Multi-Language Projects

One-Slide Summary

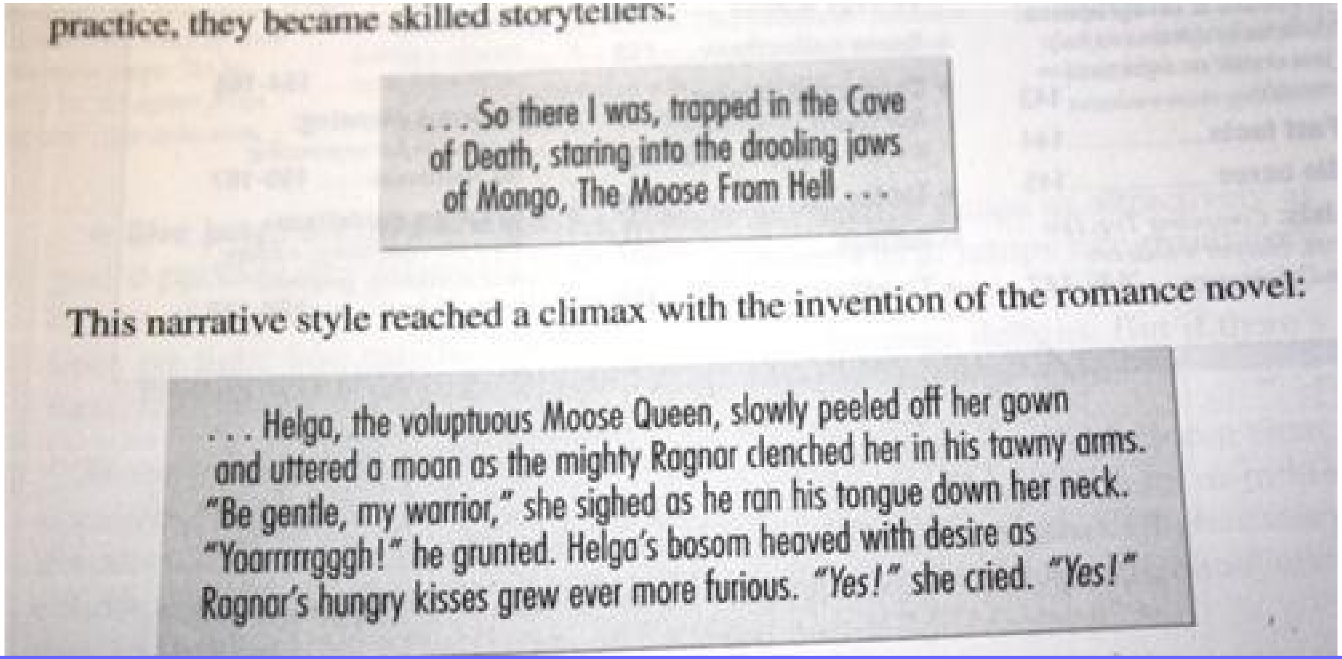
- Many modern software projects involve code written in **multiple languages**. This can involve a common **bytecode** or **C native** method interfaces.
- Native code interfaces can be understood in terms of (1) **data layout** and (2) special common **functions to manipulate** managed data.
- Almost all aspects of software engineering are impacted in multi-language projects.

Lecture Outline

- Motivating Example
  - XOR (String Cryptography)
- Python + C
  - Interfacing
- Java + C
  - Interfacing
- Ocaml/F# + C
  - Object Layout, Type Tags
- SE Implications

Motivating Example

- Take out a piece of paper
- First: record every word you heard
  - This will be hard
- Second: translate



practice, they became skilled storytellers:

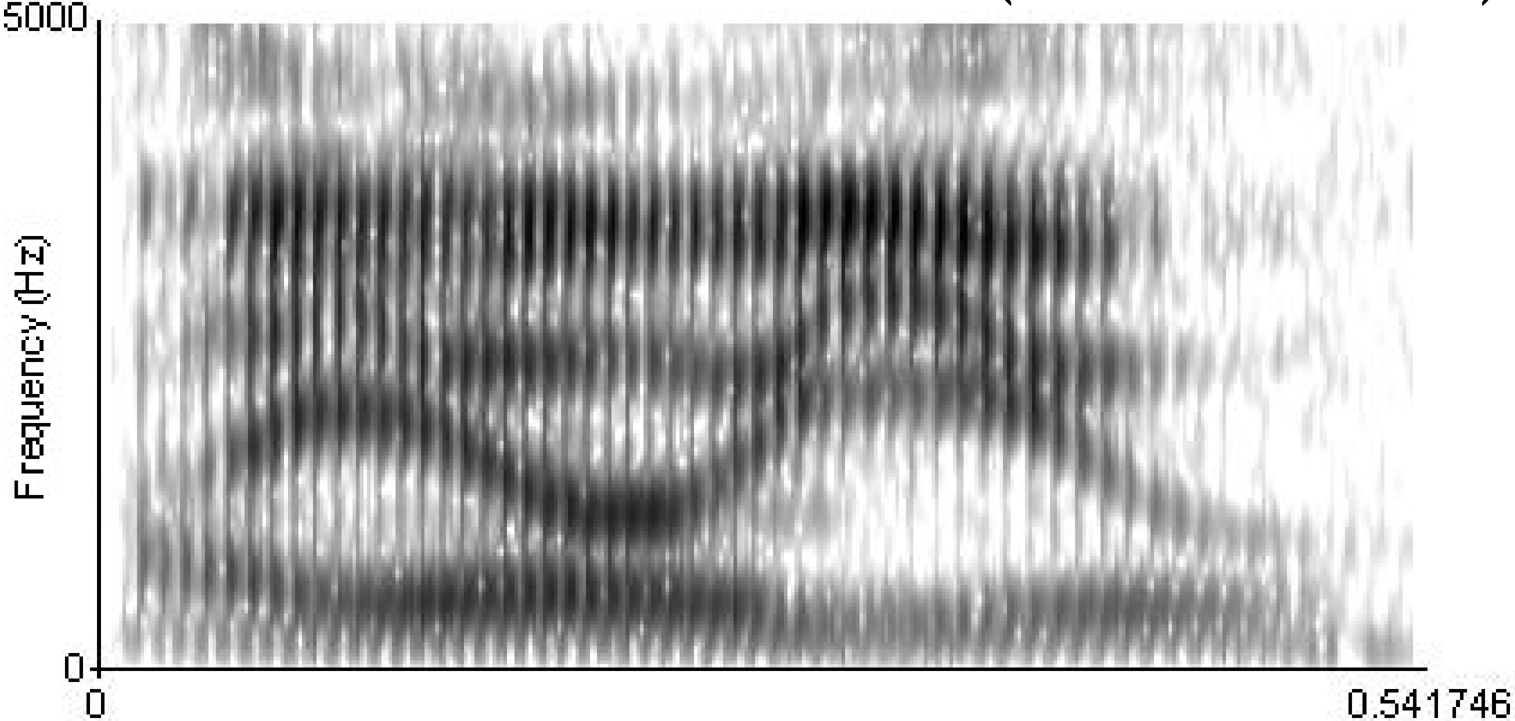
> . . . So there I was, trapped in the Cave of Death, staring into the drooling jaws of Mongo, The Moose From Hell . . .

