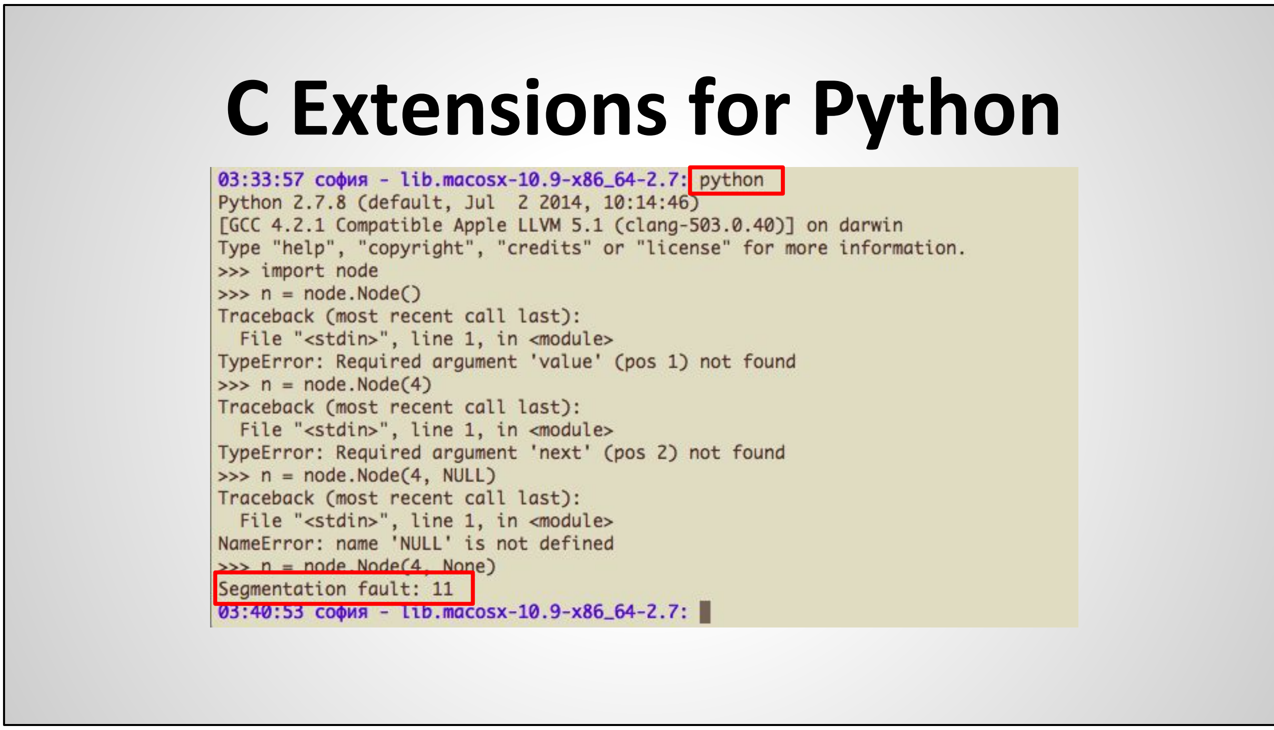


We're all here because we like Python, the programming language.

Today I'm going to talk a little about Python, the C program **underlying** that programming language, by **walking through how I learned the basics** of making a C library callable from Python code -- and vice versa.

Here's a screen shot of the first time I segfaulted the Python REPL.

Background

- Recurse Center, summer 2014
- Code & link to slides:

  github.com/sophiadavis/hash-table

I’m Sophia, an American software developer based in Amsterdam.

In the summer of 2014 I attended the Recurse Center, a sort of writers’ workshop for programmers in NYC.

This talk comes out of one of the very down-the-rabbit-hole projects I worked on while there.

Code and soon -- the slides -- for this talk are available via my github page -- my username is “sophiadavis”, and the repo is hash-table.

Background

Let’s get started. This is the story of how I shaved a yak.

Probably, if you **find yourself breaking out the Python C API docs**, you **started** with a **separate** problem --

one you thought you could solve using **tools in an existing C codebase**.

For **me**, this was a hash table implementation.

https://en.wikipedia.org/wiki/Yak

Let's talk about ~~Python~~ hash tables!

- Data structure for mapping keys to values
- `Dict`
- Very efficient:

  add -- O(1)

  lookup -- O(1)

  remove -- O(1)

This is **probably review** for most of you, but in brief:

A hash table is a **powerful** data structure for **storing key-value pairs** -- for associating keys with values, such that **every** key maps to **one** value.

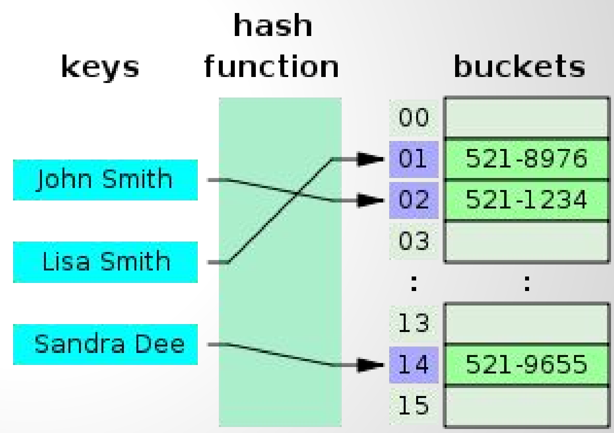
Python people tend to call them **dictionaries**.

They're **so powerful** because they're **very efficient** -- no matter how many key-value pairs you have in your hash table, the **average time complexity** of adding a key-value pair, looking up the value associated with a key, and removing a key-value pair is **constant** -- **O (1)**.

How does it achieve this amazing performance?

Hash tables -- how they work

- Array of “buckets”
- Hash function



Under the hood, a hash table is **just an array**.

We’ll call **each index** of the array a “**bucket**”. Each key-value pair **gets put** in one of these “buckets”.

And how do we know **which** key-value pair goes in which bucket? That’s where the **“hash” of “hash table”** comes in.

A “hash function” is a **mapping** of any arbitrary **input** to a **fixed set of values** -- like the set of integers.

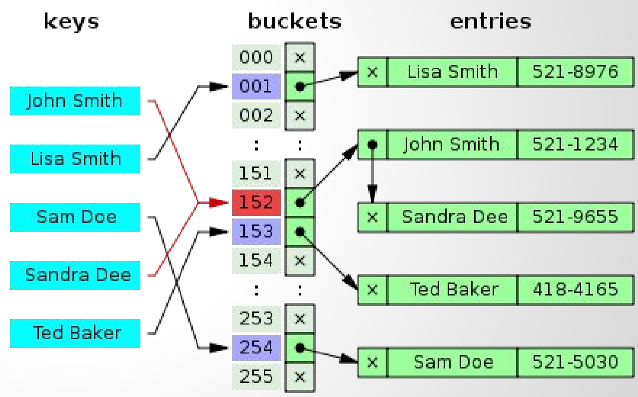
When we want to put a key and value in our hash table, we **pass the key through a hash function** to **convert** it to an integer, and use this number (**modulo** the size of the array) to determine which bucket the key-value pair should go in.
It works **similarly for** lookup and remove -- **calculate** the hash of the key, go to the **bucket associated** with the hash, and lookup or remove the value stored with that key.

Here’s a picture (thanks wikipedia) of a **phonebook stored as a hash table** -- calculate the hash value of each person’s name, **use that number to determine which bucket** in the array to put the phone number entry.

https://commons.wikimedia.org/w/index.php?curid=6471915

Hash tables -- how they work

Collisions?

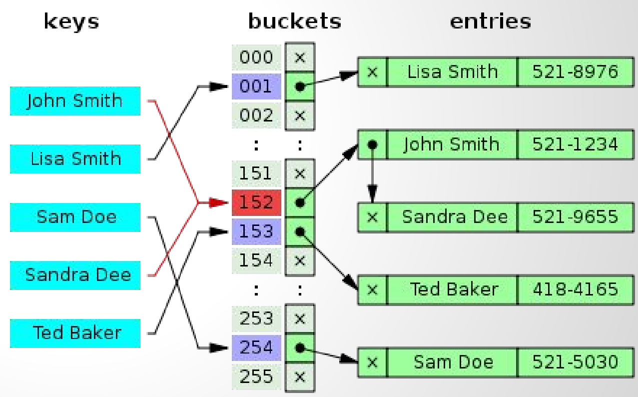


But what happens if the hash values of two keys **result in them being put in the same** bucket?

This is called a "**collision**".

Hash tables -- how they work

Collisions?



Just use a linked list!

There are a **couple ways of dealing** with this, but one way is to **store a linked list** at each bucket in the array.

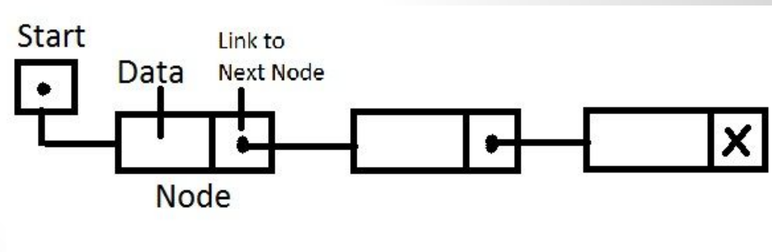
Every item that gets assigned to that bucket gets **tacked onto** the linked list.

Again looking at the **wikipedia example**, we're using a **hash function** that **results** in John Smith and Sandra Dee **being assigned to the same index** -- 152 -- so we've just **started a list** containing both entries.

Hash tables -- how they work

Linked list efficiency:

add -- O(1)
lookup -- O(n)
remove -- O(n)



But if **lots of items end up in the same** buckets, then our hash table starts to **look like a lot of linked lists**, and

the **performance** of linked lists is **not as good** as those of hash tables when **looking up or removing** an item.

A lookup or remove on a linked list, **in the average case**, involves **traversing** the list -- which is an **O(n)** operation.

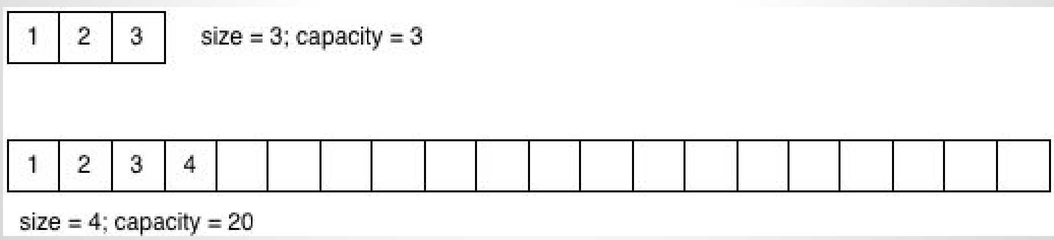
And **as we add more** items to the hash table, it is **inevitable** that more and more entries will end up in the same bins.

