Complex Libraries

Using Hash Dictionaries

Playing Hash Table

You are the new produce manager of the local grocery store. You want to use a dictionary to track your fruit inventory.

Entries have the form

("banana", 20)

where

- "banana" is the **key**
- 20 is the associated data, like the number of cases in stock

- Let's observe your initial interactions with a hypothetical hash dictionary library

This is your side

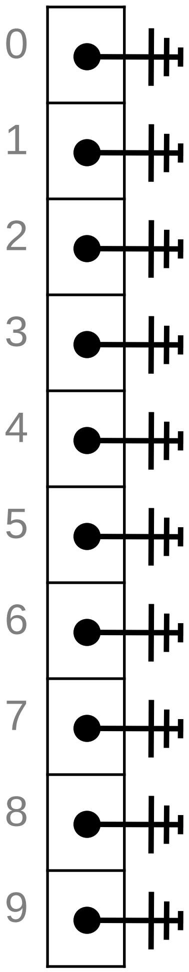
This is what is going on in the library

Client | **Implementation**

You begin by creating a new dictionary

Create a new hash dictionary

Here you go!

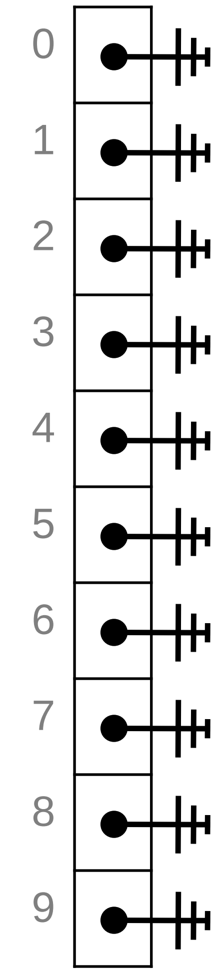


- This library uses separate-chaining hash tables to implement dictionaries
- It decides on an initial capacity of 10
  - it's probably self-resizing

Client | **Implementation**

Insert A = ("apple", 20)

What's the key of (A)?



✓ new dictionary

Next, you *insert*
A = ("apple",20)

- Why is the library asking this?
  - it does not know what entries are
    - (A) is just a pointer to some struct
    - no sense of what's in it
- ***You** need to tell it*

Client | **Implementation**

Insert A = (“apple”, 20)

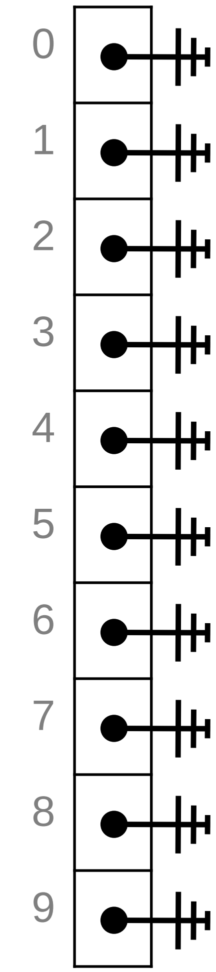
What’s the key of (A)?

“apple”

What’s its hash value?

✓ new dictionary

Next, you insert A = (“apple”,20)



- Why is the library asking this?
  - it does not know the type of keys
  - even if it did, there are many ways to hash them
- ***You** need to tell it*

Key	Hash
"apple"	-1290151091
"berry"	-514151789
"banana"	207055587
"grape"	-581390202
"lemon"	-665562942
"lime"	2086736531
"pumpkin"	-1189657311

✓ new dictionary

Next, you insert A = ("apple",20)

Client | **Implementation**

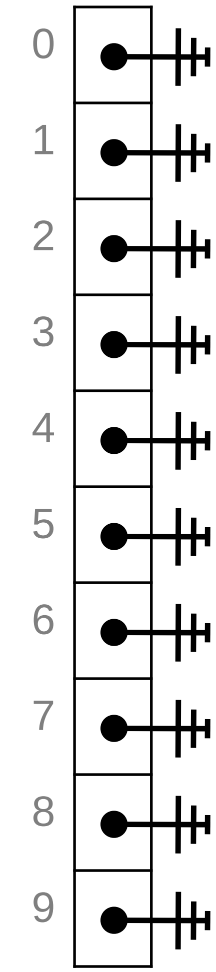
Insert A = ("apple", 20)

What's the key of (A)?

"apple"

What's its hash value?

-1290151091



- -1290151091 % 10 is -1 in C0
  - not a valid array index! ✗
  - the library needs a more robust way to compute the hash index
- Let's say it keeps the last digit

Exercise!

Key	Hash
"apple"	-1290151091
"berry"	-514151789
"banana"	207055587
"grape"	-581390202
"lemon"	-665562942
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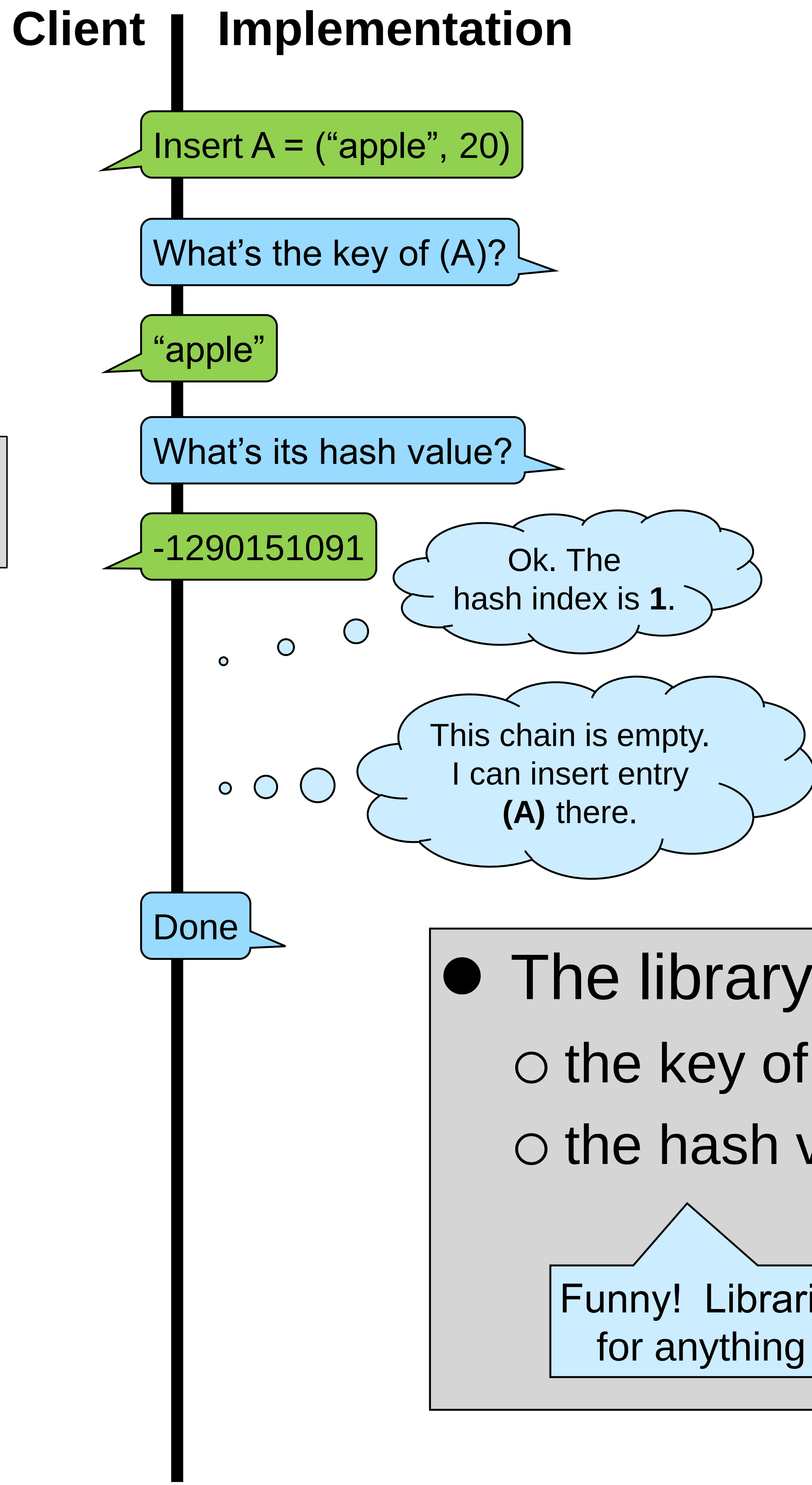
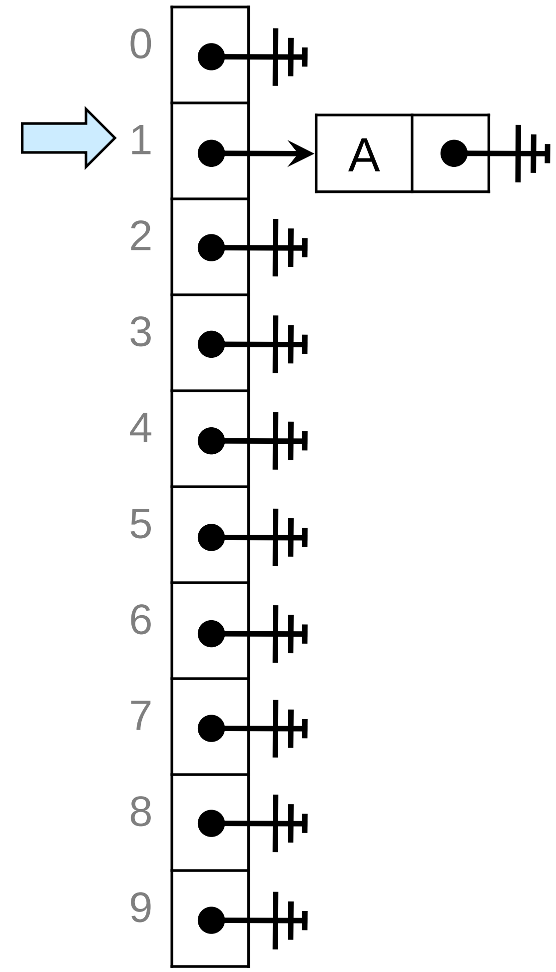
✓ new dictionary

Next, you insert A = ("apple",20)





- The library asked for
  - the key of the entry
  - the hash value of the key

Funny! Libraries didn't ask for anything in the past

Key	Hash
"apple"	-1290151091
"berry"	-514151789
"banana"	207055587
"grape"	-581390202
"lemon"	-665562942
"lime"	2086736531
"pumpkin"	-1189657311

✓ new dictionary
✓ insert A = (“apple”, 20)

Next, you insert B = (“banana”,10)

Client | **Implementation**

Insert B = (“banana”, 10)

What’s the key of (B)?