This narrative style reached a climax with the invention of the romance novel:

> . . . Helga, the voluptuous Moose Queen, slowly peeled off her gown and uttered a moan as the mighty Ragnar clenched her in his tawny arms. "Be gentle, my warrior," she sighed as he ran his tongue down her neck. "Yoarrrrgggh!" he grunted. Helga's bosom heaved with desire as Ragnar's hungry kisses grew ever more furious. *"Yes!"* she cried. *"Yes!"*

Speech Perception, Segmentation

- The spectrogram is for the phrase "I owe you"
  - cf. "Raw Data Layout"
  - Note: no obvious boundaries (cf. neural net)



Motivating Example

In un mondo splendido, colorato e magico
Little ponies vivono, in pace sempre in armonia
Timidi e simpatici, burberi e romantici
Sono i caratteri, degli amici che troverai
Ed ogni giorno crescerai, quanti problemi risolverai
Insieme agli altri pony, lo sai, ti divertirai!

Vola e vai, my little pony, se nuovi amici vorrai incontrare
Prendi il volo, ascolta il cuore, ed ogni avventura potrai affrontare!
Vola e vai, my little pony, realizza i tuoi sogni e non ti fermare!

va E ple

In a world

splendid

colorful

magical

In un mondo splendido, colorato e magico

Little ponies vivono, in pace sempre in armonia

vivacious = living

semper fi = always

harmony

atici, burb ri e ro

Sono i caratteri, degl mici che troverai

Requiescat in pace = RIP peace

Ed ogni gi problemi risolverai

Insieme agli sai, ti divertirai!

Vola e vai, my little pony, se nuovi amici vorrai incontrare

Prendi il volo, ascolta il cuore, ed ogni avventura potrai affrontare!

Vola e vai, my little pony, realizza i tuoi sogni e non ti fermare!

Motivating Example

ondo lido e

timid

sympathetic

brusque

romantic

Li le ponies vono, in p ce sempre armonia

Timidi e simpatici, burberi e romantici

Sono i caratteri, degli amici che troverai

characters

crescera quant rai

treasure trove = found

Insieme agli altr sai,

amicable = friends

Vola e vai, my little pony, se nuovi amici vorrai incontrare

Prendi il volo, ascolta il cuore, ed ogni avventura potrai affrontare!

Vola e vai, my little pony, realizza i tuoi sogni e non ti fermare!

Multi-Language Projects In Two Stages

- First, reason about the **raw data layout**
- Second, translate **concepts** you already know

- We will reason about the raw data layout using C and Assembly
  - Projects almost always use C for performance-critical kernels and low-level OS/hardware interfacing.
  - C is the Lingua Franca of multi-language projects.

Traditional Multi-Language Projects

- **Application Kernel**
  - Statically Typed, Optimized, Compiled, interfaces with OS and libraries.
- **Scripts**
  - Dynamically Typed, Interpreted, Glue Components, Business Logic.
- Examples: Emacs (C / Lisp), Adobe Lightroom (C++ / Lua), NRAO Telescope (C / Python), Google Android (C / Java), most games (C++ / Lua), etc.

Bytecode
Multi-Language Projects

- Microsoft's **Common Language Runtime** of Managed Code in the .NET Framework
  - C++, C#, J#, F#, Visual Basic, ASP, etc.
  - Common Language Infrastructure
- **Java Bytecode**, Java Virtual Machine, Java Runtime Environment
  - Java, Scala, JRuby, JScheme, Jython, Fortress, etc.
- Others: LLVM Bitcode, Python Bytecode, etc.

Why Cover "Multi-Language"?

- Increasingly **common**. Developer quote:
  - "My last 4 jobs have been apps that called: Java from C#, and C# from F#; Java from Ruby; Python from Tcl, C++ from Python, and C from Tcl; Java from Python, and Java from Scheme (And that's not even counting SQL, JS, OQL, etc.)"
- SE process: choose the **best tool** for the job
  - Example: concurrency might be better handled in F#/OCaml (immutable functional) or Ruby (designed to hide such details), while low-level OS or hardware access is much easier in C or C++, while rapid prototyping is much easier in Python or Lua, etc.

Disadvantages of Multi-Language Projects

- Integrating data and control flow across languages can be difficult
- Debugging can be harder
  - Especially as values flow and control flow from language A to language B
- Build process becomes more complicated
- Developer expertise is required in multiple languages
  - Must understand types (etc.) in all languages

How Will We Do It?

“In practice, interoperating between F# and C# (or any other CLR language) is relatively straightforward, once the 'shape' of the code (what the language turns into at the IL level) in both languages is well understood.”

– Ted Neward, Microsoft Developer Network

Worked Examples

- We are going to write a fast C-and-assembly routine for low-level processing
  - Assume you know C or C++ (e.g., libpng, afl, etc.)
- Then we will call that C code from
  - Python (e.g., avl.py, mutate.py, delta.py)
  - Java (e.g., JFreeChart, JSoup, EvoSuite)
  - OCaml/F# (e.g., Infer)
- This will involve
  - Understanding Data
  - Translating Familiar Concepts

Native Kernel: One-Time Pad

- One of the building blocks of modern cryptography is the **one-time pad**.
  - When used correctly it has a number of very desirable properties.
- To encrypt plaintext P with a key K (the one time pad) you produce cyphertext C as follows:
  - cyphertext[i] = plaintext[i] *XOR* keytext[i]
  - A constant key mask may be also used for testing.
- Decryption also just xors with the key.