Consider a hash table with an **underlying array of length 1**. No matter what hash function you use, all items will be stored in the one and only bucket -- which will rapidly turn into a large linked list.

http://4.bp.blogspot.com/-ZQub4l3oliM/UfKzmX88ofI/AAAAAAAACQw/uIdj4ZF1Y4Y/s640/Link-list.jpg

Hash tables -- how they work

- ==> resize
- Max load proportion



In order **to keep average performance constant**, we'll occasionally **increase the size** of the underlying array and **redistribute** the keys.

Then (provided we're using a decent hash function), the **number of collisions will decrease** -- because we're **spreading out** the **same number** of keys among **more buckets**.

How do we know **when** to resize?

If we **keep track of the number of items** in the hash table compared to the **length** of the underlying array, we should resize when the **proportion** of items to size reaches a certain **threshhold** -- we'll call this the **maximum load proportion**.

http://dab1nmslvvntp.cloudfront.net/wp-

content/uploads/2013/04/array5b.png

How will performance be affected by:

- Initial size of array
- Hash function
- Max load proportion

So we've talked about **three variable properties** of hash tables:

- **size** of the underlying array
- hash **function**
- **maximum load proportion**

All three can **affect performance**, for example:

- initial size helps determines how **often you'll need to resize** your array (which is a **costly** operation)
- the hash function impacts **how many collisions** you may have, and **more complicated** hash functions will take **longer to evaluate**
- the **maximum load proportion** plays a role in how **long those linked lists** may get before you resize

So I wrote a C implementation

- Choose max load proportion, initial size
- API: init, add, lookup, remove, free_table
- Integers, floats, strings

T**o explore** how these affect performance, I **wrote my own** hash table implementation.

It enabled the user to **choose** the maximum load proportion and initial size of the underlying array.

My library **provided functions** to

- **initialize** a table with the given properties
- **add, lookup, and remove** key-value pairs (of **Integer, Float, and String** type)
- **free** the memory malloc’d to store the data structure (array, linked lists, data, whatever)

C API

```
HashTable *add(
      long int hash,
      union Hashable key, hash_type key_type,
      union Hashable value, hash_type value_type,
      HashTable *hashtable);
```

I also wanted to **explore** how **different hash functions** would affect performance.

This is **the signature of the “add” function** in my C implementation.

C API

```
HashTable *add(
     long int hash,
     union Hashable key, hash_type key_type,
     union Hashable value, hash_type value_type,
     HashTable *hashtable);
```

It accepts a **“hash” argument**.

My idea was the **user should do their own hashing** of the keys and **pass the hash value** in when adding, looking up, or removing an entry.

My **library** would **find** the appropriate bucket for the key-value pair based on the passed-in hash.

My hash function

```
long int calculate_hash(union Hashable key, hash_type key_type) {
    long int hash;
    switch (key_type) {
        case INTEGER:
            hash = key.i;
            break;
        case DOUBLE:
            hash = floor(key.f);
            break;
        case STRING:
            hash = strlen(key.str);
            break;
        default:
            hash = 0;
            break;
    }
    return hash;
     // TODO actually hash the keys
}
```

If the user **chose not to pass** in a hash **with** their **key**, my library used this **hand-rolled** hash function:

My hash function

```
long int calculate_hash(union Hashable key, hash_type key_type) {
    long int hash;
    switch (key_type) {
        case INTEGER:
            hash = key.i;
            break;
        case DOUBLE:
            hash = floor(key.f);
            break;
        case STRING:
            hash = strlen(key.str);
            break;
        default:
            hash = 0;
            break;
    }
    return hash;
     // TODO actually hash the keys
}
```

- if it’s an **integer**, use that integer

My hash function

```
long int calculate_hash(union Hashable key, hash_type key_type) {
    long int hash;
    switch (key_type) {
        case INTEGER:
            hash = key.i;
            break;
        case DOUBLE:
            hash = floor(key.f);
            break;
        case STRING:
            hash = strlen(key.str);
            break;
        default:
            hash = 0;
            break;
    }
    return hash;
     // TODO actually hash the keys
}
```

- if it’s a **float**, round it down and use that integer

My hash function

```
long int calculate_hash(union Hashable key, hash_type key_type) {
    long int hash;
    switch (key_type) {
        case INTEGER:
            hash = key.i;
            break;
        case DOUBLE:
            hash = floor(key.f);
            break;
        case STRING:
            hash = strlen(key.str);
            break;
        default:
            hash = 0;
            break;
    }
    return hash;
     // TODO actually hash the keys
}
```

- if it’s a **string**, use the **length** of the string
-

inspired by the hash function that -- no joke -- an **early version of PHP** used to store function names in the **symbol table**

My hash function

```
long int calculate_hash(union Hashable key, hash_type key_type) {
    long int hash;
    switch (key_type) {
        case INTEGER:
            hash = key.i;
            break;
        case DOUBLE:
            hash = floor(key.f);
            break;
        case STRING:
            hash = strlen(key.str);
            break;
        default:
            hash = 0;
            break;
    }
    return hash;
     // TODO actually hash the keys
}
```

This is basically a **terrible** hash function.

Parsing strings with C!

(I used snprintf)

Next I **set off** to do some **hard core bit-shifting** and **string manipulation** in C to **experiment** with writing my own hash functions!

Just joking.

If I were going to experiment, I'd **rather** do it in

Python

http://natashenka.ca/posters/

Now, let’s talk about Python

Wouldn’t it be nice...

```
>>> def my_awesome_python_hash(obj):
        ...

>>> hashtable.HashTable(hash_func=my_awesome_python_hash)
```

Wouldn’t it be nice if I could **write some cool hash functions** in Python,

----

and be able to **call them from my C hashtable stuff**?

Wouldn’t it be nice...

```
>>> def my_awesome_python_hash(obj):
        ...

>>> hashtable.HashTable(hash_func=my_awesome_python_hash)
```

and be able to **call them from my C hashtable stuff**?

Now, let’s talk about Python

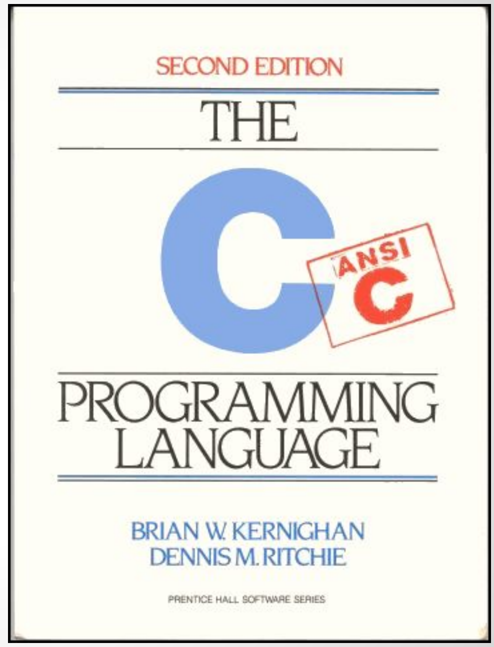
- simple
- concise
- faster to write than C...

After all, Python is so **nice and easy** to write.

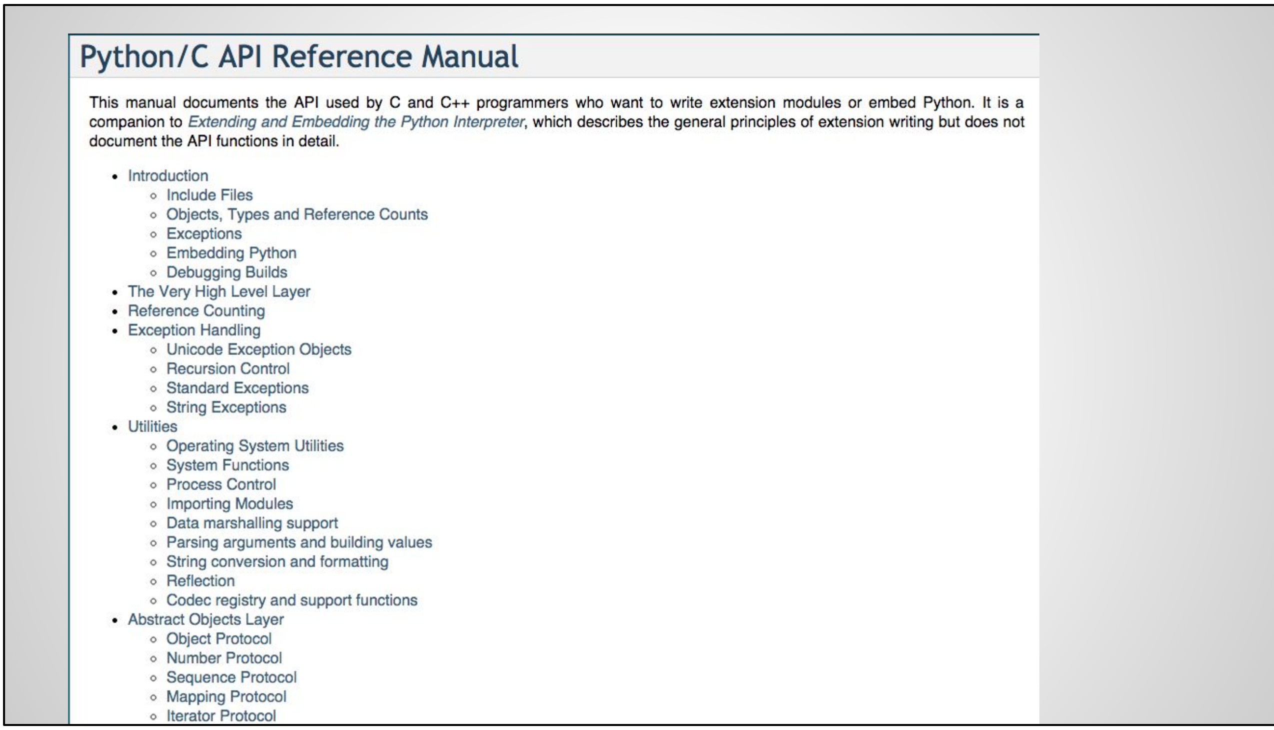
And I’m a lot **faster** writing Python than I am at writing C.

But **under the hood** ...

But it’s actually...



Python is actually a **really big and complicated C program** that **processes** the **strings of whitespace sensitive code** that we write!