“banana”

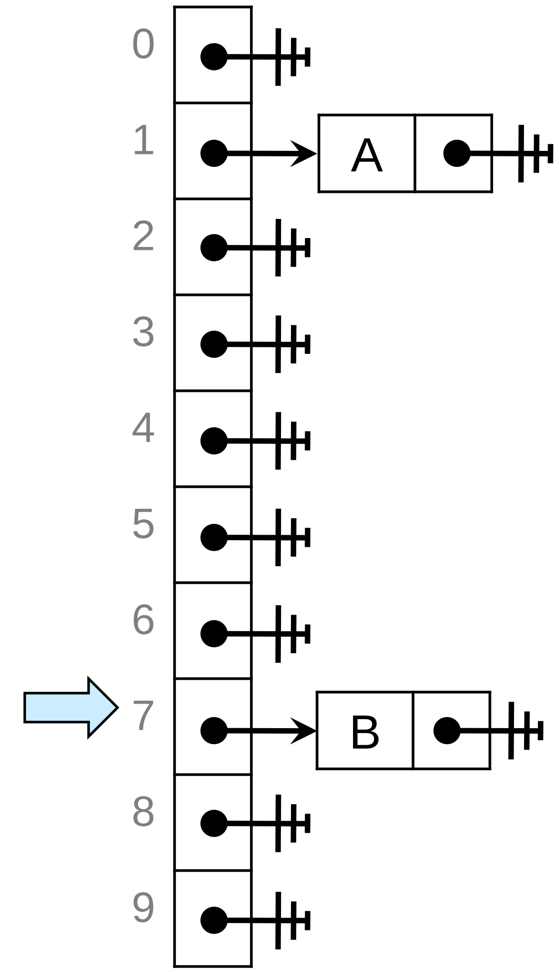
What’s its hash value?

207055587

Ok. The hash index is **7**.

This chain is empty. I can insert entry **(B)** there.

Done



Same as for (A)

Key	Hash
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"berry"	-514151789
"banana"	207055587
"grape"	-581390202
"lemon"	-665562942
"lime"	2086736531
"pumpkin"	-1189657311

- ✓ new dictionary
- ✓ insert A = (“apple”, 20)
- ✓ insert B = (“banana”, 10)

Next, you insert C = (“pumpkin”,50)

Client | **Implementation**

Insert C = (“pumpkin”, 50)

What’s the key of (C)?

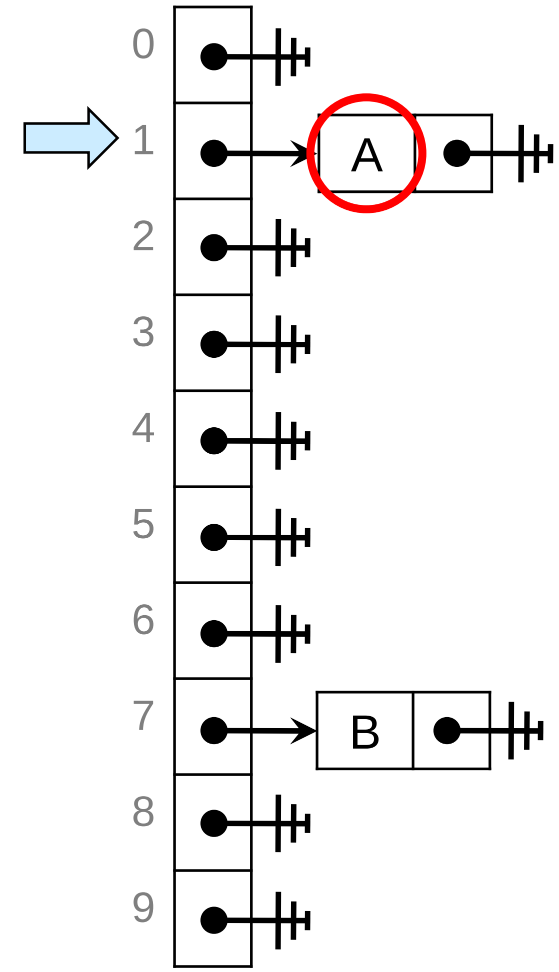
“pumpkin”

What’s its hash value?

-1189657311

Ok. The hash index is **1**.
It points to a node
for entry **(A)**

What’s the key of (A)?



- Why is the library asking this?
  - it does not know what entries are
    - (A) is just a pointer to some struct
    - no sense of what’s in it
- ***You** need to tell it*

Key	Hash
"apple"	-1290151091
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- ✓ new dictionary
- ✓ insert A = (“apple”, 20)
- ✓ insert B = (“banana”, 10)

Next, you insert C = (“pumpkin”,50)

Client | **Implementation**

Insert C = (“pumpkin”, 50)

What’s the key of (C)?

“pumpkin”

What’s its hash value?

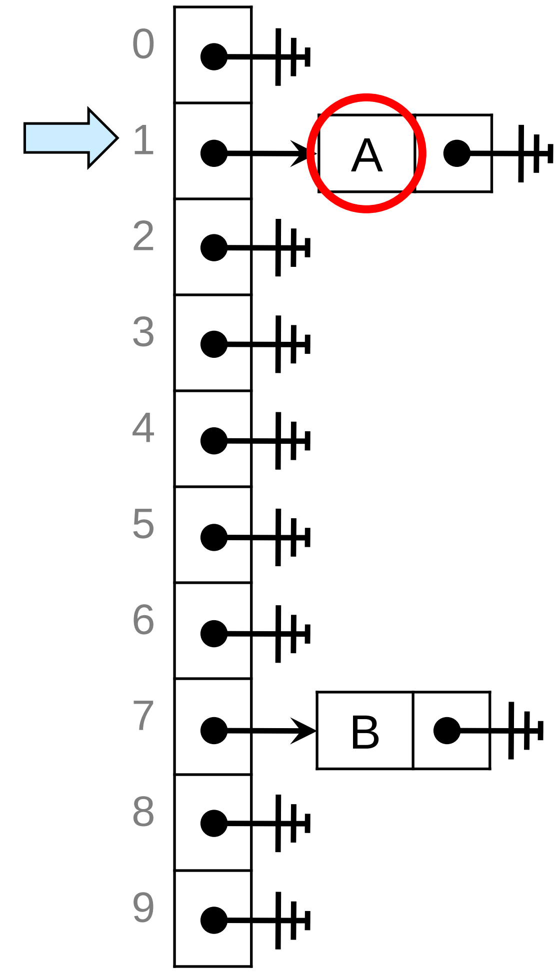
-1189657311

Ok. The hash index is **1**.
It points to a node
for entry **(A)**

What’s the key of (A)?

“apple”

Is it the same as “pumpkin”?



- Why is the library asking this?
  - it does not know the type of keys
  - even if it did, there are many ways to compare them
- ***You** need to tell it*

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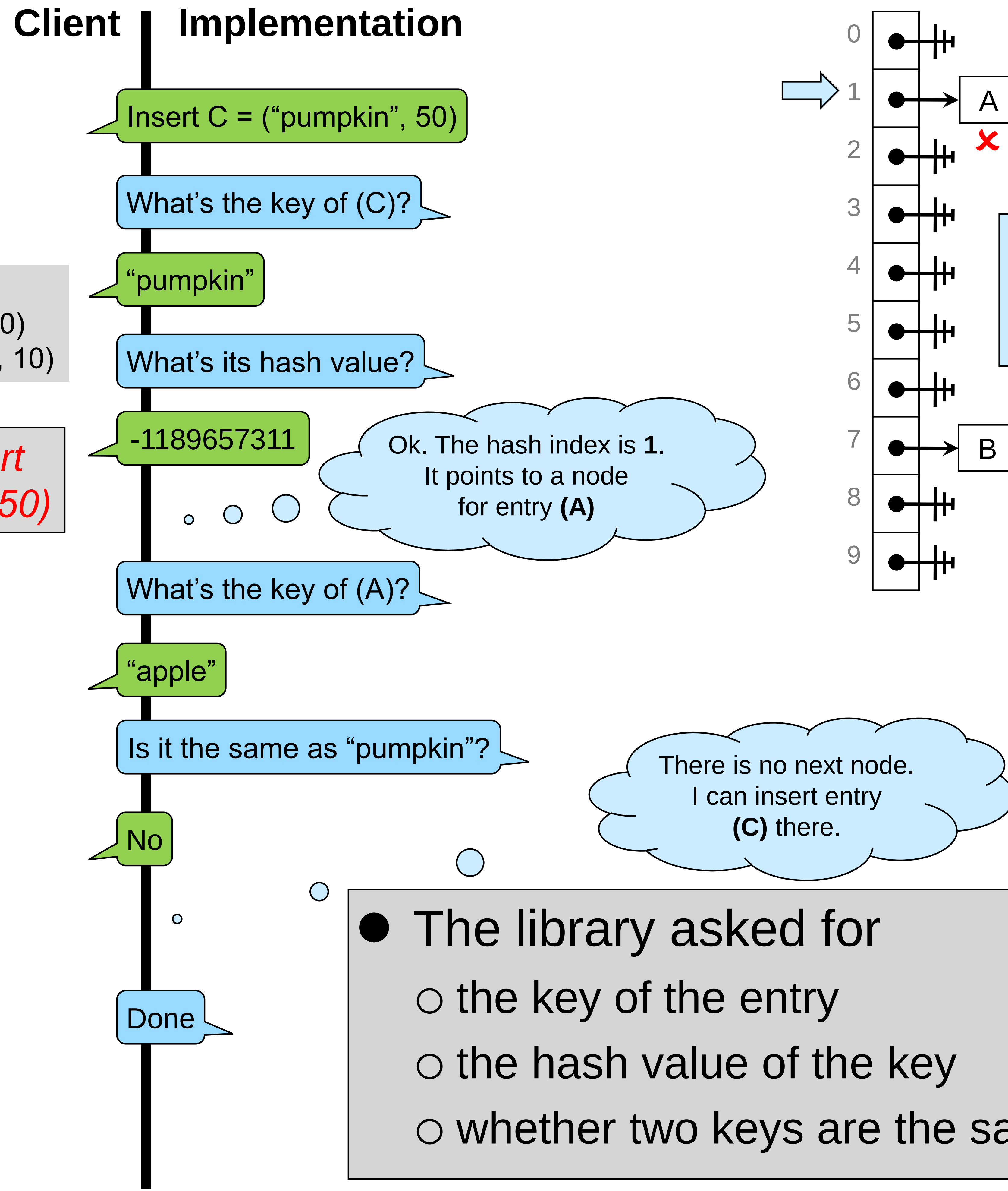
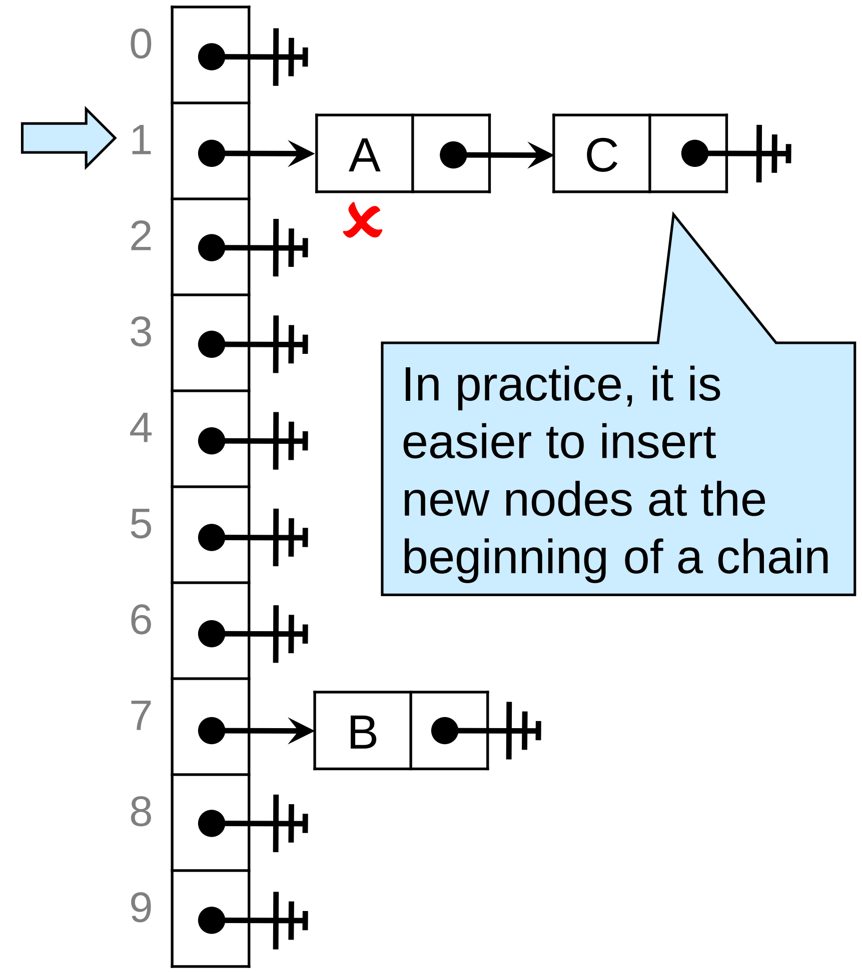
- ✓ new dictionary
- ✓ insert A = (“apple”, 20)
- ✓ insert B = (“banana”, 10)

