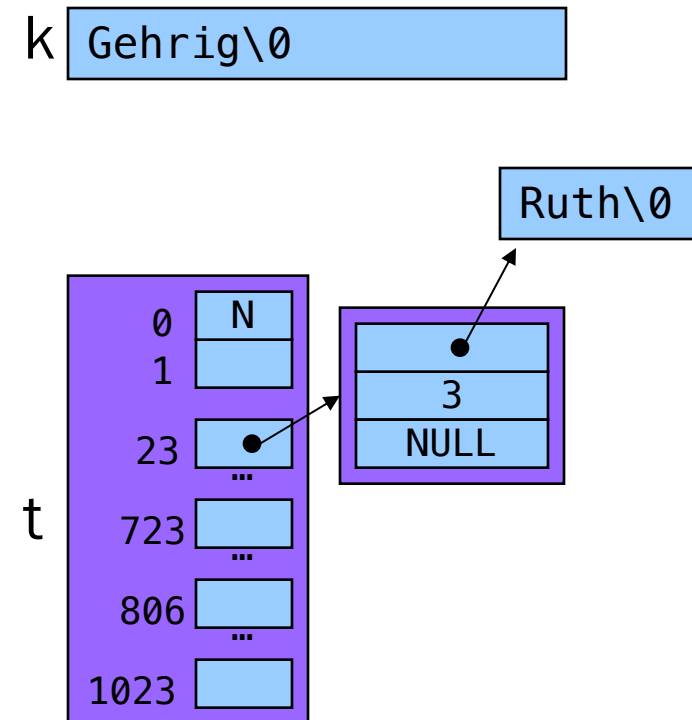


How to Protect Keys?

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 allocated the memory in which its keys reside
- `Table_remove()` function must also free the memory in which the key resides, not just its binding



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

- (Initial) Bucket array size
- Hashing algorithms

Symbol table concerns

- Key ownership