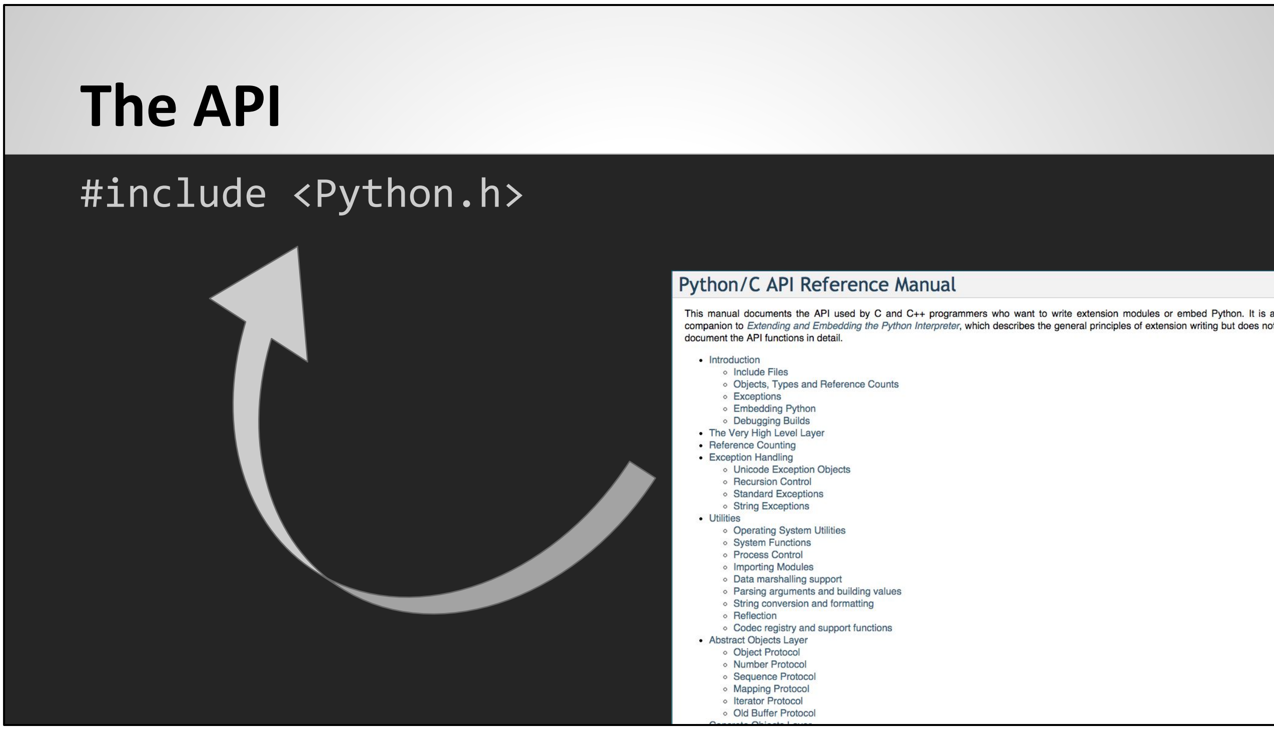


Python/C API Reference Manual

This manual documents the API used by C and C++ programmers who want to write extension modules or embed Python. It is a companion to *Extending and Embedding the Python Interpreter*, which describes the general principles of extension writing but does not document the API functions in detail.

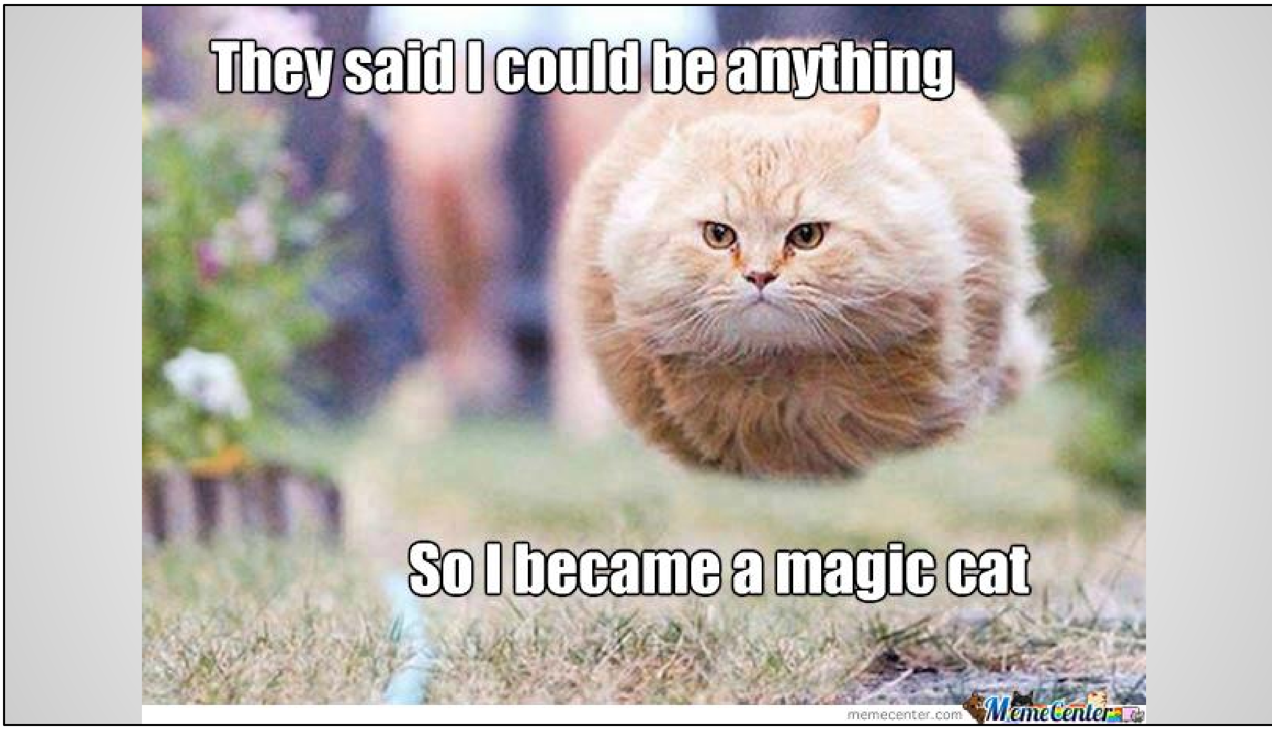
- Introduction
  - Include Files
  - Objects, Types and Reference Counts
  - Exceptions
  - Embedding Python
  - Debugging Builds
- The Very High Level Layer
- Reference Counting
- Exception Handling
  - Unicode Exception Objects
  - Recursion Control
  - Standard Exceptions
  - String Exceptions
- Utilities
  - Operating System Utilities
  - System Functions
  - Process Control
  - Importing Modules
  - Data marshalling support
  - Parsing arguments and building values
  - String conversion and formatting
  - Reflection
  - Codec registry and support functions
- Abstract Objects Layer
  - Object Protocol
  - Number Protocol
  - Sequence Protocol
  - Mapping Protocol
  - Iterator Protocol

And, thankfully, there is a **well documented API** for **bridging the gap** between python-the-programming-language and python-the-c-program.



It’s as **easy** to use this API as **including one simple line** in a C file.

Then, the magic begins.



http://img.memecdn.com/magic-cat_o_1585787.jpg

PyObject definition

```
typedef struct {
    PyObject_HEAD
    HashTable *hashtable;
    long int size;
    long int load;
    double max_load;
    PyObject *hash_func;
} HashTablePyObject;
```

My **goal** is to call a hash **function, written in pure Python**, from inside my **C hash table library**.

Disclaimer: the C API **did change** between Python **2** and Python **3**, and all code in my talk is **Python 2 specific**.

So I **started** by wrapping everything I needed to use my hash table library inside of a **struct**:

PyObject definition

```
typedef struct {
    PyObject_HEAD
    HashTable *hashtable;
    long int size;
    long int load;
    double max_load;
    PyObject *hash_func;
} HashTablePyObject;
```

- I’ve got a **pointer** to my hashtable **data structure**

PyObject definition

```
typedef struct {
    PyObject_HEAD
    HashTable *hashtable;
    long int size;
    long int load;
    double max_load;
    PyObject *hash_func;
} HashTablePyObject;
```

- some of the **other properties** associated with a hashtable -- **current load, initial size, etc.**

PyObject definition

```
typedef struct {
    PyObject_HEAD
    HashTable *hashtable;
    long int size;
    long int load;
    double max_load;
    PyObject *hash_func;
} HashTablePyObject;
```

And this PyObject **pointer** to a **hash function**.

I had **the data** that I wanted for my new Python type,

but I **needed to implement the API** telling Python **how to manage** objects of my new type.

PyObject definition

```
typedef struct {
    PyObject_HEAD
    HashTable *hashtable;
    long int size;
    long int load;
    double max_load;
    PyObject *hash_func;
} HashTablePyObject;
```

It starts with this **PyObject_HEAD**, which is a **Macro** imported with the Python headers.

This expands to **the bare minimum** you need to create a new **Python object**:

a **reference count** (I chose to ignore this at the time)

and **a pointer** to...

PyTypeObject definition

```
static PyTypeObject HashTablePyType = {
     ...
  "hashtable.HashTable",                           /* tp_name */
   (destructor)HashTablePyObject_dealloc,          /* tp_dealloc */
  (printfunc)HashTablePy_print,                    /* tp_print */
  (reprfunc)HashTablePy_repr,                      /* tp_repr */
  HashTablePy_methods,                             /* tp_methods */
  HashTable_members,                               /* tp_members */
  (initproc)HashTablePyObject_init,                /* tp_init */
  (freefunc)HashTablePyObject_free,                /* tp_free */
     ...
};
```

This “**PyTypeObject**” thing,

which is just a **struct of function pointers** defining **how Python should manage** objects of the hash table **type** -- things like:

PyTypeObject definition

```
static PyTypeObject HashTablePyType = {
    ...
  "hashtable.HashTable",                         /* tp_name */
   (destructor)HashTablePyObject_dealloc,         /* tp_dealloc */
  (printfunc)HashTablePy_print,                  /* tp_print */
  (reprfunc)HashTablePy_repr,                    /* tp_repr */
  HashTablePy_methods,                           /* tp_methods */
  HashTable_members,                             /* tp_members */
  (initproc)HashTablePyObject_init,              /* tp_init */
  (freefunc)HashTablePyObject_free,              /* tp_free */
    ...
};
```

- class name

PyTypeObject definition

```
static PyTypeObject HashTablePyType = {
     ...
  "hashtable.HashTable",                         /* tp_name */
   (destructor)HashTablePyObject_dealloc,        /* tp_dealloc */
  (printfunc)HashTablePy_print,                  /* tp_print */
  (reprfunc)HashTablePy_repr,                    /* tp_repr */
  HashTablePy_methods,                           /* tp_methods */
  HashTable_members,                             /* tp_members */
  (initproc)HashTablePyObject_init,              /* tp_init */
  (freefunc)HashTablePyObject_free,              /* tp_free */
     ...
};
```

- how to print or repr

PyTypeObject definition

```
static PyTypeObject HashTablePyType = {
    ...
  "hashtable.HashTable",                           /* tp_name */
  (destructor)HashTablePyObject_dealloc,           /*tp_dealloc */
  (printfunc)HashTablePy_print,                    /* tp_print */
  (reprfunc)HashTablePy_repr,                      /* tp_repr */
  HashTablePy_methods,                             /* tp_methods */
  HashTable_members,                               /* tp_members */
  (initproc)HashTablePyObject_init,                /* tp_init */
  (freefunc)HashTablePyObject_free,                /* tp_free */
    ...
};
```

- And how to **initialize**, **delete**, and **free the memory allocated** to hold objects --
-

I'll **come back** to these later

There's **a lot more** that I left out.