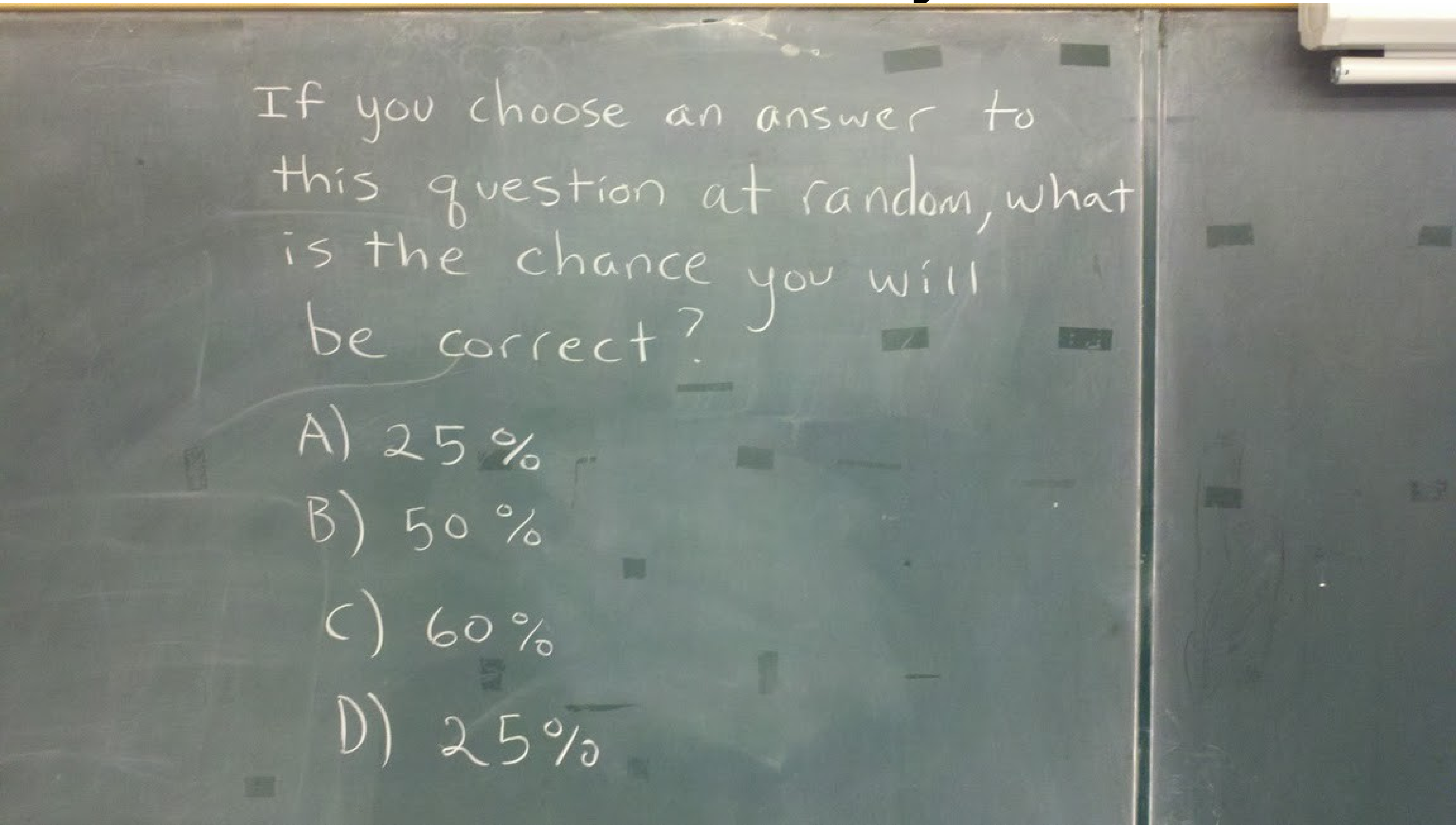
XOR In Python

```
def python_string_xor(plain, key):
  cypher = bytearray(' '*len(plain))
  if type(key) is str:
    for i in range(len(plain)):
      cypher[i] = ord(plain[i]) ^ ord(key[i])
  else: # is char
    for i in range(len(plain)):
      cypher[i] = ord(plain[i]) ^ key
  return cypher
```

Interfacing Python with C

```
static PyObject * cpython_string_xor(PyObject *self, PyObject *args)
{
  const char *n_plain, *n_keytext;
  int plain_size, i, n_mask;
  if (PyArg_ParseTuple(args, "s#s", &n_plain, &plain_size, &n_keytext)) {
    char * n_cypher = malloc(plain_size);
    for (i=0;i<plain_size;i++)
      n_cypher[i] = n_plain[i] ^ n_keytext[i];
    return Py_BuildValue("s#", n_cypher, plain_size);
  } else if (PyArg_ParseTuple(args, "s#i", &n_plain, &plain_size, &n_mask)) {
    char * n_cypher = malloc(plain_size);
    for (i=0;i<plain_size;i++)
      n_cypher[i] = n_plain[i] ^ n_mask;
    return Py_BuildValue("s#", n_cypher, plain_size);
  }
  return NULL;
}
```

“Readability”



If you choose an answer to this question at random, what is the chance you will be correct?

A) 25%

B) 50%

C) 60%

D) 25%

I ython with C

Typedef:
Opaque type for
Python-controlled
Values.

```
static PyObject *                    (PyObject *self, PyObject *args)
{
  const char *n_plain, *n_keytext;
  int plain_size, i, n_mask;
  if (PyArg_ParseTuple(args, "s#s", &n_plain, &plain_size, &n_keytext)) {
    char * n_cypher = malloc(plain_si
    for (i=0;i<plain_size;i++)
      n_cypher[i] = n_plain[i] ^ n_keyt
    return Py_BuildValue("s#", n_cypher, plain_
  } else if (PyArg_ParseTuple(args, "s#i", &n_plain, &plain_size, &n_mask)) {
    char * n_cypher = malloc(plain_size);
    for (i=0;i<plain_size;i++)
      n_cypher[i] = n_plain[i] ^ n_mask;
    return Py_BuildValue("s#", n_cypher, plain_size);
  }
  return NULL;
}
```

All functions are
“variable argument”.

Duck typing:
Can we interpret
The agruments as two strings?

Interfacing Python with C

```
static PyObject * cpython_string_xor(PyObject *self, PyObject *args)
{
  const char *n_plain, *n_keytext;
  int plain_size, i, n_mask;
  if (PyArg_ParseTuple(args, "s#s", &n_plain, &     _size, &n_keytext)) {
    char * n_cypher = malloc(plain_size);
    for (i=0;i<plain_size;i++)
      n_cypher[i] = n_plain[i] ^ n_keytext[i];
    return Py_BuildValue("s#", n_cypher, plain_size);
  } else if (PyArg_ParseTuple(args, "s#i", &n_plain, &plain_size, &n_mask)) {
    char * n_cypher = malloc(plain_size);
    for (i=0;i<plain_size;i++)
      n_cypher[i] = n_plain[i] ^ n_mask;
    return Py_BuildValue("s#", n_cypher, pla
  }
  return NULL;
}
```

Function:
Build a Python String from a C string.

Duck Typing:
Can we interpret the arguments as a string followed by an int?

Interfacing Python with C, cont'd

```
static PyMethodDef CpythonMethods[] = {
   {"string_xor", cpython_string_xor, METH_VARARGS,
    "XOR a string with a string-or-character"},
   {NULL, NULL, 0, NULL}
};

PyMODINIT_FUNC initcpython(void)
{
  (void) Py_InitModule("cpython", CpythonMethods);
}
```

This function is required (based on your module name).