Next, you insert C = (“pumpkin”,50)





- The library asked for
  - the key of the entry
  - the hash value of the key
  - whether two keys are the same

Key	Hash
"apple"	-1290151091
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"banana"	207055587
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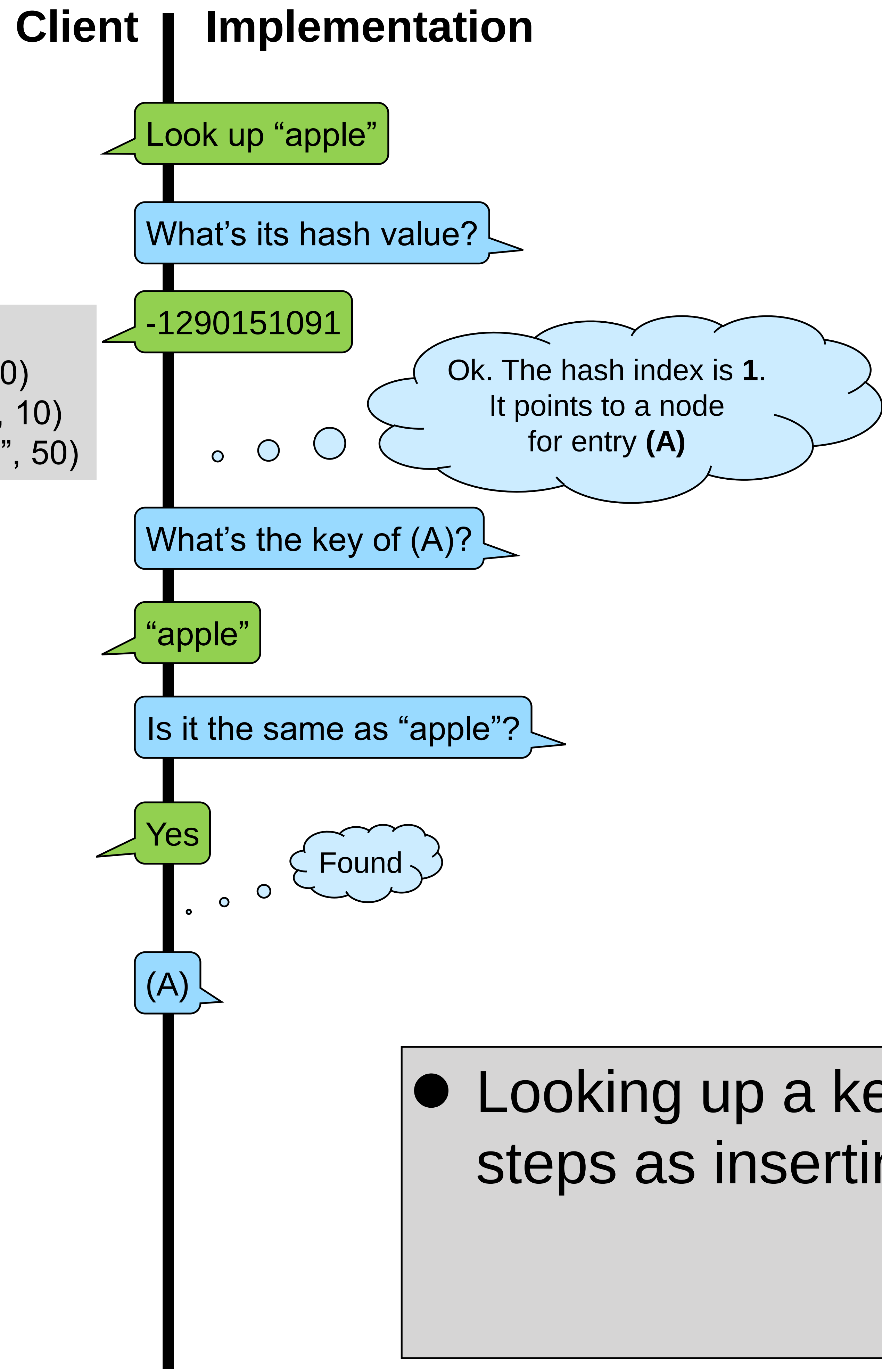
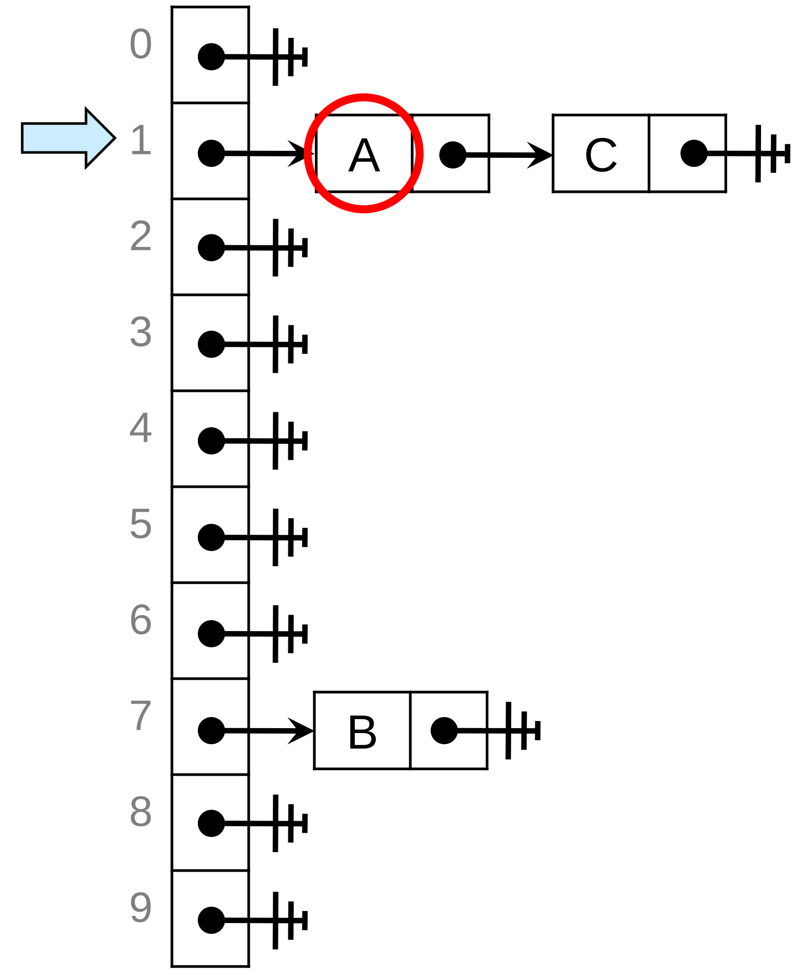
"pumpkin"	-1189657311

- ✓ new dictionary
- ✓ insert A = (“apple”, 20)
- ✓ insert B = (“banana”, 10)
- ✓ insert C = (“pumpkin”, 50)

Next, you
look up “apple”





- Looking up a key follows the same steps as inserting an entry

Key	Hash
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- ✓ new dictionary
- ✓ insert A = (“apple”, 20)
- ✓ insert B = (“banana”, 10)
- ✓ insert C = (“pumpkin”, 50)
- ✓ look up “apple”

Next, you
look up “lime”

Client | **Implementation**

Look up “lime”

What’s its hash value?

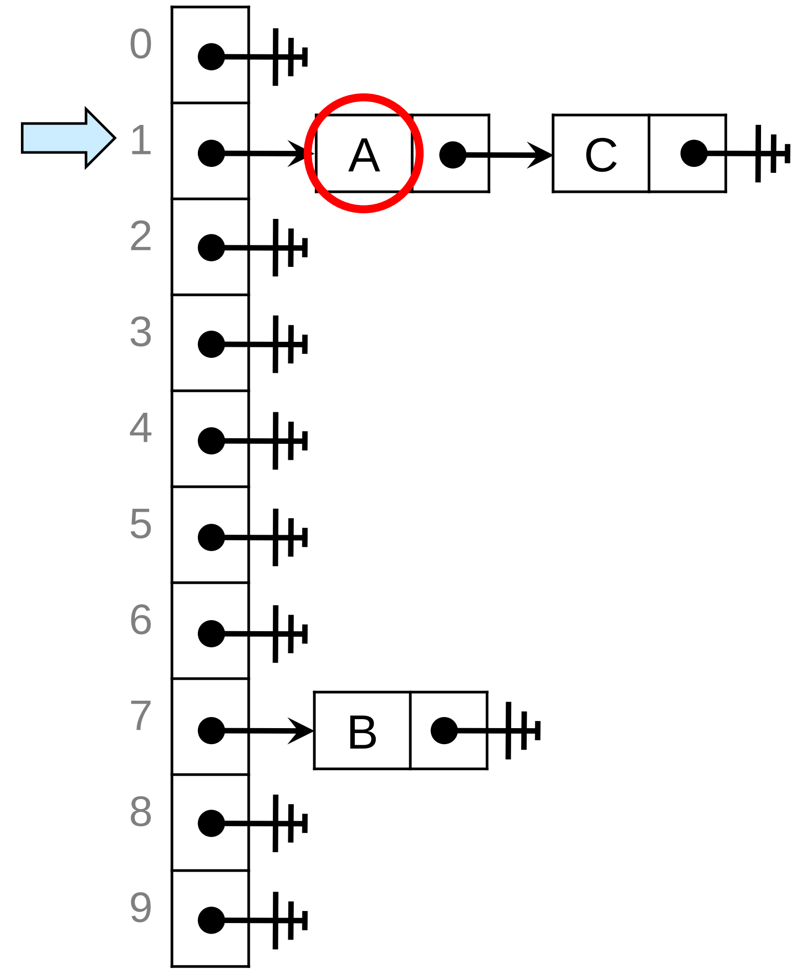
2086736531

Ok. The hash index is **1**.
It points to a node
for entry **(A)**

What’s the key of (A)?

“apple”

Is it the same as “lime”?