Module definition

```
PyMODINIT_FUNC inithashtable(void) {
  PyObject* m;
  static char hashtable__doc__[] = "This module...";

  HashTablePyType.tp_new = PyType_GenericNew;
  if (PyType_Ready(&HashTablePyType) < 0)
      return;

  m = Py_InitModule3("hashtable",HashTablePy_methods,hashtable__doc__);

  Py_INCREF(&HashTablePyType);
  PyModule_AddObject(m, "HashTable", (PyObject *)&HashTablePyType);
}
```

I had a **basic type** defined, but I needed some **way to use this type within Python code**.

So I **created a module** to contain my hash table type.

Note that module initialization is one **aspect** of the C API that **changed** between Python **2** and Python **3**, and this code is **Python 2 specific**.

In order **to initialize** a module, you need a **PyMODINIT_FUNC** function with the name **init<modulename>** (so **inithashtable** in my case).

When a **Python program imports** a module for the **first time**, this is the function that gets run.

Again, I've left a few things out, but **of note** are:

Module definition

```
PyMODINIT_FUNC inithashtable(void) {
  PyObject* m;
  static char hashtable__doc__[] = "This module...";

  HashTablePyType.tp_new = PyType_GenericNew;
  if (PyType_Ready(&HashTablePyType) < 0)
      return;

  m = Py_InitModule3("hashtable",HashTablePy_methods,hashtable__doc__);

  Py_INCREF(&HashTablePyType);
  PyModule_AddObject(m, "HashTable", (PyObject *)&HashTablePyType);
}
```

if (PyType_Ready(&HashTablePyType) < 0)
    Return;

⇒ This **initializes the type**, and **fills in** more of the **PyTypeObject** with compiler-specific functions.

Module definition

```
PyMODINIT_FUNC inithashtable(void) {
  PyObject* m;
  static char hashtable__doc__[] = "This module...";

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  PyModule_AddObject(m, "HashTable", (PyObject *)&HashTablePyType);
}
```

Initializing the module.

Module definition

```
PyMODINIT_FUNC inithashtable(void) {
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  if (PyType_Ready(&HashTablePyType) < 0)
      return;

  m = Py_InitModule3("hashtable",HashTablePy_methods,hashtable__doc__);

  Py_INCREF(&HashTablePyType);
  PyModule_AddObject(m, "HashTable", (PyObject *)&HashTablePyType);
}
```

And finally, this line **adds my new type to the module dictionary**,

allowing us to **create** new objects **via the class**.

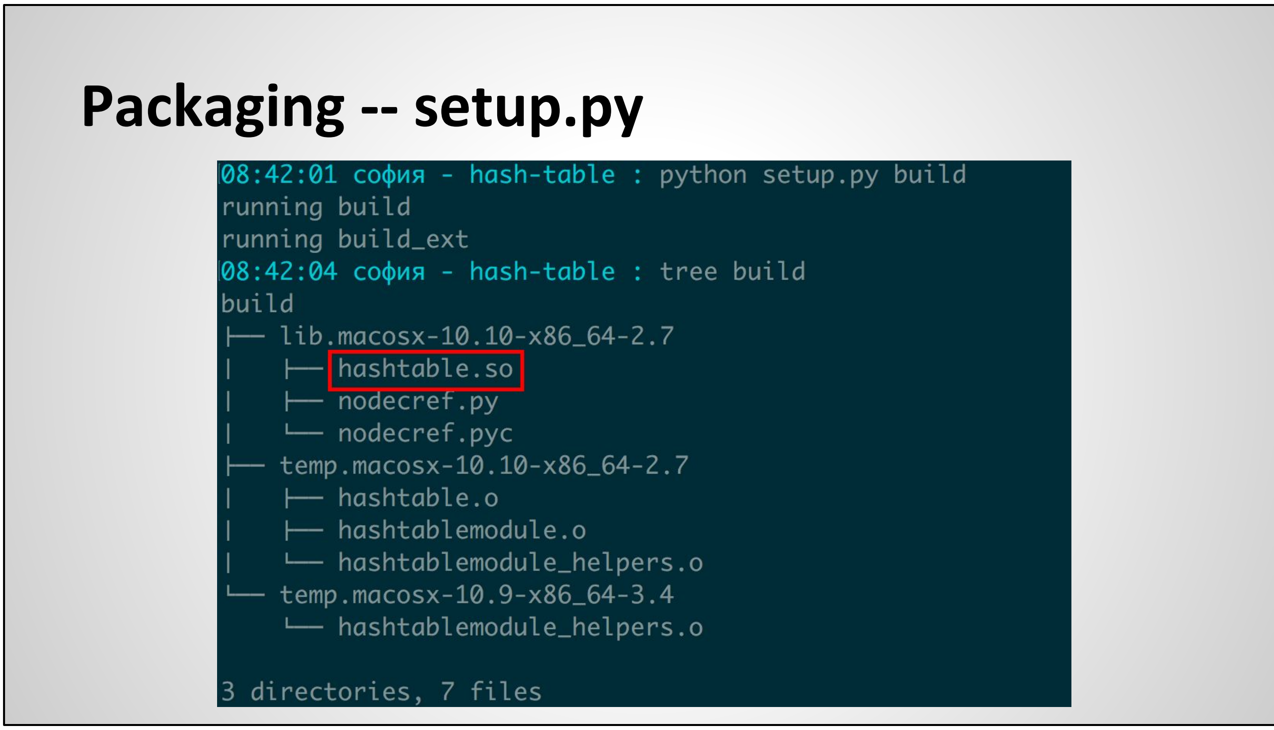
Packaging -- setup.py

```
from distutils.core import setup, Extension
setup(name="hashtable", version="1.0",
      ext_modules=[
         Extension("hashtable", ["hashtablemodule_helpers.c",
                                 "hashtablemodule.c",
                                 "hashtable.c"])])
```

There are **multiple ways to package** a Python module.

One **simple way** is to write a **setup.py** file telling Python:
the **name** of your module
which **C files** your module needs, etc.

This is the **entire contents** of my setup.py file.



Running “python setup.py **build**” creates a “build” **subdirectory** inside your working directory,

and **outputs a compiled file containing your extension**

that can be **dynamically loaded** into a Python program.

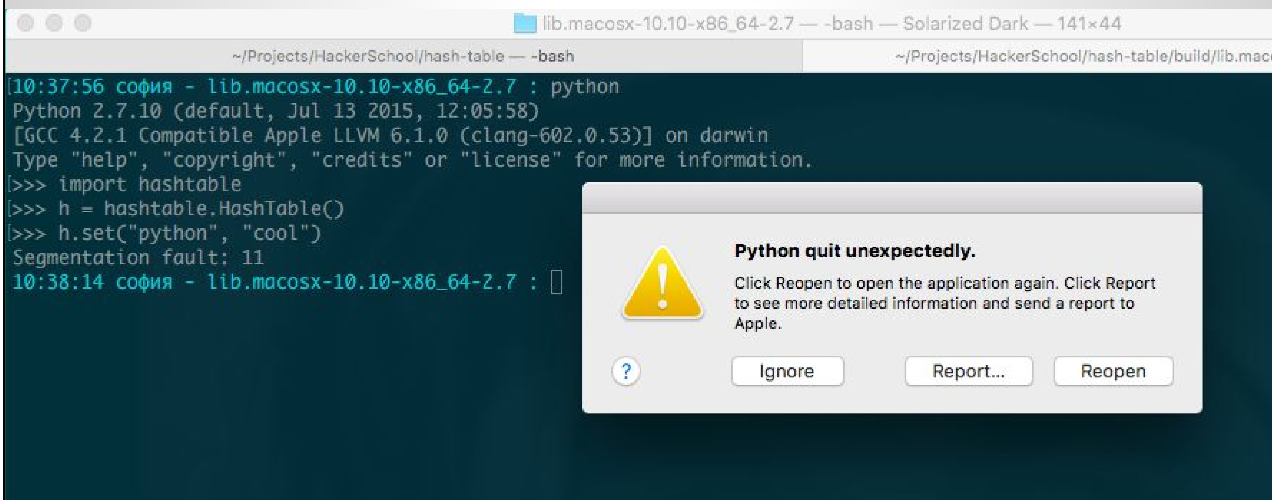
On **Unix**, this is a “**shared object**” file.

I use a mac, so my module was named “hashtable.so”.

On **Windows**, this would be a DLL with a “.pyd” extension.