Linking Our Native Python Code

- `gcc -pthread -fno-strict-aliasing -DNDEBUG -g -fwrapv -O2 -Wall -Wstrict-prototypes -fPIC -I/usr/include/python2.7 -c cpython.c -o build/temp.linux-x86_64-2.7/cpython.o`
- `gcc -pthread -shared -Wl,-O1 -Wl,-Bsymbolic-functions -Wl,-Bsymbolic-functions -Wl,-z,relro build/temp.linux-x86_64-2.7/cpython.o -o build/lib.linux-x86_64-2.7/cpython.so`

Linking Our Native Python Code

- gcc -pthre -DNDEBUG -g -fwrapv -O2 -Wall -Wstrict-prototypes -fPIC -I/usr/include/python2.7 -c cpython.c -o build/temp.linux-x86_64-2.7/cpython.o
- gcc -pthread -shared -Wl,-O1 -W Bsymbolic-functions -Wl, functions -Wl,-z,relro build/temp.linux-x86_64-2.7/cpython.o -o build/lib.linux-x86_64-2.7/cpython.so

Position Independent Code
(see EECS 483)

Build Shared Lirbary Code
(see EECS 483)

.so = .dll = shared library

Interfacing C with Python

```
import cpython    # loads cpython.so
 ...
if do_native:
  result = cpython.string_xor(plaintext, \
        char_or_string_key)
else:
  result = python_string_xor(plaintext, \
        char_or_string_key)
```

Programming Paradigms

- This “pass a string or an integer as the second argument” plan …
  - Works well for Dynamic (e.g., Python duck typing)
  - Works well for Functional (algebraic datatypes)
    - See EECS 490
  - Is not a natural fit for Object-Oriented
    - More natural: dynamic dispatch on “string-or-int”

```
abstract class StringOrInt
 class StringOrInt_IsInt extends StringOrInt
 class StringOrInt_IsString extends StringOrInt
```

Java Code (1/2)

```
abstract class StringOrInt {
    abstract public byte[] java_string_xor (byte[] str1);
  }
class StringOrInt_IsInt extends StringOrInt {
    public int my_int;
    public StringOrInt_IsInt (int i) { my_int = i; }
    public byte[] java_string_xor (byte[] plain) {
      byte [] cypher = new byte[plain.length];
      for (int i = 0; i < plain.length; i++)
          cypher[i] = (byte) ((int)plain[i] ^ my_int);
      return cypher;
  } }
```

Java Code (1/2)

```
abstract class StringOrInt {
    abstract public byte[] java_string_xor (byte[] str1);
  }
class StringOrInt_IsInt extends StringOrInt {
    public int my_int;
    public StringOrInt_IsInt (int i) { my_int = i; }
    public byte[] java_string_xor (byte[] plain) {
      byte [] cypher = new byte[plain.leng
      for (int i = 0; i < plain.length; i++)
        cypher[i] = (byte) ((int)plain[i] ^ my_int);
      return cypher;
  } }
```

Java's String is so tied up in encodings that it's not raw-content-preserving.

Cutely, Java warns about a lack of precision here (int/byte) unless you cast.

Java Code (2/2)

```
abstract class StringOrInt {
   abstract public byte[] java_string_xor (byte[] str1);
 }
 class StringOrInt_IsString extends StringOrInt {
   public byte[] my_string;
   public StringOrInt_IsString (byte[] s) { my_string = s; }
   public byte[] java_string_xor (byte[] plain) {
     byte [] cypher = new byte[plain.length];
     for (int i = 0; i < plain.length; i++)
         cypher[i] = (byte) (plain[i] ^ my_string[i]);
     return cypher;
 } }
```

Tell Java about the Native Method

```
static {
    /* load native library */
    System.loadLibrary("cjava");
}

private static native byte[]
    c_string_xor(byte[] plain, StringOrInt key);
```

C Code using JNI (1/2)

```
JNIEXPORT jbyteArray JNICALL Java_StringXOR_c_1string_1xor
(JNIEnv * env, jclass self, jbyteArray jplain, jobject jkey)
{
  jbyte * n_plain = (*env)->GetByteArrayElements
                             (env, jplain, NULL);
  size_t plainsize = (*env)->GetArrayLength(env, j_plain);
  jclass key_cls = (*env)->GetObjectClass(env, jkey);
  jfieldID fid ;
  int i;
  jbyteArray jcypher = (*env)->NewByteArray(env,plainsize);
  jbyte * n_cypher = (*env)->GetByteArrayElements(env,
                                         jcypher, NULL);

  fid = (*env)->GetFieldID(env, key_cls, "my_int", "I");
  if (fid != NULL) {
    /* key has "int my_int;" field */
    jint n_mask = (*env)->GetIntField(env, jkey, fid);
    for (i=0;i<plainsize;i++) {
      n_cypher[i] = n_plain[i] ^ n_mask;
    }
  } else {
```

Macro:
This function is visible to Java.

Typedef:
Opaque types for Java objects.

c code usin

```
JNIEXPORT jbyteArray JNICALL Java_StringXOR_c_1string_1xor
(JNIEnv * env, jclass self, jbyteArray jplain, jobject jkey)
{
  jbyte *                (*env)->GetBy
                              nv, j
                                 Ar                          n);
                                 bjecte
  ji
  int i;
  jbyteArray jcypher = (*env)->NewByteArray(env,plainsize);
  jbyte * n_cypher = (*env)->GetByteArrayElements(env,
                                       jcypher, NULL);

  fid = (*env)->GetFieldID(env, key_cls, "my_int", "I");
  if (fid != NULL) {
    /* key has "int my_int;" field */
    jint n_mask = (*env)->GetIntField(env, jkey, fid);
    for (i=0;i<plainsize;i++) {
      n_cypher[i] = n_plain[i] ^ n_mask;
    }
  } else {
```

Java Native Interface environment provides services for manipulating Java values.

The self object is passed in as a 'hidden' first paramter.

C C JNI (1/2)

Function:
extract C string from Java byte[]. “Drop tags”, etc.

```
JNIEXPORT j                                R_c_1string_1xor
(JNIEnv * env, j                         jplain, jobject jkey)
{
  jbyte * n_plain = (*env)->GetByteArrayElements
                              (env, jplain, NULL);
  size_t plainsize = (*env)->GetArrayLength(env, j_plain);
  jclass key_cls = (*env)->GetObjectClass(env, jkey);
  jfieldID fid ;
  int i;
  jbyteArray jcypher                                  ainsize);
  jbyte * n_cypher                                    env,
                                                     NULL);

  fid = (*env)->GetFieldID(env, key_cls, "my_int", "I");
  if (fid != NULL) {
    /* key has "int my_int;" field */
    jint n_mask = (*env)->GetIntField(env, jkey, fid);
    for (i=0;i<plainsize;i++) {
      n_cypher[i] = n_plain[i] ^ n_mask;
    }
  } else {
```

Function:
Extract type tag from Object. Each object is an instance of a class.