- The library goes through the chain node by node

Key	Hash
"apple"	-1290151091
"berry"	-514151789
"banana"	207055587
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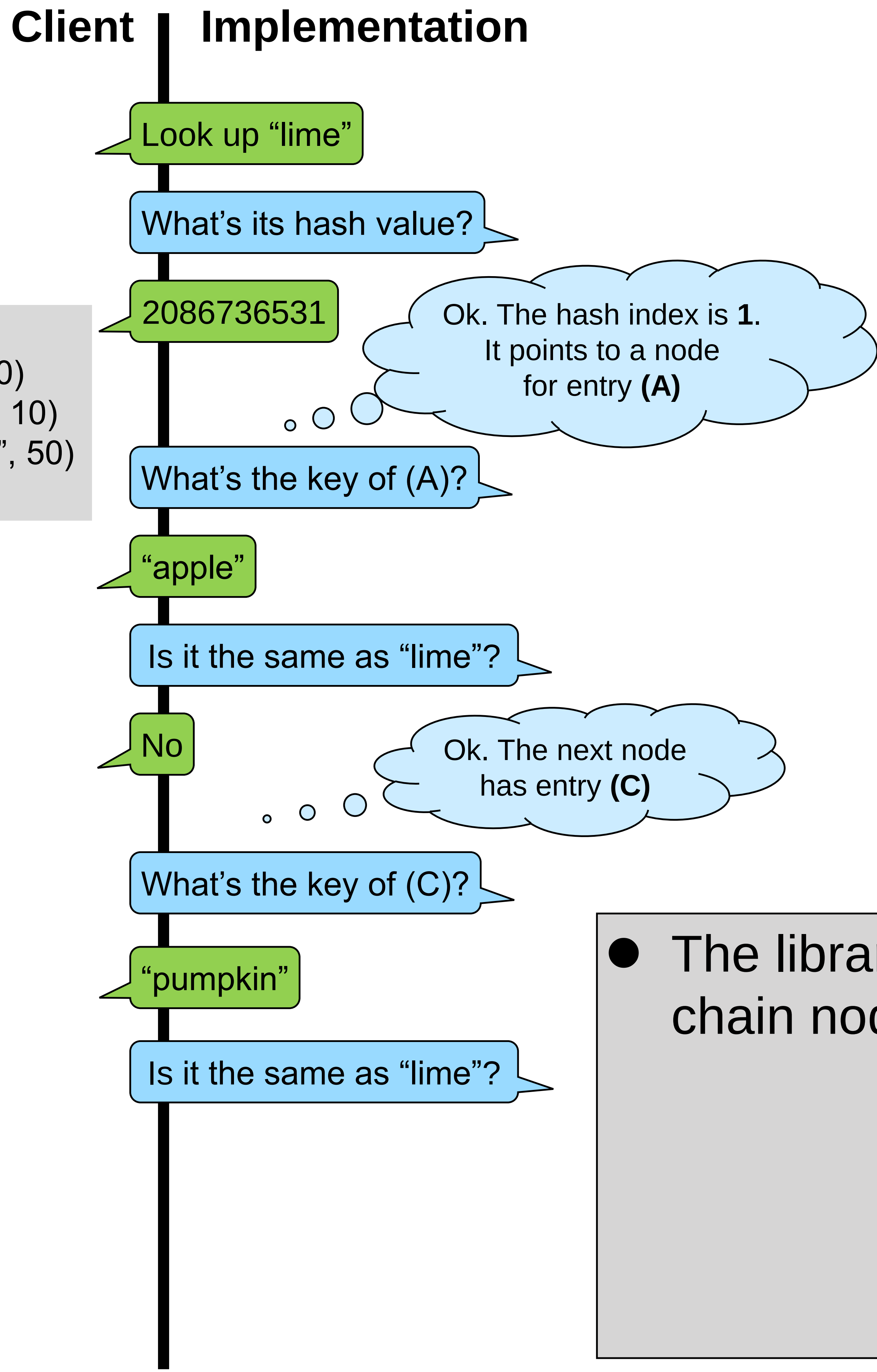
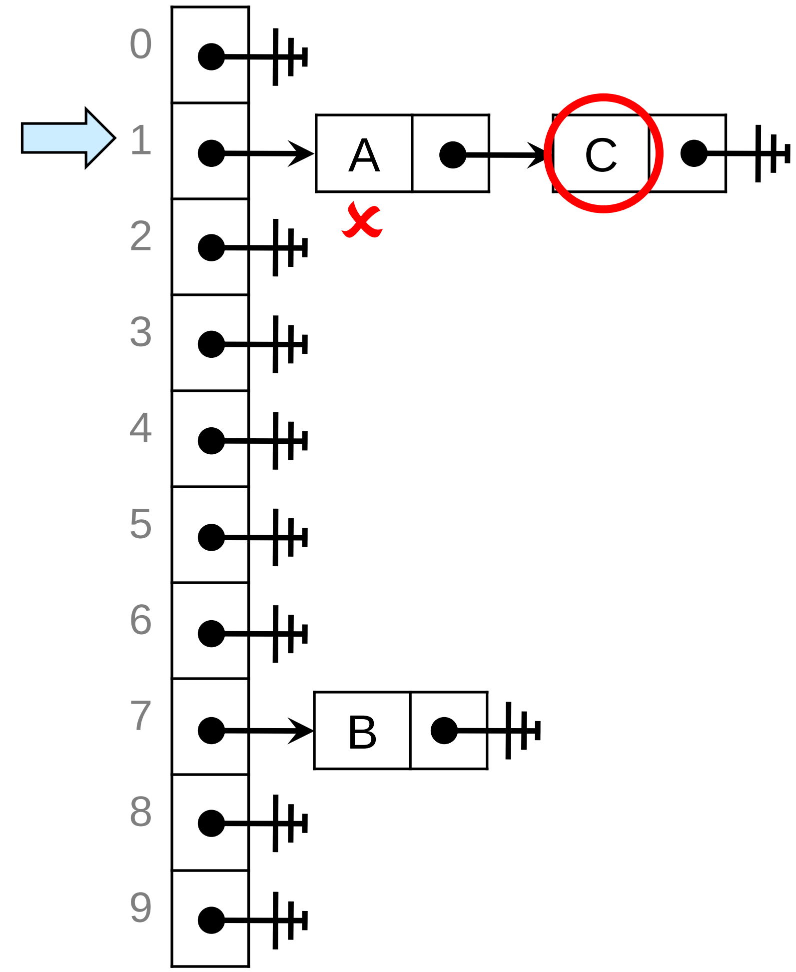
"pumpkin"	-1189657311

- ✓ new dictionary
- ✓ insert A = (“apple”, 20)
- ✓ insert B = (“banana”, 10)
- ✓ insert C = (“pumpkin”, 50)
- ✓ look up “apple”

Next, you
look up “lime”





- The library goes through the chain node by node

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"apple"	-1290151091
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"banana"	207055587
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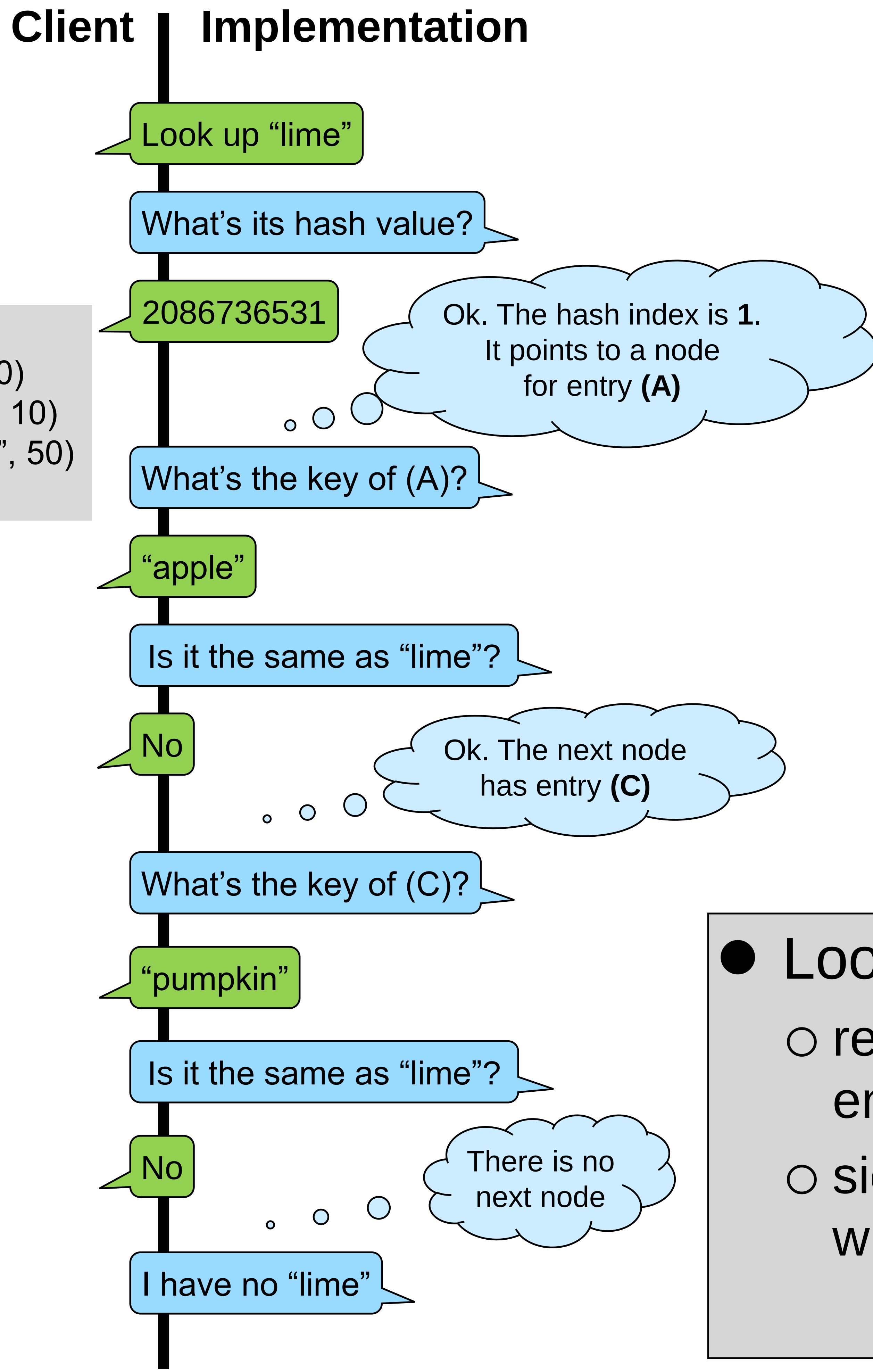
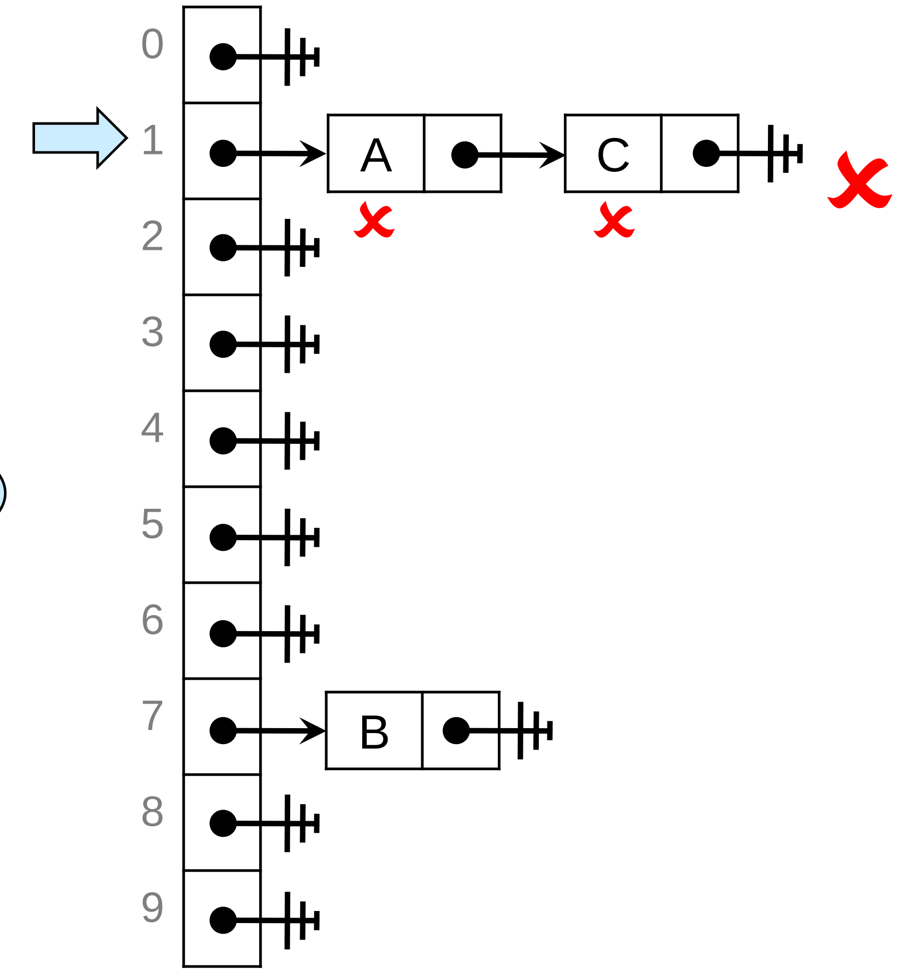
"lemon"	-665562942
"lime"	2086736531
"pumpkin"	-1189657311