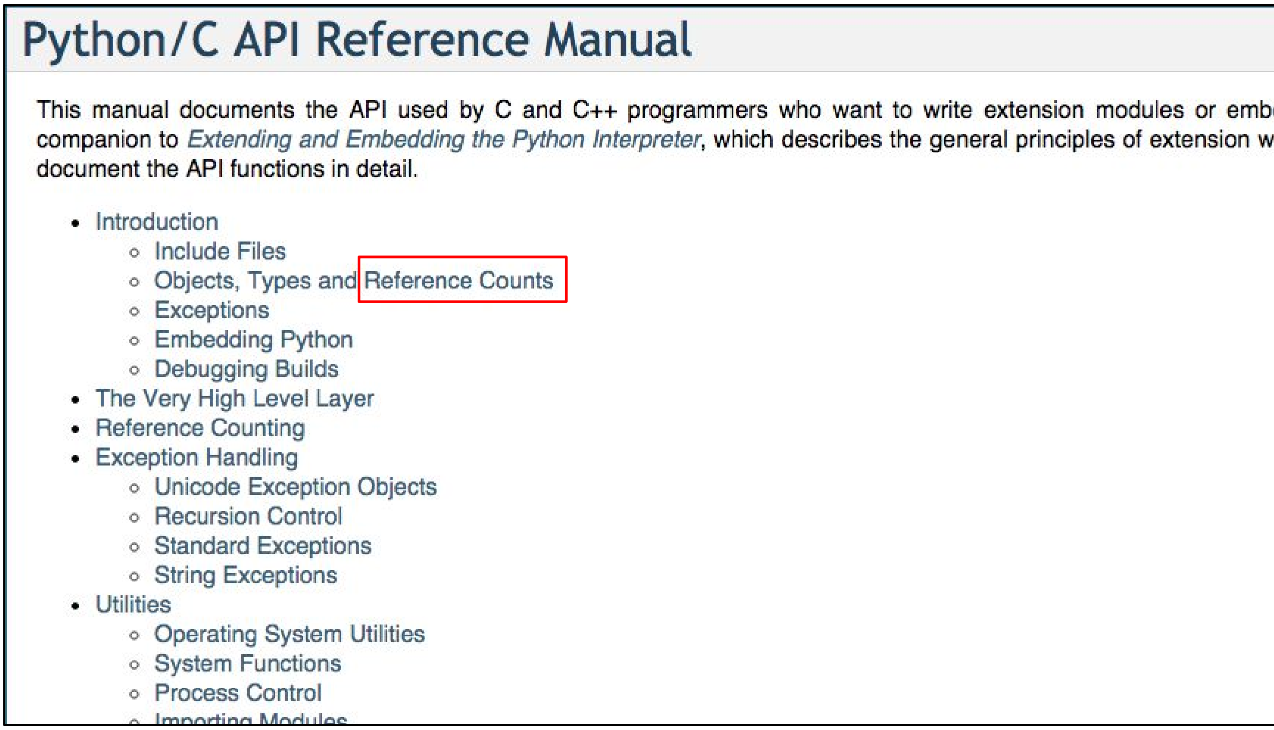
If you **start up** a Python interpreter or **run** a Python program **in the same directory** as that file,
then you can **type “import hashtable”** and do hashtable stuff from Python!

Do hashtable stuff in Python!



Well, sort of...

My program kept segfaulting.



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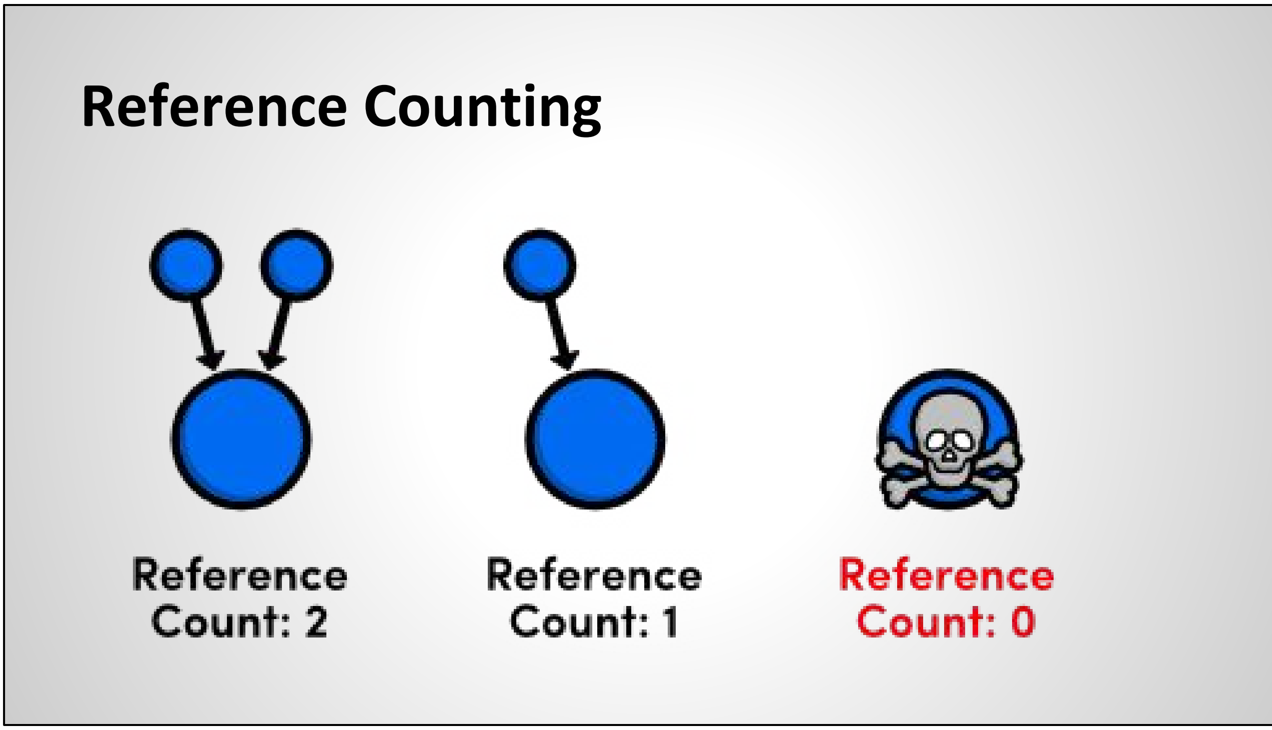
  - String Exceptions
- Utilities
  - Operating System Utilities
  - System Functions
  - Process Control
  - Importing Modules

I was forced to look at a section of the API docs that I had kinda been ignoring -- the section on reference counting.



One reason why Python is **so nice** is that it’s a **pretty high level** language. It handles a lot of things **for** the programmer -- for example, memory management.

When you **use data** in a Python program, **Python** takes care of **dealing with the os** to ensure that **the data is stored in memory**. However, if Python **only *added* to your program’s memory**, eventually the program will run out of memory.

So Python needs to know **when it can remove data** from memory, once that data isn’t being used any more.

Python-the-C-program uses a method called **reference counting to know when it can safely free objects**. It keeps track of the **number of other things referring to a given object**.
When that “reference count” **drops to 0**, **Python cleans up** the unneeded object by **calling the “deallocation” function** defined for its type.

http://rypress.com/tutorials/objective-c/media/memory-management/reference-counting.png

Here are **two tools** that can help us understand reference counting:

From the sys module, we have the **getrefcount** function.

From the gc, "**garbage collection**", module, we have **get_referrers**, which returns a list of all things referencing an object.

Reference Counting

```
import gc
import sys
def show_ref_counts(an_object, times_to_call=1, show_referrers=False):
       if times_to_call > 0:
          referrers = gc.get_referrers(an_object)
          refcount = len(referrers)

          print "--> In function, refcount: {}".format(refcount)

          if show_referrers:
               print "---> referrers: {}".format(referrers)

          show_ref_counts(an_object, times_to_call - 1)
```

Here, I've written a function, show_ref_counts.

Reference Counting

```
import gc
import sys
def show_ref_counts(an_object, times_to_call=1, show_referrers=False):
       if times_to_call > 0:
          referrers = gc.get_referrers(an_object)
          refcount = len(referrers)

          print "--> In function, refcount: {}".format(refcount)

          if show_referrers:
               print "---> referrers: {}".format(referrers)

          show_ref_counts(an_object, times_to_call - 1)
```

All it does is **find the objects referring** to the **argument named an_object**.

Reference Counting

```
import gc
import sys
def show_ref_counts(an_object, times_to_call=1, show_referrers=False):
       if times_to_call > 0:
          referrers = gc.get_referrers(an_object)
          refcount = len(referrers)

          print "--> In function, refcount: {}".format(refcount)

          if show_referrers:
               print "---> referrers: {}".format(referrers)

          show_ref_counts(an_object, times_to_call - 1)
```

And **print out how many** there are.

Reference Counting

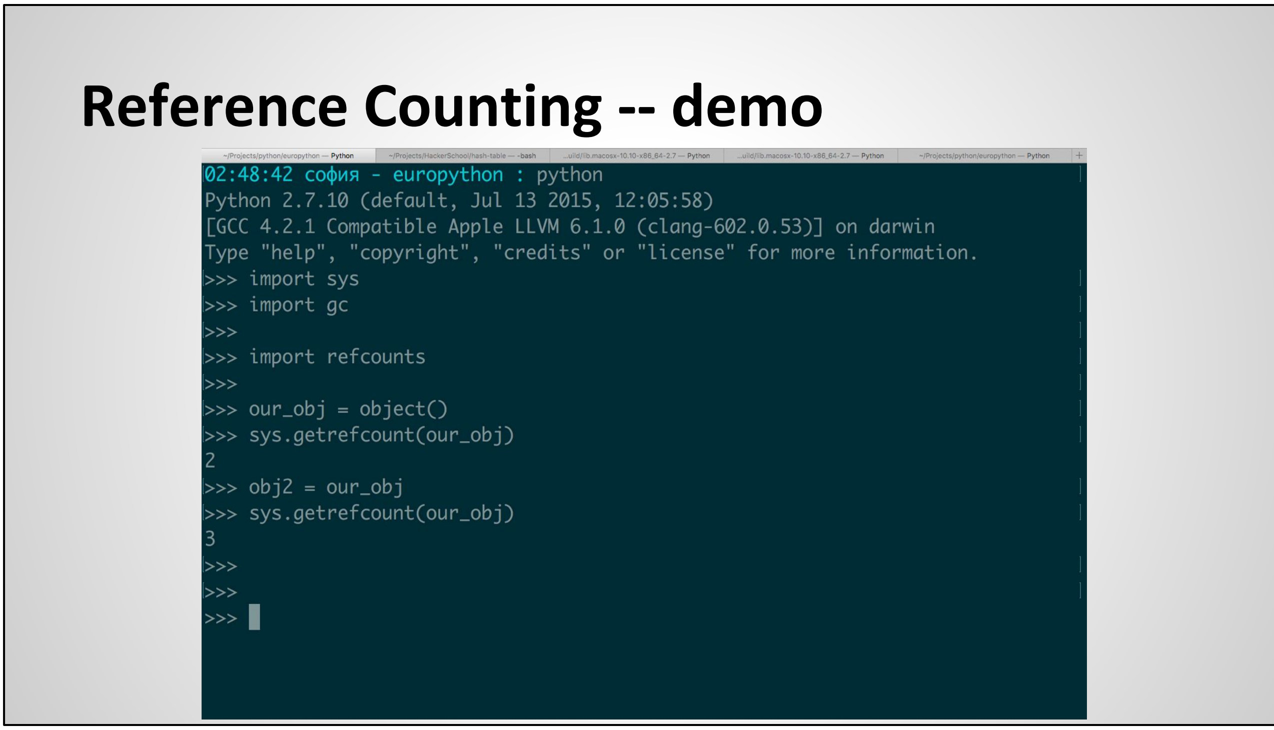
```
import gc
import sys
def show_ref_counts(an_object, times_to_call=1, show_referrers=False):
       if times_to_call > 0:
          referrers = gc.get_referrers(an_object)
          refcount = len(referrers)

          print "--> In function, refcount: {}".format(refcount)

          if show_referrers:
               print "---> referrers: {}".format(referrers)

          show_ref_counts(an_object, times_to_call - 1)
```

Plus, it can **optionally call itself** multiple times.

