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
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!
Motivating Example

In un mondo splendido, colorato e magico
Little ponies vivono, in pace sempre in armonia
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Vola e vai, my little pony, realizza i tuoi sogni e non ti fermare!

- In a world
- splendid
- colorful
- magical

- vivacious = living
- Requiescat in pace = RIP
- peace
- semper fi = always
- harmony
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
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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.
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%
static PyObject *
cython_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;
}
Interfacing Python with C

```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, &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, plain_size);
    }
    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?
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);
}
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 -pthread -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,-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 Library Code (see EECS 483)

.so = .dll = shared library
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
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;
    }
}
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;
    }
}
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

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

private static native byte[]
    c_string_xor(byte[] plain, StringOrInt key);
```
C Code using JNI (1/2)

```c
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.

```
JNIEXPORT jbyteArray JNICALL Java_StringXOR_c_1string_1xor
    (JNIEnv * env, jclass self, jbyteArray jplain, jobject jkey)
```

Typedef:
Opaque types for Java objects.

```
jclass key_cls = (*env)->GetObjectClass(env, jkey);
```

Java Native Interface environment provides services for manipulating Java values.

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

```
jbyte * n_plain = (*env)->GetByteArrayElements(env, jplain, NULL);
size_t plainsize = (*env)->GetArrayLength(env, j_plain);
```

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

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_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 {
        // 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?
    }
}
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;
}
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;
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.

- Example: العربية - العربية
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.

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

type char_or_string =
  | MyChar of char (* constant bit pattern *)
  | MyersString 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
  | MyersString(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

```ocaml
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;
  - 00 00 00 7f

- char * p = “hi”;
  - 8d 50 00 62
    - *p
      - 68 69 00

- let cos = MyChar('\127') in
  - ???
The Problem

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

  \begin{verbatim}
  ff 00 00 00 00 00 00 00 fc 08 00 00 00 00 00 00 ..
  \end{verbatim}

- let cos2 = MyString(“hi”) in

  \begin{verbatim}
  60 8d 62 00 00 00 00 00 fc 04 00 00 00 00 00 00 ..
  \end{verbatim}
• let cos = MyChar('\127')
  cos
  ff 00 00 00 00 00 00 00 fc 08 00 00 00 00 00 00 ..

• let cos2 = MyString("hi")
  cos2
  60 8d 62 00 00 00 00 00 fc 04 00 00 00 00 00 00 ..
  ff 00 00 00 00 00 00 00 fc 08 00 00 00 00 00 00 ..

shhh, i know of a place where they will never find us.
The Problem

- `let cos = MyChar(\127)` in
  
  ```
  ff 00 00 00 00 00 00 00 fc 08 00 00 00 00 00 00 ..
  ```

- `let cos2 = MyString(“hi”)` in
  
  ```
  60 8d 62 00 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

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

• let cos2 = MyString("hi") in

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

0x628d60

```
68 69 00 00 ..
```
Run-Time Type Tags

- let cos = MyChar('\127') in
- let cos2 = MyString("hi") in

Type Tag 0

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

Type Tag 0

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

Type Tag 252 = String

"hi"

Pointer To String (little endian)

0x628d60
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);
}
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);
    char * n_plain = String_val(o_plain);
    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);
    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);
}
CAMLprim value c_string_xor(value o_plain, value o_key)
{
  CAMLparam2 (o_plain, o_key);
  CAMLlocal1 (o_key);
  int len = caml_string_length(o_plain);
  char * n_plain = String_val(o_plain);
  char * n_cypher = NULL;
  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);
}
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/stdlib.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)

<table>
<thead>
<tr>
<th>Language</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocaml - Ocaml</td>
<td>143</td>
</tr>
<tr>
<td>Ocaml - Native</td>
<td>103</td>
</tr>
<tr>
<td>Python - Python</td>
<td>598</td>
</tr>
<tr>
<td>Python - Native</td>
<td>29</td>
</tr>
<tr>
<td>Java - Java</td>
<td>165</td>
</tr>
<tr>
<td>Java - Native</td>
<td>183</td>
</tr>
<tr>
<td>C</td>
<td>22</td>
</tr>
</tbody>
</table>
## Actual Numbers (You Explain)

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

<table>
<thead>
<tr>
<th>Language 1</th>
<th>Language 2</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocaml</td>
<td>Ocaml</td>
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<td>C</td>
<td></td>
<td>22</td>
</tr>
</tbody>
</table>

What?
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 ffff7 a648 bd32 f128

• What's the bug in your code?