- ✓ new dictionary
- ✓ insert A = (“apple”, 20)
- ✓ insert B = (“banana”, 10)
- ✓ insert C = (“pumpkin”, 50)
- ✓ lookup “apple”

Next, you
look up “lime”





- Looking up a key can
  - return the associated entry, or
  - signal there is no entry with this key

Key	Hash
"apple"	-1290151091
"berry"	-514151789
"banana"	207055587
"grape"	-581390202
"lemon"	-665562942
"lime"	2086736531
"pumpkin"	-1189657311

- ✓ new dictionary
- ✓ insert A = (“apple”, 20)
- ✓ insert B = (“banana”, 10)
- ✓ insert C = (“pumpkin”, 50)
- ✓ look up “apple”
- ✓ look up “lime”

Next, you insert D = (“banana”, 20)

Client | **Implementation**

Client: Insert D = (“banana”, 20)

Implementation: What’s the key of (B)?

Client: “banana”

Implementation: What’s its hash value?

Client: 207055587

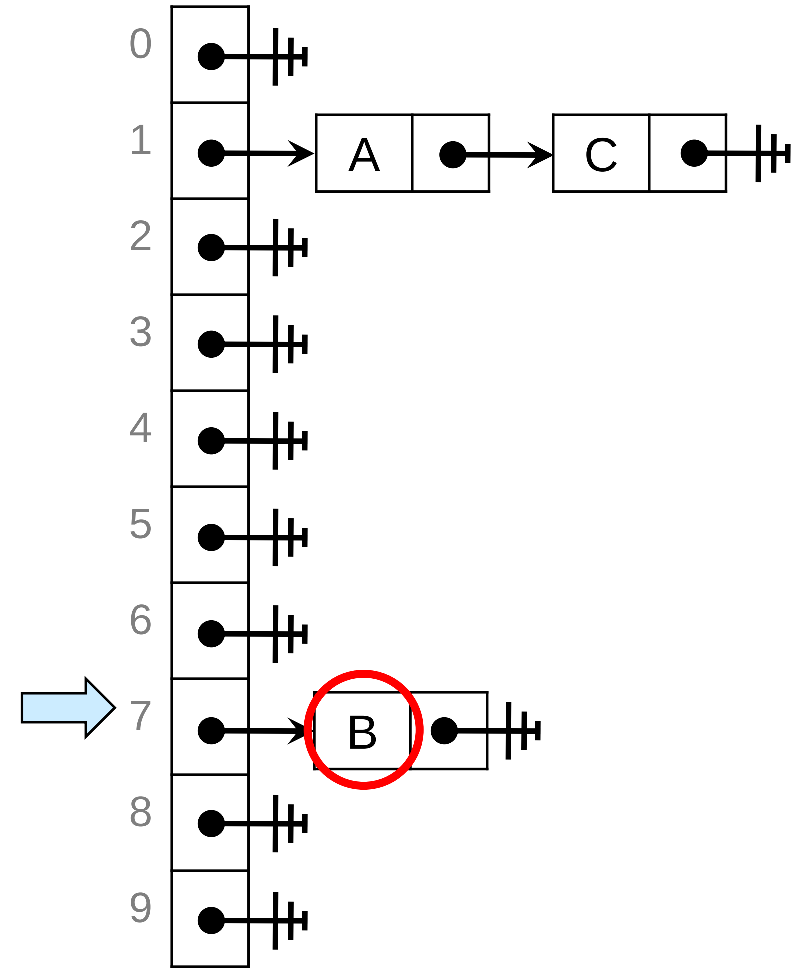
Implementation (thinking): Ok. The hash index is **7**. It points to a node for entry **(B)**

Implementation: What’s the key of (B)?

Client: “banana”

Implementation: Is it the same as “banana”?

Client: Yes



- What to do if the key is already there?

Key	Hash
"apple"	-1290151091
"berry"	-514151789
"banana"	207055587
"grape"	-581390202
"lemon"	-665562942
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"pumpkin"	-1189657311

- ✓ new dictionary
- ✓ insert A = ("apple", 20)
- ✓ insert B = ("banana", 10)
- ✓ insert C = ("pumpkin", 50)
- ✓ look up "apple"
- ✓ look up "lime"

Next, you insert
D = ("banana", 20)

Client | **Implementation**

Insert D = ("banana", 20)

What's the key of (B)?

"banana"

What's its hash value?

207055587

Ok. The hash index is **7**.
It points to a node
for entry **(B)**

What's the key of (B)?

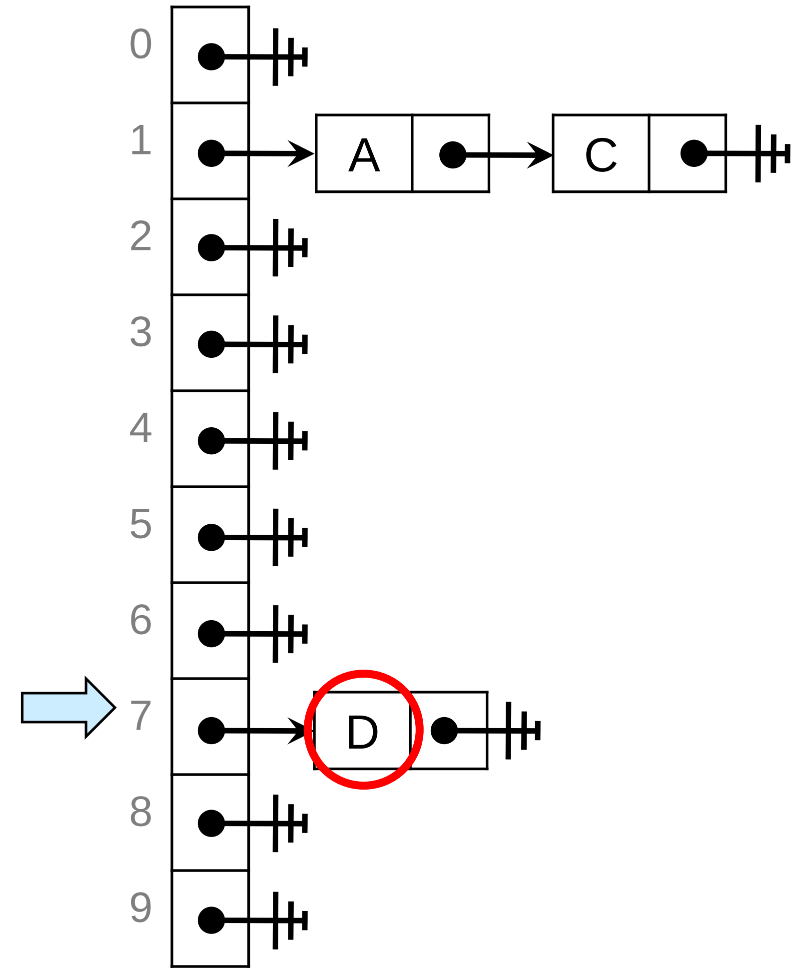
"banana"

Is it the same as "banana"?

Yes

Ok. This is where
to insert (D)

Done



- What to do if the key is already there?
- **Overwrite** the stored entry

What Have we Learned?

- The library needs information from the client to do its job
  - the key of an entry
  - the hash value of a key
  - whether two keys are the same

- How shall the client provide this information?
  - Back and forth like we did?
    - Too cumbersome
      - we want to just call lookup and get a result
  - Supply **functions** the library can use to find this information
    - a function that returns the key of an entry
    - a function that computes the hash value of a key
    - a function that determines whether two keys are the same

Hash Dictionary Interface

What the Library Provides

- A type for using dictionaries
  - hdict_t

hdict_t because we will be implementing it using hash tables

- Some operations
  - creating a new dictionary
    - hdict_new
  - looking up a key in a dictionary
    - hdict_lookup
  - inserting an entry into a dictionary
    - hdict_insert

Real dictionary libraries provide many more operations.
Let's keep it simple

Let's write the interface of this library

Creating a Dictionary

By now we anticipate this will be a pointer …

… and that a dictionary shall never be NULL

Library Interface

```
// typedef ______* hdict_t;

hdict_t  hdict_new(int capacity)
  /*@requires capacity > 0;                @*/
  /*@ensures \result != NULL;              @*/ ;

// …
```

- Clients have a sense of how many entries may end up in a dictionary
  - Let them specify an initial capacity
    - whether the implementation is self-resizing or not
  - An initial capacity of 0 makes no sense
    - disallow it in precondition

Looking up a key

- hdict_lookup looks up a key in a dictionary …
  - we need a type key of keys
- … and returns the associated entry …
  - we need a type entry of entries

Library Interface

```
// typedef ______* hdict_t;

hdict_t  hdict_new(int capacity)
  /*@requires capacity > 0;                    @*/
  /*@ensures \result != NULL;                  @*/ ;

entry hdict_lookup(hdict_t D, key k)
  /*@requires D != NULL;                       @*/ ;

// …
```

- .. unless there is no entry with this key in the dictionary
  - it then must signal that no entry was found
  - Arrange so that entry is a **pointer type**
    - either a pointer to the entry it found
    - or NULL to represent “not found”

Key and Entry Types

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

// …
```

The client needs to define types entry and key, and entry had better be a pointer

Library Interface

```
// typedef ______* hdict_t;

hdict_t  hdict_new(int capacity)
  /*@requires capacity > 0;                    @*/
  /*@ensures \result != NULL;                  @*/ ;

entry hdict_lookup(hdict_t D, key k)
  /*@requires D != NULL;                       @*/ ;

// …
```

- It's the client who decides what keys and entries are
  - the interface must tell the client to do this
- The interface has two parts
  - the **client interface**: what the client needs to supply to the library
  - the **library interface**: what the library provides to the client

Inserting an Entry

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

// …
```

Library Interface

```
// typedef ______* hdict_t;

hdict_t  hdict_new(int capacity)
  /*@requires capacity > 0;                        @*/
  /*@ensures \result != NULL;                      @*/ ;

entry hdict_lookup(hdict_t D, key k)
  /*@requires D != NULL;                           @*/ ;

void hdict_insert(hdict_t D, entry e)
  /*@requires D != NULL && e != NULL;              @*/ ;
```

e cannot be NULL

- If NULL stands for an entry that was not found, no entry shall ever be NULL

What about all those Questions?