Reference Counting

```
import gc
import sys
def show_ref_counts(an_object, times_to_call=1, show_referrers=False):
       if times_to_call > 0:
           referrers = gc.get_referrers(an_object)
           refcount = len(referrers)

           print "--> In function, refcount: {}".format(refcount)

           if show_referrers:
                print "---> referrers: {}".format(referrers)

           show_ref_counts(an_object, times_to_call - 1)
```

And **optionally print out extra details** -- about exactly ***which*** objects **own references** to the argument "an_object".



So, in a **Python shell**, we're going to **import** the tools we need: the sys and gc modules, and **my function** (from a file called "refcounts").

First, we'll **instantiate** an object...
If we **assign another variable** to that object...

What exactly is referring to our object? We'll use the **get_referrers** function...
So there's a **dict,** with the two variables we assigned to our object at memory location blah. That dictionary is the **namespace of local variables**.

Now, what happens to the reference count on our object **if we pass it as an argument to a function**?

We'll use that function "**show_ref_counts**".
First we'll just **call it once**, passing in our object, *showing* details on the referrers.
There's still the local namespace, **plus something new** -- a "frame" object, that now owns a reference to our_object.

And if we call "show_ref_counts" **again**, this time having it **call itself lots** of

times.
We see that each time, the **reference count increases** by one -- and if we were looking at the details, we'd **see a new "frame" object added** to the referrers with each call.

Reference Counting

PyINCREF

PyDECREF

If you're going to **write a C extension** and **work with Python objects**, first, you need to **signal to Python** when your program **starts working** with a certain object, by triggering Python to **increase the reference count** on this object by one, thereby keeping it in memory while you -- represented by that one -- need it. Otherwise, **if** this reference count **drops** to 0, Python will free the object.
When your program tries to use the object -- now in a piece of memory that has been **released back** to the os, your program will crash (hopefully, or weird shit will happen).

You also need to take care to **tell Python when you're done** working with a certain object **by decrementing** its reference count by one.
If you **don't** do your part in decrementing the ref count on that object, its reference count **can never decrease** to 0, and **it will never**

be freed from memory. This is a **memory leak**.

The Python C API provides **two macros** to communicate when you're starting to work with an object and when you're finished working with an object.
Calling **PyINCREF** on an object increases its reference count by 1.
Calling **PyDECREF** decreases its reference count by one, and, if the reference count has reached 0, it **calls the deallocation** function for the type.

Forgetting to PyINCREF

```
static void
HashTablePyObject_dealloc(HashTablePyObject* self)
{
    printf("C: ---------> Dealloc-ing\n");

    Py_XDECREF(self->hash_func);
    if (self->hashtable != NULL) {
        self->ob_type->tp_free((PyObject*)self);
    }
}
```

So, what happens when you **forget to PyINCREF** an object that you need to work on?

Remember that **PyTypeObject** thing -- the struct of function pointers that defined the Python API for my type?

I had **defined** this as the “**deallocation**” function for Python to call when the reference count of a hash table object reaches 0.

It does **2 important** things:

- **printf debugging** so we can see when it’s being called
- AND

Forgetting to PyINCREF

```
static void
HashTablePyObject_dealloc(HashTablePyObject* self)
{
    printf("C: ---------> Dealloc-ing\n");

    Py_XDECREF(self->hash_func);
    if (self->hashtable != NULL) {
        self->ob_type->tp_free((PyObject*)self);
    }
}
```

Calling the free function that I had defined for my type (**via** the PyTypeObject struct).

Forgetting to PyINCREF

```
static void
HashTablePyObject_free(HashTablePyObject* self)
{
    printf("C: ---------> Free-ing\n");
    free_table(self->hashtable);
}
```

That free function (has some nice **printf's**),

then calls the **free_table** function provided by my **initial C program** to free the memory malloc'd for the hash table.

Forgetting to PyINCREF

```
static HashTablePyObject *
HashTablePy_set(HashTablePyObject *self, PyObject *args)
{
        ## parse key/value types, handle errors, etc. ...

        # At first, I didn't have this:
        // Py_INCREF(self);

        ## Update the hashtable...

        # But
        return self;
}
```

Initially, the `**set**` method of my hashtable **returned the hashtable object** -- see: “return self”.

Now, there are a **lot of rules (and exceptions)** about in which situations **the caller vs the callee is responsible** for PyINCREFing arguments, and I barely scratched the surface.

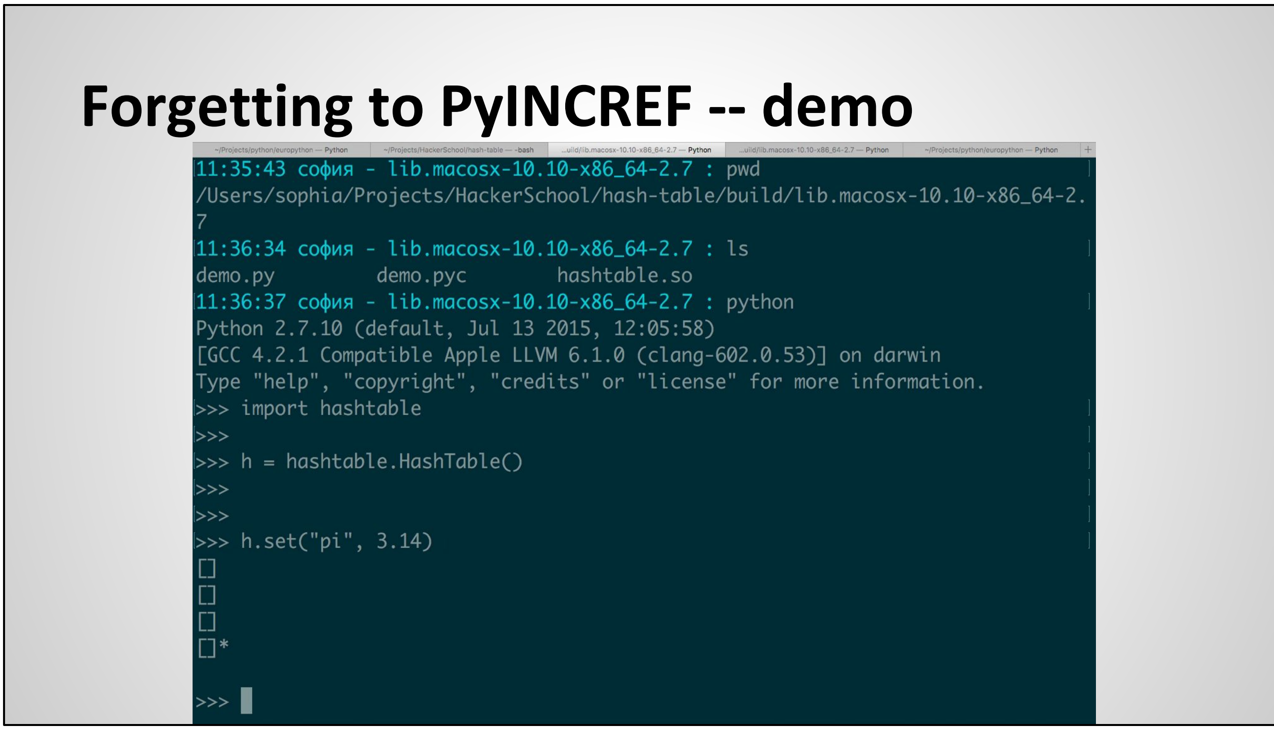
However, I think I **caused a problem** here
because if a C function **returns a reference** to an object -- like ‘self’ here -- then that reference **must be owned by the function** --

i.e. the object must have been PyINCREF’d inside the function.

Forgetting to PyINCREF

```
static HashTablePyObject *
HashTablePy_set(HashTablePyObject *self, PyObject *args)
{
        ## parse key/value types, handle errors, etc. ...

        # At first, I didn't have this:
        // Py_INCREF(self);

        ## Update the hashtable...

       # But
       return self;
}
```

But I had left that out.



First, we’ll use the **setup.py script** to build our module.
And I have **another window** open to the **build** directory.
There’s our **.so file**.
And if we **start up** the python repl, then we can **import** the module.
I’ll **instantiate** a new hash table object, and start **setting** some values.

Remember that `set` returns the hash table object -- so **that’s the string representation** of our object which was just returned from the method: each **square** represents a **bucket**, and each **star** represents a key-value **pair** that was assigned to the **linked list** at that bucket.

Uh - oh, so we just saw the **printfs** --
we didn’t tell Python to increase the reference count on that hash table.
But all other referrers must have **released their references** to that hash table, its reference count **has dropped to 0**, and the **clean-up**

functions have been called.

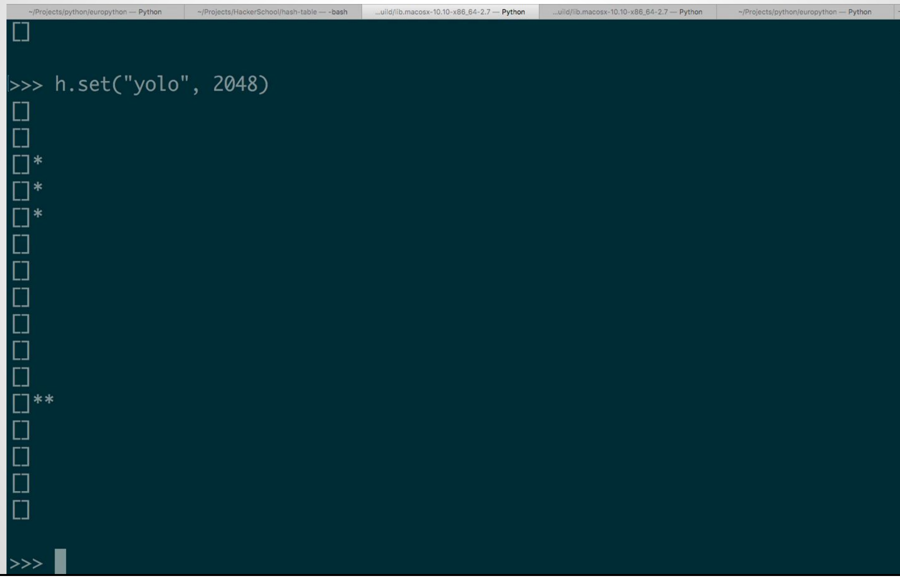
So now if we try to do anything with the object... Python **segfaults**.