C Code using JNI (1/2)

```
JNIEXPORT jbyteArray JNICALL Java_StringXOR_c_1string_1xor
(JNIEnv * env, jclass self, jbyteArray jplain, jobject jkey)
{
  jbyte * n_plai              GetByteArrayElements
                                      in, NULL);
                                          h(env, j_plain);
                                             , jkey);


                                          (env,plainsize);
  jby                                   yElements(env,
                                         jcypher, NULL);

  fid = (*env)->GetFieldID(env, key_cls, "my_int", "I");
  if (fid != NULL) {
    /* key has "int my_int;" field */
    jint n_mask = (*env)->GetIntField(env, jkey, fid);
    for (i=0;i<plainsize;i++) {
      n_cypher[i] = n_plain[i] ^ n_mask;
    }
  } else {
```

Is there an int field named “my_int” in this class (or inherited from its parents)? If so, at what position/offset does it live?

C Code using JNI (2/2)

```
  else {
    fid = (*env)->GetFieldID(env, key_cls, "my_string", "[B");
    if (fid != NULL) {
      /* key has "byte[] my_string;" field */
      jbyteArray jkeyt = (*env)->GetObjectField(env, jkey, fid);
      jbyte * n_keytext = (*env)->GetByteArrayElements
                                           (env, jkeyt, NULL);
      for (i=0;i<plainsize;i++)
        cypher[i] = n_plain[i] ^ n_keytext[i];
      (*env)->ReleaseByteArrayElements(env,jkeyt,n_keytext,0);
    }
  }
  (*env)->ReleaseByteArrayElements(env, jplain, n_plain, 0);
  (*env)->ReleaseByteArrayElements(env, jcypher, n_cypher, 0);
  return jcypher;
}
```

C Code using JNI (2/2)

```
  else {
    fid = (*env)->GetFieldID(env, key_cls, "my_string", "[B");
    if (fid != NULL) {
      /* key has "byte[] my_str
      jbyteArray jkeyt = (*env)->GetObjectField(env, jkey, fid);
      jbyte * n_keytext = (*env)->GetByteArrayElements
                                            (env, jkeyt, NULL);

                       _plain[i] ^ n_keytext[i];
      (*env)->Releas                                   _keytext,0);
    }
  }
  (*env)->ReleaseByteArrayElements(env, jplain, n_plain, 0);
  (*env)->ReleaseByteArrayElements(env, jcypher, n_cypher, 0);
  return jcypher;
}
```

Field lookup again.
“[B” == “[] Byte”

Can indicate whether
elements were copied or shared.

Playing nice with
the garbage collector.

Compiling, Linking and Running JNI

```
gcc -I $(JAVA)/include \
             -o libcjava.so -shared -fPIC cjava.c
javac StringXOR.java
java -Djava.library.path=. StringXOR
```

- That's it!
- "javap" also exists to automatically generate header files for C JNI implementations.

Medieval History

- This Greek-speaking descendant of the Roman Empire centered around Istanbul (was Constantinople) and conquered much of the Mediterranean coast. Greek fire, mosaics, orthodox Christianity, the crusades, and the Hagia Sophia are all associated with this empire.

Politics of India

- The first female Prime Minister of India was known for her centralization of power, the Indo-Pakistani war of 1971, the conflict over the creation of Bangladesh, authorizing the development of nuclear weapons, and a suspension of civil liberties. She stood firm in the face of American pressure, but is also associated with a culture of nepotism.

Zoology

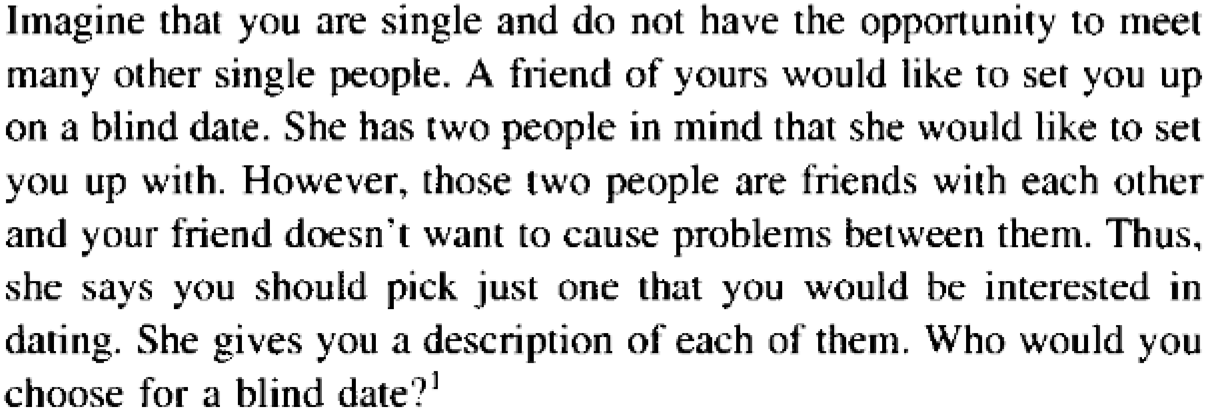
- These ray-finned fish hatch in fresh water, migrate to the ocean, and then return to fresh water to reproduce. Tracking studies have shown that they often return to the same spot they hatched from to spawn. Commercial production of them is currently over three million tonnes. They are often a keystone species, supporting bears, birds and otters.

Modern Languages

- This Central Semitic language is closely related to Hebric, Phoenician and Aramaic. Used as a liturgical language for ~1.8 billion Muslims as well as a native language for ~300M speakers, it features a right-to-left script, open and closed syllables, elided vowels, and a rich literary tradition.
  - العَرَبِيَّة : Example

Psychology: Memory?