Entries cannot be NULL

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

key entry_key(entry  e)
  /*@requires e != NULL;          @*/ ;

int key_hash(key k);

bool key_equiv(key k1, key k2);
```

Library Interface

```
// typedef ______* hdict_t;

hdict_t  hdict_new(int capacity)
  /*@requires capacity > 0;                    @*/
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entry hdict_lookup(hdict_t D, key k)
  /*@requires D != NULL;                       @*/ ;

void hdict_insert(hdict_t D, entry e)
  /*@requires D != NULL && e != NULL;          @*/ ;
```

- The library needs information from the client to do its job
  - *Supply **functions** the library can use to find this information*
    - *a function that returns the key of an entry* entry_key
    - *a function that computes the hash value of a key* key_hash
    - *a function that determines whether two keys are the same* key_equiv
  - Add their prototype in the client interface!

A Postcondition for hdict_insert

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

key entry_key(entry  e)
  /*@requires e != NULL;          @*/ ;

int key_hash(key k);

bool key_equiv(key k1, key k2);
```

Library Interface

```
// typedef ______* hdict_t;

hdict_t  hdict_new(int capacity)
  /*@requires capacity > 0;                            @*/
  /*@ensures \result != NULL;                          @*/ ;

entry hdict_lookup(hdict_t D, key k)
  /*@requires D != NULL;                               @*/ ;

void hdict_insert(hdict_t D, entry e)
  /*@requires D != NULL && e != NULL;                  @*/
  /*@ensures hdict_lookup(D, entry_key(e)) == e; @*/ ;
```

- If we insert an entry and lookup its key, we should find that entry
  - i.e., hdict_lookup(D, entry_key(e)) == e
    - lookup returns the very entry e
    - not a different entry with the same data

e is a pointer

A Postcondition for hdict_lookup

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

key entry_key(entry  e)
  /*@requires e != NULL;          @*/ ;

int key_hash(key k);

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Library Interface

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// typedef ______* hdict_t;

hdict_t  hdict_new(int capacity)
  /*@requires capacity > 0;                              @*/
  /*@ensures \result != NULL;                            @*/ ;

entry hdict_lookup(hdict_t D, key k)
  /*@requires D != NULL;                                 @*/
  /*@ensures \result == NULL
               || key_equiv(entry_key(\result), k);      @*/ ;

void hdict_insert(hdict_t D, entry e)
  /*@requires D != NULL && e != NULL;                    @*/
  /*@ensures hdict_lookup(D, entry_key(e)) == e; @*/ ;
```

- If we look up a key
  - either we get back NULL
    - \result == NULL
  - or the key of the returned entry is our key
    - key_equiv(entry_key(\result), k)

- The client interface functions give us a way to write very precise postconditions

The Hash Dictionary Interface

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

key entry_key(entry  e)
  /*@requires e != NULL;          @*/ ;

int key_hash(key k);

bool key_equiv(key k1, key k2);
```

Library Interface

```
// typedef ______* hdict_t;

hdict_t  hdict_new(int capacity)
  /*@requires capacity > 0;                              @*/
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entry hdict_lookup(hdict_t D, key k)
  /*@requires D != NULL;                                 @*/
  /*@ensures \result == NULL
               || key_equiv(entry_key(\result), k);      @*/ ;

void hdict_insert(hdict_t D, entry e)
  /*@requires D != NULL && e != NULL;                    @*/
  /*@ensures hdict_lookup(D, entry_key(e)) == e; @*/ ;
```
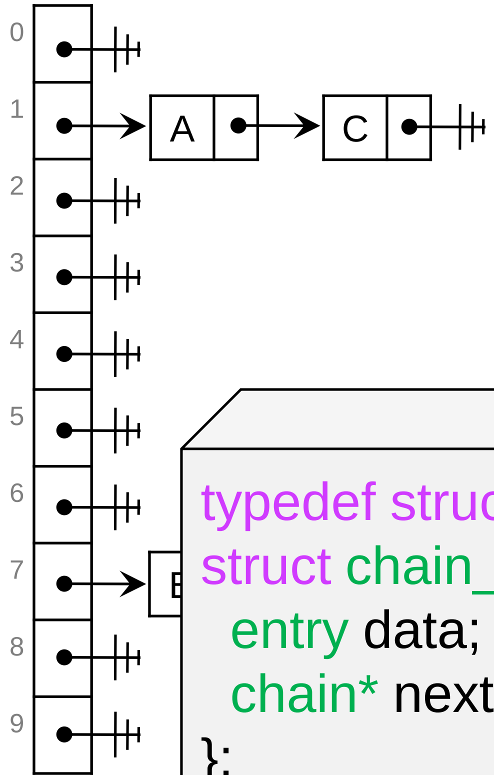

What the library needs from the client

What the library provides to the client

Hash Dictionary Implementation



Library Interface

```
// typedef ______* hdict_t;
// …
```

Hash Dictionary Types

Implementation

```
typedef struct chain_node chain;
struct chain_node {
  entry data;      // data != NULL
  chain* next;
};

struct hdict_header {
  int size;        // size >= 0
  int capacity;    // capacity > 0
  chain*[] table;  // \length(table) == capacity
};
typedef struct hdict_header hdict;

// … rest of implementation

typedef hdict* hdict_t;
```

These are expected constraints on the fields

As usual, the abstract client type is a pointer to the concrete implementation type

- Each chain is a NULL-terminated linked list of entries
  - entries can't be NULL
- A dictionary is implemented as a hash table
- We need to keep track of
  - size: the number of entries
  - capacity: the length of the hash table
  - the hash table itself
    - an array of pointers to chain nodes

Representation Invariants

```
typedef struct hdict_header hdict;
struct hdict_header {
  int size;             // size >= 0
  int capacity;         // capacity > 0
  chain*[] table;  // \length(table) == capacity
};
```

- We need to capture the field constraints in the type

```
bool is_array_expected_length(chain*[] A, int len)  {
   //@assert \length(A) == len;
  return true;
}

// Representation invariant
bool is_hdict(hdict* H) {
  return H != NULL
       && H->size >= 0
       && H->capacity > 0
       && is_array_expected_length(H->table, H->capacity);
}

// … rest of implementation
```

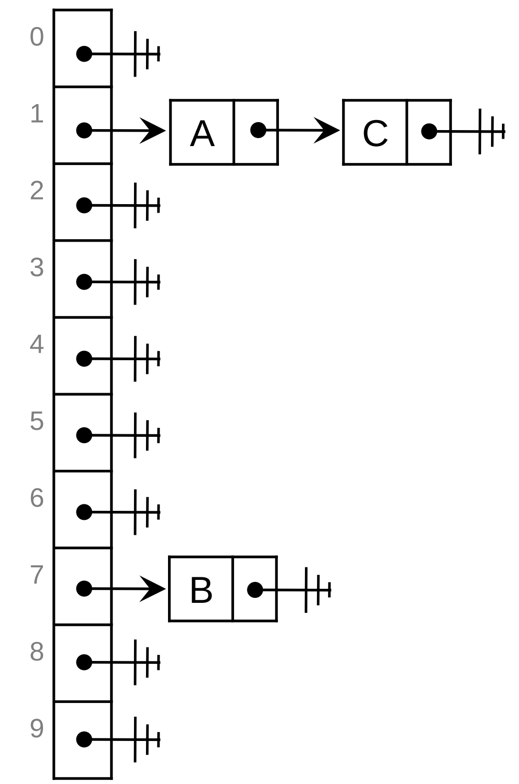
Implementation

Usual trick to check the length of an array

Abstract data structures are never NULL

Field constraints

More Representation Invariants



- Hash tables have a much more involved structure than previous concrete library types
  - the chains are acyclic
  - no two entries have the same key
  - each entry hashes to the right index
  - no entry is NULL
  - the number of entries equals the size field

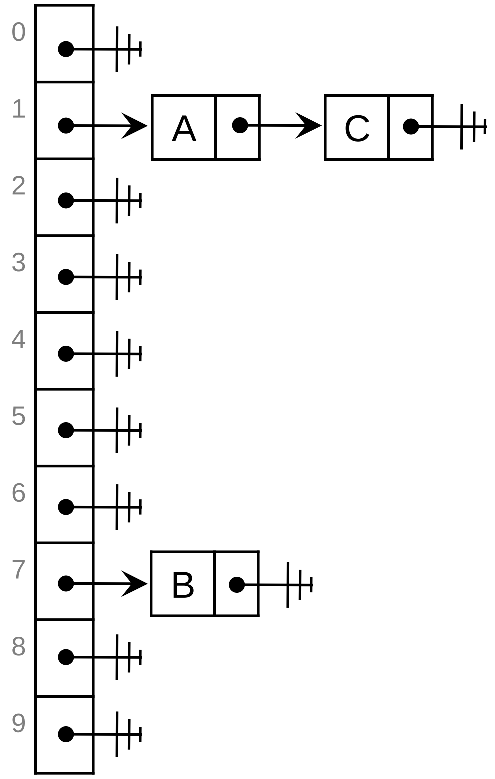
```
// Representation invariant
bool is_hdict(hdict* H) {
  return H != NULL
      && H->size >= 0
      && H->capacity > 0
      && is_array_expected_length(H->table, H->capacity)
      && is_valid_hashtable(H);
}
```

Implementation

This tests all these structural constraints

Exercise!

Invalidating Invariants



- The client can modify the keys **after** they have been inserted in the hash table
  - The chains contain **pointers** to entries
- This can invalidate the data structure invariants
  - is_dict fails the next time it is called
    - this is not because of a bug in the library
    - this is because the client manipulated the entries through aliases

This couldn't happen in any of the data structures we studied so far

- Aliasing is dangerous!

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

key entry_key(entry e)
  /*@requires e != NULL;   @*/ ;

int key_hash(key k);

bool key_equiv(key k1, key k2);
```

Implementing hdict_lookup

Library Interface

```
entry hdict_lookup(hdict_t D, key k)
  /*@requires D != NULL;                          @*/
  /*@ensures \result == NULL
             || key_equiv(entry_key(\result), k);  @*/ ;
```

- First we need to find the right bucket
  - determine the hash index of k

key → hash function → hash value → % m → hash index

```
int i = key_hash(k) % D->capacity;
```

What's its hash value?

The library's questions are answered by the client interface functions

- This won't work if hash_key(k) is negative!

```
int i = abs(key_hash(k) % D->capacity);
```

Finding the Right Bucket

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

key entry_key(entry e)
  /*@requires e != NULL;   @*/ ;

int key_hash(key k);

bool key_equiv(key k1, key k2);
```

- ➢ determine the hash index of k

```
int i = abs(key_hash(k) % H->capacity);
```

- We will need to do the same in hdict_insert
  - ○ **factor it out** in a function that computes the hash index of a key

Implementation

```
int index_of_key(hdict* H, key k)
//@requires is_hdict(H);
//@ensures 0 <= \result && \result < H->capacity;
{
  return abs(key_hash(k) % H->capacity);
}
```

Implementing hdict_lookup

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

key entry_key(entry e)
  /*@requires e != NULL;   @*/ ;

int key_hash(key k);

bool key_equiv(key k1, key k2);
```

Library Interface

```
ry hdict_lookup(hdict_t D, key k)
/ @requires D != NULL;                    @*/
sures \result == NULL
          || key_equiv(entry_key(\result), k);  @*/ ;
```

- First we need to find the right bucket
- Then we go through its chain
  - extract the key of each entry
  - check if it is equal to k

What's its key?

Is it the same as k?