Forgetting to PyINCREF

```
static HashTablePyObject *
HashTablePy_set(HashTablePyObject *self, PyObject *args)
{
       ## parse key/value types, handle errors, etc. ...

       # At first, I didn't have this:
       Py_INCREF(self);

       ## Update the hashtable...

       # But
       return self;
}
```

So let’s add that Py_INCREF.

Forgetting to PyINCREF -- demo



I’ve **rebuilt** the module and am **starting** up the python repl again...

Import the module, **instantiate** a new hash table and start setting values.

We’ll set pi, set some squares, hey look! It **resized**! .... set “yolo”! It resized again, great. Looks like we’re **not segfaulting** any more.

Forgetting to PyDECREF

```
typedef struct {
    PyObject_HEAD
    HashTable *hashtable;
    long int size;
    long int load;
    double max_load;
    PyObject *hash_func;
} HashTablePyObject;
```

The **other type of mistake** you can make is **forgetting** to call **PyDECREF** when you're done with an object.

Remember that my Python HashTable type struct contained a pointer to **another Python object** --

namely, the **hash function** used to hash keys.

Forgetting to PyDECREF

```
static int
HashTablePyObject_init(HashTablePyObject *self, PyObject *args)
{
 ...
    if (hash_func == NULL) {
        self->hash_func = default_py_hash_func();
    }
    else {
        self->hash_func = hash_func;
    }
    Py_INCREF(self->hash_func);
}
```

Here’s a snippet from the **initialization** function of my HashTable.

Forgetting to PyDECREF

```
static int
HashTablePyObject_init(HashTablePyObject *self, PyObject *args)
{
 ...
    if (hash_func == NULL) {
        self->hash_func = default_py_hash_func();
    }
    else {
        self->hash_func = hash_func;
    }
    Py_INCREF(self->hash_func);
}
```

Along with some **other stuff**, I **set** the object’s **hash_func attribute**:

either to the hash function **passed in** when the instance was **initialized**

Forgetting to PyDECREF

```
static int
HashTablePyObject_init(HashTablePyObject *self, PyObject *args)
{
 ...
    if (hash_func == NULL) {
        self->hash_func = default_py_hash_func();
    }
    else {
        self->hash_func = hash_func;
    }
    Py_INCREF(self->hash_func);
}
```

or to Python's **built-in** hash function by **default**

Forgetting to PyDECREF

```
static int
HashTablePyObject_init(HashTablePyObject *self, PyObject *args)
{
 ...
    if (hash_func == NULL) {
        self->hash_func = default_py_hash_func();
    }
    else {
        self->hash_func = hash_func;
    }
    Py_INCREF(self->hash_func);
}
```

And I **increase** the reference count on this hash_function **object** --

I need to **tell Python** that I'm going to be working with this function for a while, please **don't clean it up**.

We say that **each hash table object owns a reference** to a hash function object.

Forgetting to PyDECREF

```
static void
HashTablePyObject_dealloc(HashTablePyObject* self)
{
    Py_XDECREF(self->hash_func);
    if (self->hashtable != NULL) {
        self->ob_type->tp_free((PyObject*)self);
    }
}
```

Conversely, in the deallocation function for my type, I tell Python to **decrement the reference count** on that hash function object.

Here's a simple demo.

Forgetting to PyDECREF

```
def main():
    print "main: {} referrers".format(sys.getrefcount(hash))
    do_hashtable_stuff()
    do_hashtable_stuff()
    do_hashtable_stuff()
    print "main: {} referrers".format(sys.getrefcount(hash))

def do_hashtable_stuff():
    h = hashtable.HashTable(hash_func=hash)
    print "do_ht_stuff: {} referrers".format(sys.getrefcount(hash))
    print "leaving do_ht_stuff"
```

We’re going to **look at the reference count** on Python’s **built-in hash function**.

We have **a function do_hashtable_stuff**, which

Forgetting to PyDECREF

```
def main():
    print "main: {} referrers".format(sys.getrefcount(hash))
    do_hashtable_stuff()
    do_hashtable_stuff()
    do_hashtable_stuff()
    print "main: {} referrers".format(sys.getrefcount(hash))

def do_hashtable_stuff():
    h = hashtable.HashTable(hash_func=hash)
    print "do_ht_stuff: {} referrers".format(sys.getrefcount(hash))
    print "leaving do_ht_stuff"
```

initializes a hash table **with the built-in hash function**.

So our hash table object will **own a reference** to the built-in hash function.

Forgetting to PyDECREF

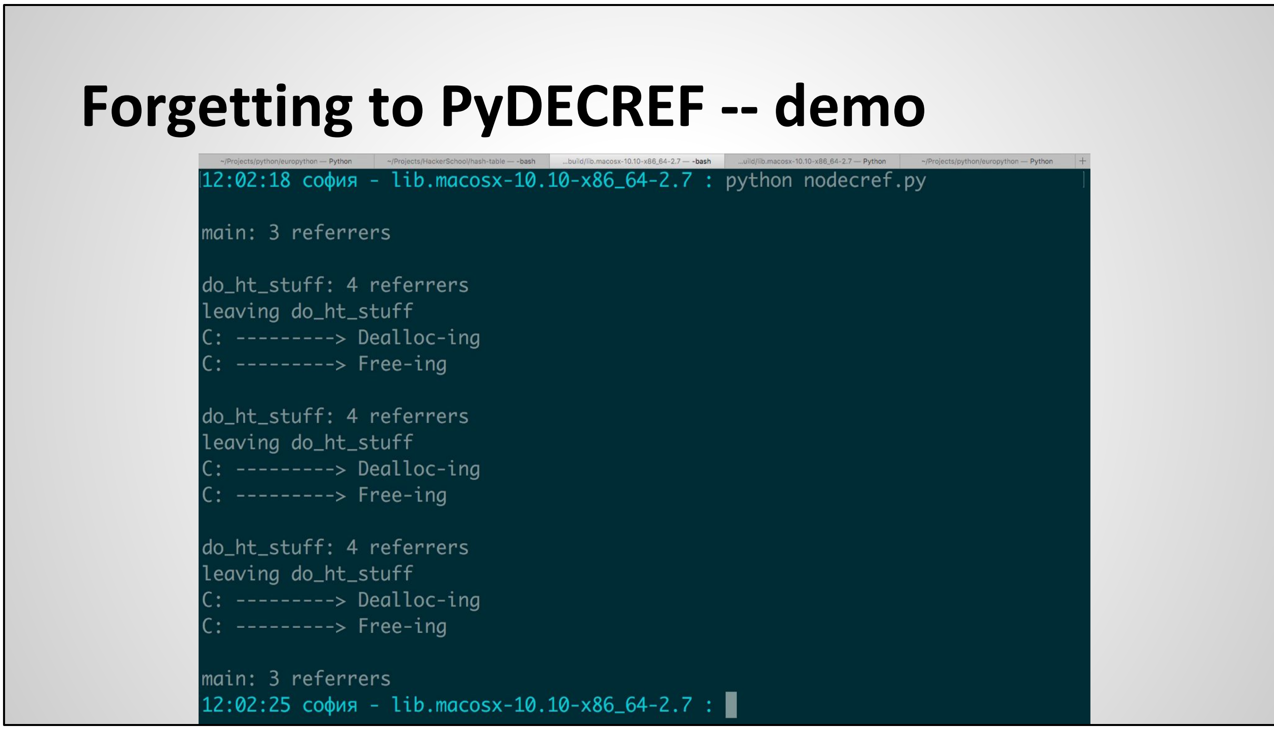
```
def main():
    print "main: {} referrers".format(sys.getrefcount(hash))
    do_hashtable_stuff()
    do_hashtable_stuff()
    do_hashtable_stuff()
    print "main: {} referrers".format(sys.getrefcount(hash))

def do_hashtable_stuff():
    h = hashtable.HashTable(hash_func=hash)
    print "do_ht_stuff: {} referrers".format(sys.getrefcount(hash))
    print "leaving do_ht_stuff"
```

It prints the reference count on the hash function object

Forgetting to PyDECREF

```
def main():
    print "main: {} referrers".format(sys.getrefcount(hash))
    do_hashtable_stuff()
    do_hashtable_stuff()
    do_hashtable_stuff()
    print "main: {} referrers".format(sys.getrefcount(hash))

def do_hashtable_stuff():
    h = hashtable.HashTable(hash_func=hash)
    print "do_ht_stuff: {} referrers".format(sys.getrefcount(hash))
    print "leaving do_ht_stuff"
```

This program just calls do_hashtable_stuff a couple times.



Let's look at **how the reference count** on the built-in hash function **changes**.

So, I've just run the **build step**, and I'm going to **run my program**.

Initially, the reference count is 3.

Each time we **enter** do_hashtable_stuff and **instantiate** a new hash table that **owns a reference** to the builtin hash function,
the **reference count on that function object** increases by one -- to 4.

And each time **do_hashtable_stuff completes**, the hash table that initialized inside **goes out of scope**.
The reference count on the *hash table* drops to 0, **triggering the deallocation function** for hash tables.

Forgetting to PyDECREF

```
static void
HashTablePyObject_dealloc(HashTablePyObject* self)
{
    Py_XDECREF(self->hash_func);
    if (self->hashtable != NULL) {
        self->ob_type->tp_free((PyObject*)self);
    }
}
```

This function.

Which **triggers a PyDECREF** on the built-in hash function object.