- 54 students and 108 community members were posed questions like:

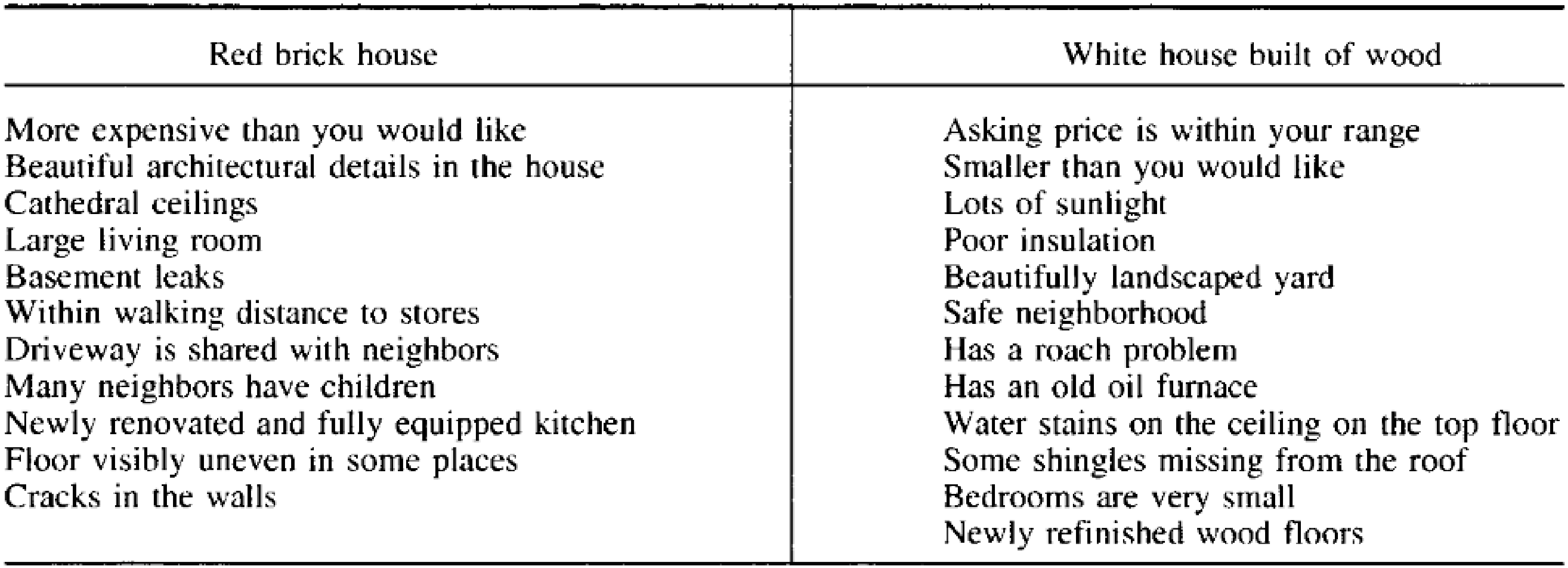


Imagine that you are single and do not have the opportunity to meet many other single people. A friend of yours would like to set you up on a blind date. She has two people in mind that she would like to set you up with. However, those two people are friends with each other and your friend doesn't want to cause problems between them. Thus, she says you should pick just one that you would be interested in dating. She gives you a description of each of them. Who would you choose for a blind date?[1]

- Days later, they were given a memory task related to features in the questions (e.g., was it a “red brick house”, a “white house built of wood”, or “neither”).

Psychology: Value Judgment

- Finally, they were asked to rate how positive or negative the feature would be in the context of making the decision



Red brick house	White house built of wood
More expensive than you would like	Asking price is within your range
Beautiful architectural details in the house	Smaller than you would like
Cathedral ceilings	Lots of sunlight
Large living room	Poor insulation
Basement leaks	Beautifully landscaped yard
Within walking distance to stores	Safe neighborhood
Driveway is shared with neighbors	Has a roach problem
Many neighbors have children	Has an old oil furnace
Newly renovated and fully equipped kitchen	Water stains on the ceiling on the top floor
Floor visibly uneven in some places	Some shingles missing from the roof
Cracks in the walls	Bedrooms are very small
	Newly refinished wood floors

Choice-Supportive Bias

- Humans attributed significantly more positive and fewer negative features to their chosen options than to foregone options.
  - "Remembering that the option we chose was the better one is more emotionally gratifying than remembering that the foregone option was better."

    [Mara Mather and Marcia Johnson. *Choice-Supportive Source Monitoring: Do our decisions seem better to us as we age?* J. Psychology and Aging.]
- Example SE Implication: Once you have chosen a language or tool for Project 1, you are likely to remember positives about that when choosing for Project 2.

Exotic Language Example

- How do you maintain code in a language you don't really know?
- First, look for common patterns or markers!
  - cf. “song” exercise

“NOBODY UNDERSTANDS ME.”

Basic Ocaml Implementation

```
type char_or_string =
  | MyChar of char          (* constant bit pattern *)
  | MyString of string      (* one-time pad *)

let ocaml_xor_function plain key =
  let cypher = String.create (String.length plain) in
  ( match key with
  | MyChar(mask) ->
    for i = 0 to pred (String.length plain) do
      cypher.[i] <- Char.chr
        ((Char.code plain.[i]) lxor (Char.code mask))
    done
  | MyString(keyt) ->
    for i = 0 to pred (String.length plain) do
      cypher.[i] <- Char.chr
      ((Char.code plain.[i]) lxor (Char.code keyt.[i]))
    done
  ) ; cypher
```

Telling Ocaml about C

```
external
ocaml_name_for_c_xor_function :
string -> char_or_string -> string
= "c_string_xor"
```

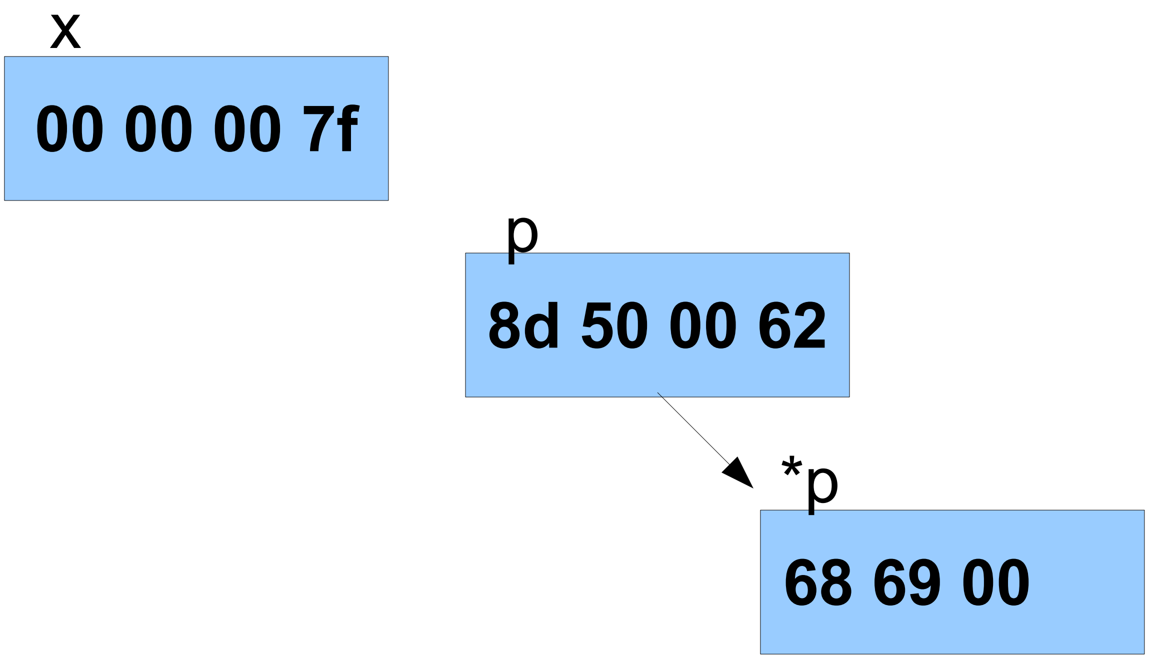
- We are promising to provide a Native C function called “c_string_xor” that takes a “string”, a “char_or_string”, and returns a “string”.