```
entry hdict_lookup(hdict* H, key k)
//@requires is_hdict(H);
//@ensures \result == NULL
           || key_equiv(entry_key(\result), k);
{
  int i = index_of_key(H, k);
  for (chain* p = H->table[i]; p != NULL; p = p->next) {
    if (key_equiv(entry_key(p->data), k))
      return p->data;
  }
  return NULL;
}
```

Implementation

H must satisfy the representation invariant

i is the hash index of k

This is the start of the chain

Return the entry if k is found …

… and signal it's not there otherwise

Implementing hdict_insert

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

key entry_key(entry  e)
  /*@requires e != NULL;   @*/ ;

int key_hash(key k);

bool key_equiv(key k1, key k2);
```

Library Interface

```
void hdict_insert(hdict_t D, entry e)
  /*@requires D != NULL && e != NULL;            @*/
  /*@ensures hdict_lookup(D, entry_key(e)) == e;  @*/ ;
```

Implementation

```
void hdict_insert(hdict* H, entry e)
//@requires is_hdict(H) && e != NULL;
//@ensures \ hdict_lookup(D, entry_key(e)) == e;
//@ensures is_hdict(H);
{
  key k = entry_key(e);
  int i = index_of_key(H, k);
  for (chain* p = H->table[i]; p != NULL; p = p->next) {
    if (key_equiv(entry_key(p->data), k)) {
        p->data = e;
        return;
      }
  }
  chain* p = alloc(chain);
  p->data = e;
  p->next = H->table[i];
  H->table[i] = p;
  (H->size)++;
}
```

H must remain valid after the insertion

Check if there is already an entry with the same key
(similar code to hdict_lookup)

If so overwrite it

Otherwise, prepend a new node containing e

Implementing hdict_new

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

key entry_key(entry  e)
  /*@requires e != NULL;   @*/ ;

int key_hash(key k);

bool key_equiv(key k1, key k2);
```

Library Interface

```
hdict_t  hdict_new(int capacity)
  /*@requires capacity > 0;       @*/
  /*@ensures \result != NULL;   @*/ ;
```

Implementation

```
hdict* hdict_new(int capacity)
//@requires capacity > 0;
//@ensures is_hdict(\result);
{
  hdict* H = alloc(hdict);
  H->size = 0;
  H->capacity = capacity;
  H->table = alloc_array(chain*, capacity);
  return H;
}
```

Returned dictionary must be valid

Initialized to default pointer value, NULL

The Hash Dictionary Library

Overall Implementation

Implementation

```
// Implementation-side types
typedef struct chain_node chain;
struct chain_node {
  entry data;              // data != NULL
  chain* next;
};
struct hdict_header {
  int size;                // size >= 0
  int capacity;            // capacity > 0
  chain*[] table;          // \length(table) == capacity
};
 typedef struct hdict_header hdict;

// Representation invariant
bool is_hdict(hdict* H) {
  return H != NULL
      && H->size >= 0
      && H->capacity > 0
      && is_array_expected_length(H->table, H->capacity)
      && is_valid_hashtable(H);
}

// Implementation of interface functions
int index_of_key(hdict* H, key k)
//@requires is_hdict(H);
//@ensures 0 <= \result && \result < H->capacity;
{
  return abs(key_hash(k) % H->capacity);
}

entry hdict_lookup(hdict* H, key k)
//@requires is_hdict(H);
//@ensures \result == NULL
                || key_equiv(entry_key(\result), k);
{
  int i = index_of_key(H, k);
  for (chain* p = H->table[i]; p != NULL; p = p->next)
     if (key_equiv(entry_key(p->data), k))
        return p->data;
  return NULL;
}

void hdict_insert(hdict* H, entry e)
//@requires is_hdict(H) && e != NULL;
//@ensures \ hdict_lookup(D, entry_key(e)) == e;
//@ensures is_hdict(H);
{
  key k = entry_key(e);
  int i = index_of_key(H, k);
  for (chain* p = H->table[i]; p != NULL; p = p->next) {
     if (key_equiv(entry_key(p->data), k)) {
        p->data = e;
        return;
     }
  }
  chain* p = alloc(chain);
  p->data = e;
  p->next = H->table[i];
  H->table[i] = p;
  (H->size)++;
}

hdict* hdict_new(int capacity)
//@requires capacity > 0;
//@ensures is_hdict(\result);
{
  hdict* H = alloc(hdict);
  H->size = 0;
  H->capacity = capacity;
  H->table = alloc_array(chain*, capacity);
  return H;
}

// Client type
typedef hdict* hdict_t;
```

Client Interface

```
// typedef ______* entry;
// typedef ______ key;

key entry_key(entry  e)
  /*@requires e != NULL;   @*/ ;

int key_hash(key k);

bool key_equiv(key k1, key k2);
```

Library Interface

```
// typedef ______* hdict_t;

hdict_t  hdict_new(int capacity)
  /*@requires capacity > 0;                      @*/
  /*@ensures \result != NULL;                    @*/ ;

entry hdict_lookup(hdict_t D, key k)
  /*@requires D != NULL;                         @*/
  /*@ensures \result == NULL
            || key_equiv(entry_key(\result), k);  @*/ ;

void hdict_insert(hdict_t D, entry e)
  /*@requires D != NULL && e != NULL;            @*/
  /*@ensures hdict_lookup(D, entry_key(e)) == e;  @*/ ;
```

How

What

Complex Libraries

- The hash dictionary library is a **complex library**
  - it needs the client to supply code and functions
  - so that it can provide its services

Stacks and queues were **elementary libraries**

- Complex libraries consist of
  - a **client interface**
  - an **implementation**
  - a **library interface**

They consisted of only an implementation and a library interface

- The client sees the client and library interfaces
  - but not the implementation

Their client only saw the library interface

Structure of a Complex C0 Library File

```
/************ CLIENT INTERFACE ***********/
// typedef ______ *entry;
…
key entry_key(entry e)
/*@requires e != NULL;              @*/ ;
…
/************ IMPLEMENTATION ************/
// Implementation-side types
struct hdict_header {…};
typedef struct hdict_header hdict;

// Representation invariant
bool is_hdict(hdict* H) { … }

// Implementation of interface functions
entry hdict_lookup(hdict* H, key k)
/*@requires is_hdict(H);            @*/
/*@ensures ….                       @*/
{ … }
 …
// Client type
typedef hdict* hdict_t;

/*********** LIBRARY INTERFACE ***********/
// typedef ______ *hdict_t;

entry hdict_lookup(hdict_t D, key k)
/*@requires D != NULL;              @*/
/*@ensures ….                       @*/ ;
…
```

Client interface

Implementation

Library interface

NEW

- Client interface
  - Client type names
  - Prototype of client functions
- Implementation
  - Concrete type definition
  - Representation invariant function
  - Implementation of interface functions
  - Actual abstract type definition
- Library interface
  - Abstract type name
  - Prototype of exported functions

Structure of a Complex C0 Library File

```
/************ CLIENT INTERFACE ***********/
// typedef ______ *entry;
…
key entry_key(entry e)
/*@requires e != NULL;                @*/ ;
…
/************ IMPLEMENTATION ************/
// Implementation-side types
struct hdict_header {…};
typedef struct hdict_header hdict;

// Representation invariant
bool is_hdict(hdict* H) { … }

// Implementation of interface functions
entry hdict_lookup(hdict* H, key k)
/*@requires is_hdict(H);              @*/
/*@ensures ….                         @*/
{ … }
 …
// Client type
typedef hdict* hdict_t;

/*********** LIBRARY INTERFACE ***********/
// typedef ______ *hdict_t;

entry hdict_lookup(hdict_t D, key k)
/*@requires D != NULL;                @*/
/*@ensures ….                         @*/ ;
…
```

Client interface

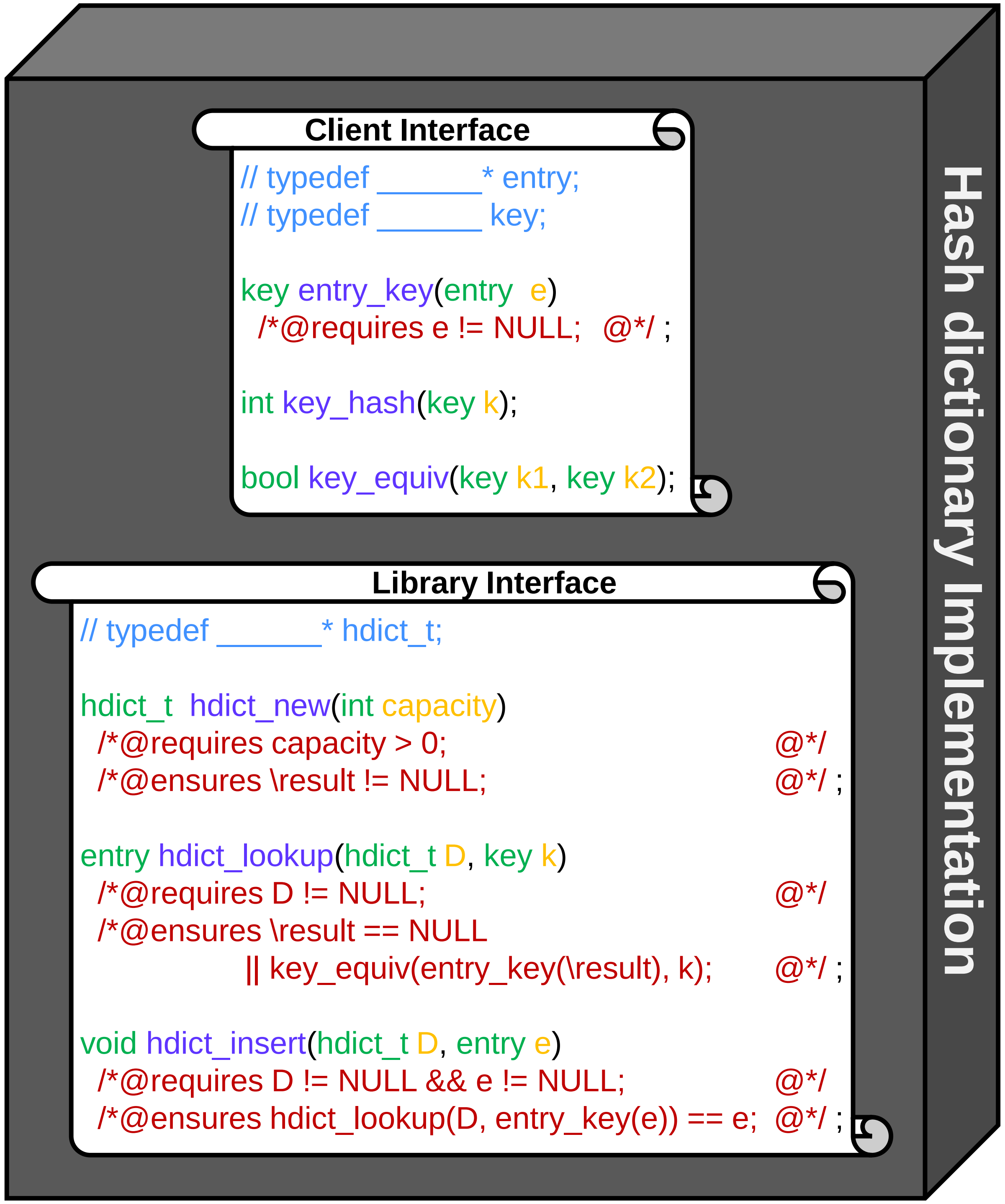
Implementation

Library interface

- By convention,
  - the client interface is on top
    - because the implementation uses the types and functions it mentions
  - the implementation is in the middle
    - it relies on the concrete client definitions
    - it ends with the definition of the abstract client type
  - the library interface is at the bottom
    - it only mentions the abstract types

Using the Library

Using the Hash Dictionary Library



- The client needs to **define** the types and functions listed in **the client interface**
- It can **use** the types and functions exported by **the library implementation**
- The client must not rely on the implementation details

Implementing our Example

You are the new produce manager of the local grocery store. You want to use a dictionary to track your fruit inventory.

- Defining the **types** requested in the client interface
  - **entries** are inventory items consisting of a fruit and a quantity
  - the fruit name is the **key**