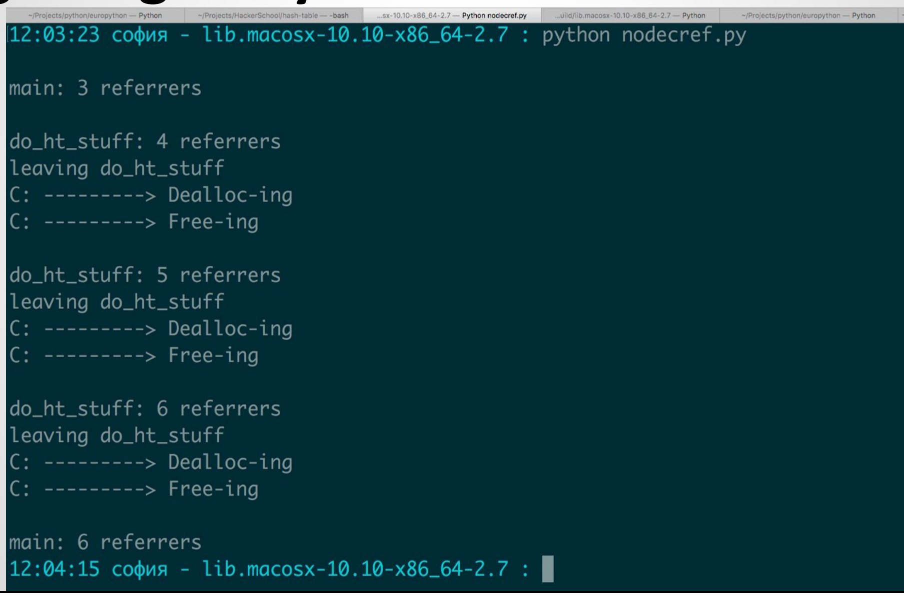
So after calling do_hashtable_stuff a couple of times, we **still** just have a **reference count of 3 on the builtin hash function**!

Forgetting to PyDECREF

```
static void
HashTablePyObject_dealloc(HashTablePyObject* self)
{
    // Py_XDECREF(self->hash_func);
    if (self->hashtable != NULL) {
        self->ob_type->tp_free((PyObject*)self);
    }
}
```

But let’s just say we had forgotten to decrease that ref count.

Forgetting to PyDECREF -- demo



So, I've just run **the build step** -- **removing** that PyDECREF, and I'm going to **run the program** again.

Initially, the reference count is still 3.

Each time we enter do_hashtable_stuff and instantiate a new hash table owning a reference to the builtin hash function, the reference count on the function object increases by one.

And each time do_hashtable_stuff completes, its hash table goes out of scope, the reference count on the *hash table* drops to 0, and its deallocation function is called.

But **nowhere did we release the reference on the built-in hash function**.

So after calling do_hashtable_stuff a couple of times, the reference count on the builtin hash function has **increased from 3 to 6**.

Even though **the objects that owned those last three references have themselves been freed**.

This is a **memory leak**!

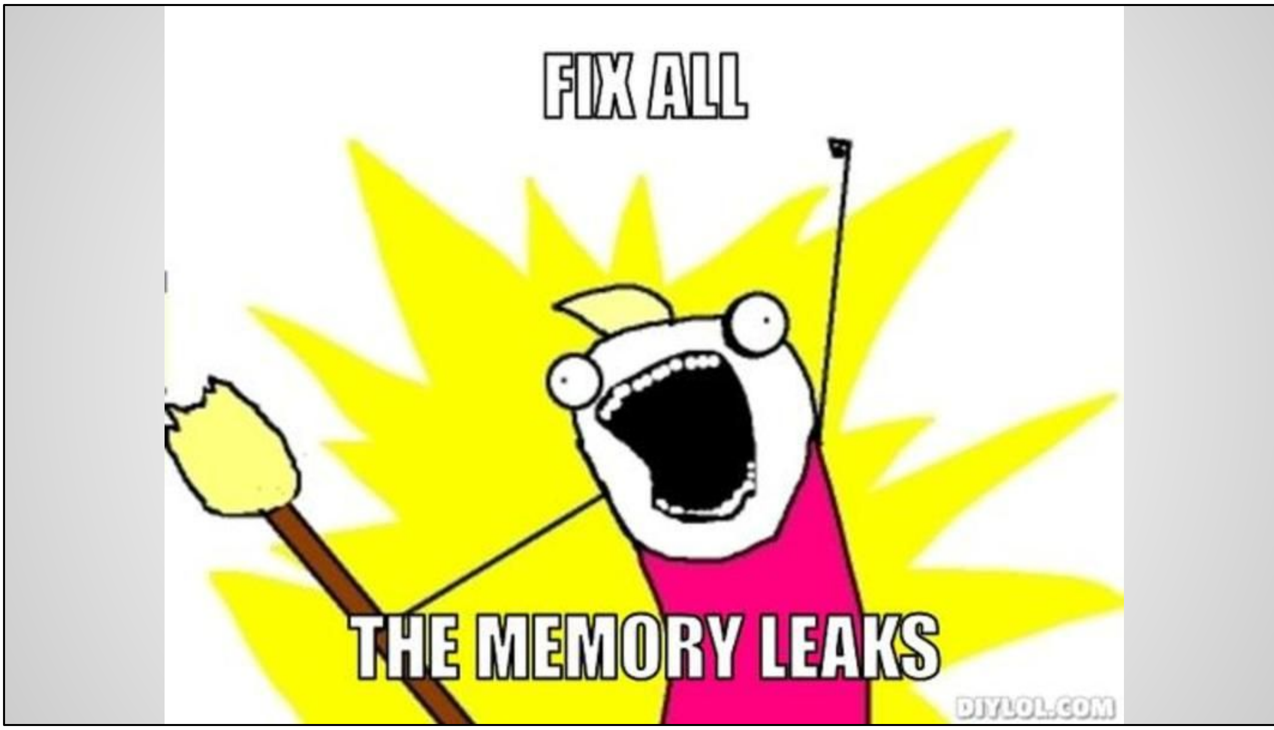
Those **three extra references** were **owned** by objects that **Python has cleaned up**.

They **no longer exist**, so we've **lost our opportunity** to **signal** to Python that those **references are no longer needed**.

The reference count **can never drop** to 0, so Python **will never remove** the function object from memory.

Now, we're talking about the built-in hash function here -- so it's not like we even really want it removed from memory.
But imagine a **more memory-intensive object**, and a **long-running program** that **created tons** of these objects that **could never be cleaned up** -- eventually, this type of error will become a problem.

https://media.makeameme.org/created/memory-leaks-memory.jpg



So I added back that PyDECREF and rebuilt my program...

http://treasure.diylol.com/uploads/post/image/409955/resized_all-the-things-meme-generator-fix-all-the-memory-leaks-ed0d0c.jpg

It’s useable!

```
>>> def my_awesome_python_hash(obj):
        ...

>>> hashtable.HashTable(hash_func=my_awesome_python_hash)
```

After all that, I finally had a module that worked well enough!

So I wrote my very own Python hash function.

It’s useable!

```
>>> def my_awesome_python_hash(obj):

    if isinstance(obj, int):
        return obj*2654435761 % 2**32
    if isinstance(obj, float):
        return int(math.ceil(obj*2654435761 % 2**32))




>>> hashtable.HashTable(hash_func=my_awesome_python_hash)
```

If the item to hash is an int or a float, it does this one thing I found suggested on SO.

It’s useable!

```
>>> def my_awesome_python_hash(obj):

    if isinstance(obj, int):
        return obj*2654435761 % 2**32
    if isinstance(obj, float):
        return int(math.ceil(obj*2654435761 % 2**32))
    else:
        ord3 = lambda x : '%.3d' % ord(x)
        return int(''.join(map(ord3, obj)))

>>> hashtable.HashTable(hash_func=my_awesome_python_hash)
```

Else, we clearly must be hashing a string, so it does this other thing I found suggested on Stack Overflow. Awesome.

It’s useable!

```
>>> def my_awesome_python_hash(obj):
    print "Python:      -> now hashing " + str(obj)
    if isinstance(obj, int):
        return obj*2654435761 % 2**32
    if isinstance(obj, float):
        return int(math.ceil(obj*2654435761 % 2**32))
    else:
        ord3 = lambda x : '%.3d' % ord(x)
        return int(''.join(map(ord3, obj)))

>>> hashtable.HashTable(hash_func=my_awesome_python_hash)
```

Plus, I’ve included a print statement -- prefixed by the word “Python” -- so we can see when this function is called.

I’ve also added more print statements to the C wrapper module and my original C library, which are prefixed by their source.

So here I've started an iPython repl with that awesome hash function loaded. We can import the hashtable module -- and we see debug statements from C module initialization function.

Now I'm going to instantiate a new hashtable object, such that its hash_function will be the awesome hash function from before.
Via the C module, the inner C library is put to work -- mallocing space and creating our data structure.

Let's look at the new hashtable -- it's empty, great. Next, let's set some values. We see the C module's "set" function is calling the function that I wrote in Python to get the hash value of our key, then coordinating with the C library to actually add the key-value pair.

Set some more items. Hey look -- the C library has taken care of resizing! So that's what our hash table now looks like -- It's a lot bigger.

And the hash table part actually works -- we can look up the value associated with "pi". We can remove it.
And if we try to look "pi" up again, the C library can't find it and the C module

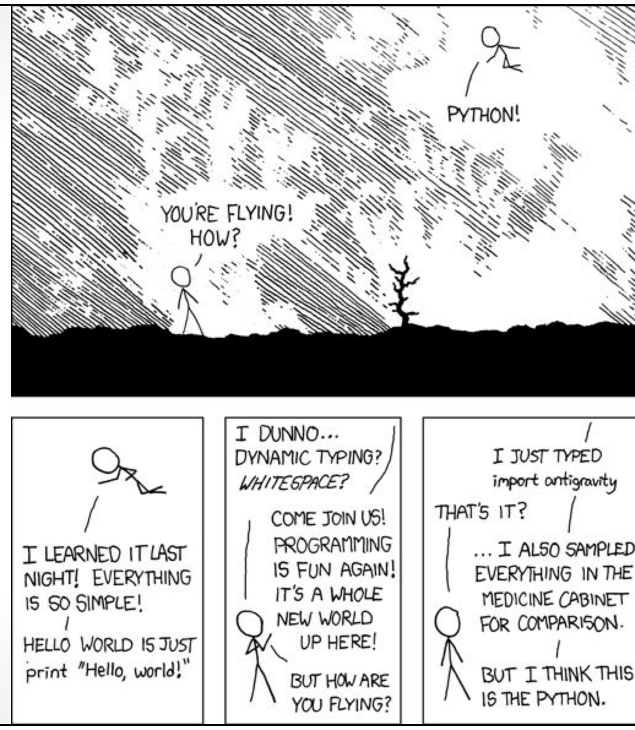
returns None.

When I exit the shell and the deallocation function from the module is called, and the library does the heavy-hitting of actually freeing the memory.

So I’ve got the Python repl calling the functions from my C module, and the C code executing this hash function that I wrote in Python, and ... anyway, I thought it was pretty cool.

Questions?

scdgrapefruit@gmail.com



https://xkcd.com/353/

Sources

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Hashtable illustrations:

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Linked List illustrations:

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http://dab1nmslvvntp.cloudfront.net/wp-content/uploads/2013/04/array5b.png

Reference counting illustration: http://rypress.com/tutorials/objective-c/media/memory-management/reference-counting.png
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Memes:

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