Native C Implementation

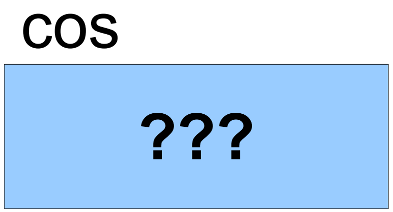
- Basic idea:
  - accept “string” and “char_or_string” as args
  - extract contents of “string” (plaintext)
  - examine “char_or_string”
    - If “char” (mask), extract character code value
    - If “string” (keytext), extract contents of string
  - create a new string (return value, cyphertext)
  - for loop (over length of string)
    - cyphertext = plaintext xor key
  - return cyphertext

The Problem

- int x = 127;
- char * p = “hi”;



- let cos = MyChar('\127') in



The Problem

- let cos = MyChar('\127') in

cos

```
ff 00 00 00 00 00 00 00 fc 08 00 00 00 00 00 00 ..
```

- let cos2 = MyString(“hi”) in

cos2

```
60 8d 62 00 00 00 00 00 fc 04 00 00 00 00 00 00 ..
```

- let cos = MyCh

cos

ff 00 00 00 0

- let cos2 = MyS

cos2

60 8d 62 00 0

The Problem

- let cos = MyChar('\127') in

cos

ff 00 00 00 00 00 00 00 fc 08 00 00 00 00 00 00 ..

- let cos2 = MyString(“hi”) in

cos2

60 8d 62 00 00 00 00 00 fc 04 00 00 00 00 00 00 ..

0x628d60

68 69 00 00 ..

Run-Time Type Tags

- let cos = MyChar('\127') in

cos

```
00 04 00 00 00 00 00 00 | ff 00 00 00 00 00 00 00 fc 08 00 00
```

- let cos2 = MyString(“hi”) in

cos2

```
01 04 00 00 00 00 00 00 | 60 8d 62 00 00 00 00 00 fc 04 00 00
```

0x628d60

```
68 69 00 00 ..
```

Run-Time Type T

- let cos = MyChar('\127') in

cos

```
00 04 00 00 00 00 00 00   ff 00 00                08 00 00
```

- let cos2 = in

cos2

```
01 04 00 00 00 00 00 00   60 8d 62 00 00 00 00 00 fc 04 00 00
```

0x628d60

```
fc 04 00 00 00 00 00 00   68 69 00 00 ..
```

Type Tag 0

C(127) == Ocaml(255)
(garbage collection)

Pointer To String
(little endian)

Type Tag 0

"Color" (2 bits)
and Size (54 bits)

Type Tag 252 = String

"hi"

Special C File

```
CAMLprim value c_string_xor(value o_plain, value o_key){
  CAMLparam2 (o_plain, o_key);
  CAMLlocal1 (o_cypher);
  int len = caml_string_length(o_plain) ;
  int i;
  char * n_plain = String_val(o_plain);
  char * n_cypher ;
  o_cypher = caml_alloc_string(len);
  n_cypher = String_val(o_cypher);
  if (Tag_val(o_key) == 0) { /* MyChar:Mask  */
    char n_mask = Int_val(Field(v2, 0));
    for (i=0;i<len;i++) n_cypher[i] = n_plain[i]^n_mask;
  } else if (Tag_val(o_key) == 1) { /* MyString:Key */
    char * n_keytext = String_val(Field(v2, 0));
    for (i=0;i<len;i++) n_cypher[i] = n_plain[i] ^
                                        n_keytext[i];
  }
  CAMLreturn(o_cypher);
}
```

Special C File

```
CAMLprim value c_string_xor(value o_plain, value o_key){
  CAMLparam2 (o_plain, o_key);
  CAM  local1 (o_  ypher);
  int       = caml_st  ing_length(o_plain) ;

                      trin                ) ;
                    ,
  o_cypher = caml_all
  n_cypher = String_val(o_
  if (Tag_val(o_key) == 0) { /* MyChar:Mask  */
    char n_mask = Int_val(Field(v2, 0));
    for (i=0;i<len;i++) n_cypher[i] = n_plain[i]^n_mask;
  } else if (Tag_val(o_key) == 1) { /* MyString:Key */
    char * n_keytext = String_val(Field(v2, 0));
    for (i=0;i<len;i++) n_cypher[i] = n_plain[i] ^
                                      n_keytext[i];
  }
  CAMLreturn(o_cypher);
}
```

Macro:
This C function will be called from Ocaml.

Typedef:
Opaque type for Ocaml-managed data values

Special C File

```
CAMLprim value c_string_xor(value                                  {
   CAMLparam2 (o_plain, o_key);
   CAMLlocal1 (o_cypher);
   int len = caml_string_length(o_plain) ;
   int i;
   char * n_plain = String_val(o_pl
   char * n_cypher ;
   o_cypher = caml_alloc_string(len);
   n_cypher = String_val(o_cypher);
   if (Tag_val(o_key) == 0) { /* MyCh
      char n_mask = Int_val(Field(v2,
      for (i=0;i<len;i++) n_cypher[i] = n_               _ask;
   } else if (Tag_val(o_key) == 1) { /* MyString:Key */
      char * n_keytext = String_val(Field(v2, 0));
      for (i=0;i<len;i++) n_cypher[i] = n_plain[i] ^
                                        n_keytext[i];
   }
   CAMLreturn(o_cypher);
}
```

Macros:
Play nice with Ocaml's garbage collector.