```
// What the client wants to store in the dictionary
struct inventory_item {
  string fruit;         // key
  int quantity;
};

/******* Fulfilling the library  interface *******/
typedef struct inventory_item* entry;
typedef string key;
```

This is the concrete definition of
// typedef ______* entry;

This is the concrete definition of
// typedef ______ key;

Implementing our Example

You are the new produce manager of the local grocery store. You want to use a dictionary to track your fruit inventory.

- Defining the **functions** requested in client interface

```
/******* Fulfilling the library  interface *******/
key entry_key(entry e)
//@requires e != NULL;
{
  return e->fruit;
}

bool key_equiv(key k1, key k2) {
  return string_equal(k1, k2);
}

int key_hash(key k) {
  return lcg_hash_string(k);
}
```

The key is the fruit field of an inventory item

Two fruit are the same if they have the same name (string_equals is defined in **<string>**)

lcg_hash_string is a good hash function on strings

Client Interface Implementation

Here's the full definition of lcg_hash_string

- This defines every type and function in the client interface

Client Interface

```
// typedef _______* entry;
// typedef _______ key;

key entry_key(entry  e)
  /*@requires e != NULL;   @*/ ;

int key_hash(key k);

bool key_equiv(key k1, key k2);
```

- We store this code in a file called **produce.c0**

Client definition file

```
#use <string>

int lcg_hash_string(string s) {
  int len = string_length(s);
  int h = 0;
  for (int i = 0; i < len; i++) {
    h = h + char_ord(string_charat(s, i));
    h = 1664525 * h + 1013904223;
  }
  return h;
}

// What the client wants to store in the dictionary
struct inventory_item {
  string fruit;         // key
  int quantity;
};

/******* Fulfilling the library  interface *******/
typedef struct inventory_item* entry;
typedef string key;

key entry_key(entry e)
//@requires e != NULL;
{
  return e->fruit;
}

bool key_equiv(key k1, key k2) {
  return string_equal(k1, k2);
}

int key_hash(key k) {
  return lcg_hash_string(k);
}
```

Implementing our Example

You are the new produce manager of the local grocery store. You want to use a dictionary to track your fruit inventory.

- We can now implement the inventory application that uses hash dictionaries

  - ✓ new dictionary
  - ✓ insert A = (“apple”, 20)
  - ✓ insert B = (“banana”, 10)
  - ✓ insert C = (“pumpkin”, 50)
  - ✓ look up “apple”
  - ✓ look up “lime”
  - ✓ insert D = (“banana”, 20)

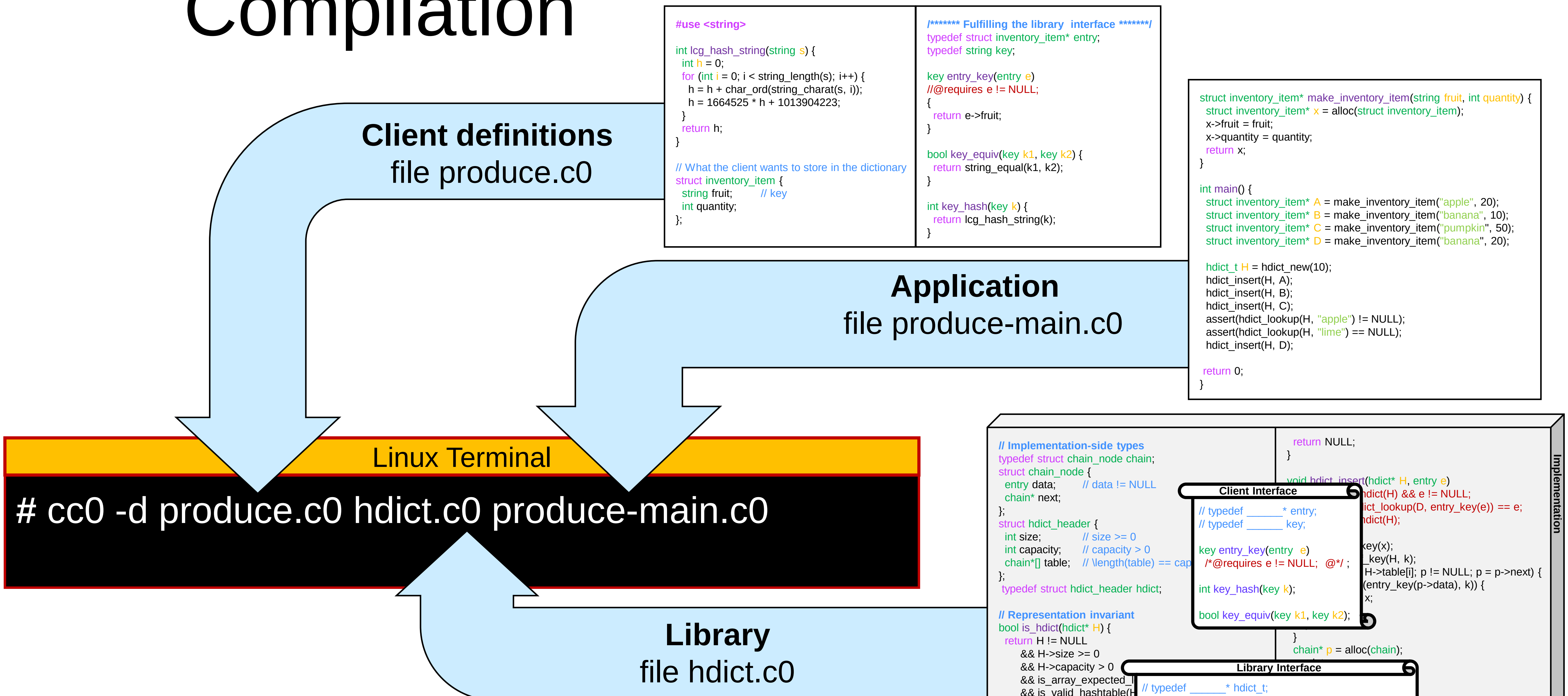
- We store this code in a file called **produce-main.c0**

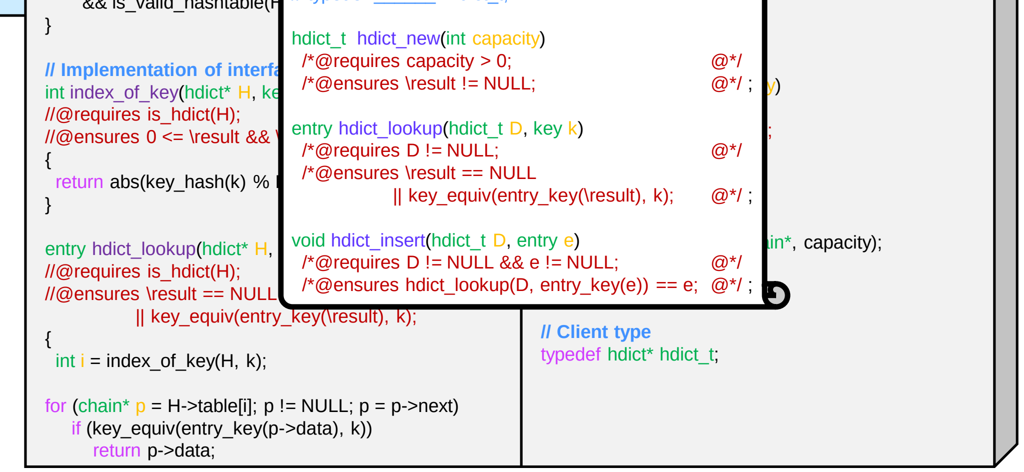
Client application file

```
struct inventory_item* make_inventory_item(string fruit, int quantity) {
  struct inventory_item* x = alloc(struct inventory_item);
  x->fruit = fruit;
  x->quantity = quantity;
  return x;
}

int main() {
  struct inventory_item* A = make_inventory_item("apple", 20);
  struct inventory_item* B = make_inventory_item("banana", 10);
  struct inventory_item* C = make_inventory_item("pumpkin", 50);
  struct inventory_item* D = make_inventory_item("banana", 20);

  hdict_t H = hdict_new(10);
  hdict_insert(H, A);
  hdict_insert(H, B);
  hdict_insert(H, C);
  assert(hdict_lookup(H, "apple") != NULL);
  assert(hdict_lookup(H, "lime") == NULL);
  hdict_insert(H, D);

 return 0;
}
```

Function that creates inventory items

Compilation





- The definition file comes **before** the library
  - the library needs the definitions it supplies
- The library comes **before** the application file
  - the application needs the functionalities it provides

Compilation

Linux Terminal

```
# cc0 -d produce.c0 hdict.c0 produce-main.c0
```

- *The definition file comes **before** the library*
  - *the library needs the definitions it supplies*
- *The library comes **before** the application file*
  - *the application needs the functionalities it provides*

- The client must split the application code into two files
  - This leads to an unnatural compilation pattern
    - We would like to compile the hash dictionary library just the way we compile a stack library

We will address this shortly

Hash Sets

Towards an Interface

- keys = entries
  - these are the elements of the set
  - a single type elem replaces key and entry
- lookup can simply return true or false
  - this now checks set membership
  - return type is bool
  - no need to signal “not found” in a special way
    - elem does not have to be a pointer type

What about Sets?

- A **set** can be understood as a special case of a dictionary
  - keys = entries
    - these are the elements of the set
  - **lookup** can simply return true or false
    - this now checks set membership
- A set implemented as a hash dictionary is called a **hash set**

The Hash Set Interface

Client Interface

```
// typedef ______ elem;

int elem_hash(elem k);

bool elem_equiv(elem k1, elem k2);
```

Library Interface

```
// typedef ______* hset_t;

hset_t  hset_new(int capacity)
  /*@requires capacity > 0;           @*/
  /*@ensures \result != NULL;         @*/ ;

bool hset_contains(hset_t S, elem e)
  /*@requires S != NULL;              @*/ ;

void hset_insert(hset_t S, elem e)
  /*@requires S != NULL;              @*/
  /*@ensures hset_contains(S, e);     @*/ ;
```

- A single type elem replaces key and entry
  - it does not need to be a pointer
- lookup checks membership
  - renamed hset_contains
  - it returns a bool
- Everything else remains the same

The implementation is left as exercise