Functions:
Extract C-string From Ocaml-string (drop header)

Functions:
Make Ocaml-string (create header)

Special C File

```
CAMLprim value c_string_xor(value o_plain, value o_key){
  CAMLparam2 (o_plain, o_key);
  CAML              er);
  i                   _length(o_plain) ;
  i
  char *            String_v
  char * n   ypher ;
  o_cypher = caml_alloc_string(l      ) ;
  n_cypher = String_val(o_cyph  ) ;
  if (Tag_val(o_key) == 0) {  /* MyChar:Mask  */
    char n_mask = Int_val(Field(v2, 0));
    for (i=0;i<len;i++) n_  ypher[i           lain[i]^n_mask;
  } else if (Tag_val(o_key) =                        Key */
    char * n_keytext = Strin
    for (i=0;i<len;i++) n_cyphe                   [i] ^
                                     n_keytext[i];
  }
  CAMLreturn(o_cypher);
}
```

Macros, Functions:
Check Type Tag
(from Ocaml Header)

Macros, Functions:
Extract Fields of
Ocaml Tuple (Block)

Macros:
Convert Ocaml-Int
To C-Int
(bit shift/mask)

Linking C and OCaml

```
$ ocamlopt -verbose -o odemo ocaml.ml cocaml.c
+ as -o 'ocaml.o' '/tmp/camlasmb117d1.s'
+ gcc -D_FILE_OFFSET_BITS=64 -D_REENTRANT -c
-I'/usr/lib/ocaml' 'cocaml.c'
+ as -o '/tmp/camlstartupf4cd24.o'
'/tmp/camlstartup31ba44.s'
+ gcc -o 'odemo'   '-L/usr/lib/ocaml'
'/tmp/camlstartupf4cd24.o'
'/usr/lib/ocaml/std_exit.o' 'ocaml.o'
'/usr/lib/ocaml/stdlib.a' 'cocaml.o'
'/usr/lib/ocaml/libasmrun.a' -lm  -ldl
```

- **Just pass C files on the end of ocamlopt command line.**

Cross-Cutting Implications for Software Engineering

- Hiring and Expertise
  - You need developers experienced with “both” languages
  - Per-language experience may not be equal
- Code Inspection and Review
  - Recall Google's per-language “badge” policy
    - Need badges in all relevant languages
  - How would you evaluate a pull request if you do not know all of the languages?

Cross-Cutting Implications for Software Engineering

- Design
  - Because cross-language coding is so difficult and error-prone, you must design those interfaces very carefully in advance
    - cf. native method *interface* ← key word
  - Think carefully about relevant metrics (e.g., coupling, cohesion, etc.)
  - Design patterns can help, but you typically want to encapsulate any cross-language code inside one
    - e.g., don't have some native code in the Model and some in the View and have them share: backdoor?

Cross-Cutting Implications for Software Engineering

- Readability
  - “Glue” code is typically incomprehensible without training
  - Recall: look for familiar motifs
    - All of our examples have parts that “do the same thing” (e.g., convert value from X to C)
  - But comprehension may also require knowing about both languages
    - Python and Java field queries
    - Ocaml integer conversions

Cross-Cutting Implications for Software Engineering

- Test Input Generation
  - Most tools do not support test input generation across multiple language layers (it is an open research problem)
  - AFL is popular because it works on binaries (and thus any compiled language)
  - Microsoft's PEX works for any .NET / common language runtime program
  - But do not assume tools will work for multi-language projects: plan in advance to mitigate risk!

Cross-Cutting Implications for Software Engineering

- Test Coverage
  - Outside of giant ecosystems (e.g., Java Bytecode, Microsoft Common Language Runtime), coverage tools do *not* span languages
    - Pick one or run them separately
- Mutation Analysis
  - Similarly, mutation tools are typically language specific
  - Exam-style thought question: should you mutate the glue code when doing mutation testing?

Cross-Cutting Implications for Software Engineering

- Debugging
  - Outside of some bytecode/CLR instances, debuggers almost never help with multi-language projects
  - You “can” run GDB on an Ocaml-produced (etc.) executable, but it won't see any of your function or variable names
    - Basically just a raw assembly view
    - cf. C++ name mangling

Cross-Cutting Implications for Software Engineering

- Debugging
  - Typically you pick one language's debugger
  - Augment that with print-statement debugging at interface boundaries
  - Debugging multi-language code is merely “annoying” if the bug is isolated to code in just one language
  - It is “very, very difficult” if the bug actually involves crossing the boundary

Cross-Cutting Implications for Software Engineering

- Static Analysis and Refactoring
  - Unless the tool happens to support all relevant languages it will only report defects in some of the code
    - And it will make conservative assumptions about what happens at the cross-language interface
      - Result: more false positives and/or false negatives
  - Multi-language refactoring is an open research problem

Cross-Cutting Implications for Software Engineering

- Dynamic Analyses and Profiling
  - Similar story: unless the tool happens to support multiple languages (and most do not), you will have to pick one language and just use that language's tool
  - Example: you *can* run gprof on a non-C-produced binary, but it probably will not be able to give recognizable function names or useful call graphs
  - Thought question: would CHESS or Eraser work on multi-language projects?

Cross-Cutting Implications for Software Engineering

- Process, Planning and Metrics
  - Will developers be as precise at effort estimation for coding in multi-language projects?
  - How will you make high-level QA decisions (e.g., “is it good enough to ship?”) if coverage metrics only apply to part of the code?
  - What additional risks do you take on by choosing to carry out a multi-language project?
    - How would you mitigate those risks?
  - Do the benefits outweigh the costs?

Cross-Cutting Implications for Software Engineering

- Requirements and Quality Properties
  - The dominant reason to use multiple languages is to gain the ease and safety of a high-level language for most of your program and the speed of a low-level one for critical kernels
    - This is a quality (non-functional) requirement
  - Another common reason is to make use of an already-written library (COTS)
    - This is usually a functional requirement
  - Elicitation: how critical are those to stakeholders?

Actual Numbers (Quality)

(20 trials, best wall-clock ms time reported)

Ocaml – Ocaml	143
Ocaml – Native	103
Python – Python	598
Python – Native	29
Java – Java	165
Java – Native	183
C	22

Installing Office 2011 14.3.9 Update

Running package scripts...

Install time remaining: About −2 minutes

Actual Numbers (You Explain)

(20 trials, best wall-clock ms time reported)

Ocaml - Ocaml	143	
Ocaml - Native	103	
Python - Python	598	**What?**
Python - Native	29	
Java - Java	165	**What?**
Java - Native	183	
C	22	

Homework

- Exam 2 *In Class* Wednesday
  - Cumulative
  - One Page (= Two Sides) of Notes

Bonus: Ocaml Native Interface Debugging Example

- You try to write this C/OCaml code, but …
- Input:
  - `4b50 0403 0014 0000 0008 59b7 42cd 0ed7`
- Expected Output, XOR with '\127':
  - `342f 7b7c 7f6b 7f7f 7f77 26c8 3db2 71a8`
- Actual Output, Deterministic:
  - `b4af fbfc ffeb ffff fff7 a648 bd32 f128`

- What's the bug in your code?