CS 6371: Advanced Programming Languages

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Today’s Agenda

• Course overview and logistics
• Course philosophy and motivation
  – What is an “advanced” programming language?
  – Type-safe vs. Unsafe languages
  – Functional vs. Imperative programming
• Introduction to OCaml
  – The OCaml interpreter and compiler
  – An OCaml demo
Course Overview

• How to design a new programming language
  – specifying language formal semantics
  – bad language design and the “software crisis”
  – “new” programming paradigms: functional & logic
  – how to formally prove program correctness

• Related courses
  – CS 4337: Organization of Programming Languages
  – CS 5349: Automata Theory
  – CS 6301: Language-based Security
  – CS 6353: Compiler Construction
  – CS 6367: Software Verification & Testing
Course Logistics

• Class Resources:
  – Course homepage: www.utdallas.edu/~hamlen/cs6371sp23.html
  – My homepage: www.utdallas.edu/~hamlen
  – Tentative office hours: 1 hr immediately after each class
  – Email: hamlen AT utdallas DOT edu

• Grading
  – Homework: 25%
  – In-class quizzes: 15%
  – Midterm exam: 25%
  – Final exam: 35%

• Homework
  – 9 assignments: 6 programming + 3 written
  – Homework must be turned in by 1:05pm on the due date. Programming assignments submitted through eLearning; written assignments submitted in hardcopy at start of class.
  – Late homeworks NOT accepted!

• Modality: in-person (lectures recorded for later review)
Homework Policy

• Students MAY work together with other current students on homework
• You MAY NOT consult homework solution sets from prior semesters (or collaborate with students who are consulting them).
• CITE ALL SOURCES
  – includes web pages, books, other people, etc.
  – citation is required even if you don’t copy the source word-for-word
  – there is nothing wrong with using someone else’s ideas as long as you cite it
  – you will not lose any marks or credit as long as you cite
• Violating the above policies is PLAGIARISM (cheating).
• Cheating will typically result in automatic failure of this course and possible expulsion from the CS program.
• It is much better to leave a problem blank than to cheat!
  – Usually ~60% is a B and ~80% is an A.
  – However, cheating earns you an F. It’s not worth it!
Quizzes

• in-class on specified homework due dates
• about 15-20 min. each
• approximately 1 quiz per unit, so about 8 total
  – lowest one dropped, so you can miss one without penalty
  – other misses only permitted in accordance with university policy (e.g., illness with doctor’s note, etc.)
• closed-book, closed-notes
• think of them as extensions to the homework
  – length/difficulty similar to one or two homework problems
  – To prepare, be sure you can solve problems like those seen on the most recent homework in about 15-20 minutes each and without group help!
Difficulty Level

• Warning: This is a tough course for some
  – “strange” math, brain-bending programming style, some PhD-level material
  – difficulty ranked high by past students
• No required text book
  – few approachable texts cover this advanced material
  – no large pools of sample problems exist to my knowledge
  – useful texts:
    • book by Glynn Winskel available from UTD library
    • online text and several online manuals linked from webpage
  – Warning: Some online web resources devoted to this material that you may randomly find are INCORRECT (e.g., certain Wikipedia pages). Rely only on authoritative sources.
• What you’ll get out of taking this course
  – excellent preparation for PhD APL qualifier exam
  – solid understanding of language design & semantics
  – modern issues in declarative vs. imperative languages
  – deep connections between abstract logic and programming
About me…

• PhD & Masters from Cornell University, B.S. in CS & Math from Carnegie Mellon University
• Research: Computer Security, PL, Compilers
• Industry/Government Experience: Microsoft Research; PI for Navy, Air Force, Army, DARPA, NSF, NSA, ...
• Personal
  – Christian
  – married, three sons (one 10-year-old, and twin 7-year-olds)
• Programming habits
  – C/C++ (for low-level work)
  – assembly (malware reverse-engineering)
  – C#, Java (toy programs)
  – Prolog (search-based programs)
  – Gallina/Coq (high-assurance algorithm development)
  – OCaml, F#, Haskell (everything else)
Course Plan

- Running case-study: We will design and implement a new programming language
- Code an interpreter in OCaml
  - OCaml (“Objective Categorical Abstract Meta-Language”) is an open-source variant of ML
  - Microsoft F# is OCaml for .NET (but not fully compatible with OCaml, so don’t use it for homework)
  - Coq/Gallina is better (and harder) than OCaml (see me if you want to use it for homework)
  - Warning: OCaml has a STEEP learning curve!
- Pre-homework: Install OCaml
  - Go to the course website and follow the instructions entitled “To Prepare for the Course...” by next time
What is an “Advanced” Programming Language?
int __nss_hostname_digits_dots( ... ) {

...  
size_needed = sizeof(*host_addr) + sizeof(*h_addr_ptrs) + strlen(name) + 1;
*buffer = (char*)malloc(size_needed);
... 35 lines of code ...
host_addr = (host_addr_t*)*buffer;
h_addr_ptrs = (host_addr_list_t*)((char*)host_addr + sizeof(*host_addr));
h_alias_ptr = (char**)((char*)h_addr_ptrs + sizeof(*h_addr_ptrs));
name = (char*)h_alias_ptr + sizeof(*h_alias_ptr);

...  
if (isdigit(name[0])) {
    for (cp=name; ; ++cp) {
        if (*cp == '\0') {
            if (*--cp == '.') break;
            if ((af == AF_INET) ? inet_aton(name, host_addr) : inet_pton(af, name, host_addr))
                result_buf->h_name = strcpy(hostname, name);
        goto done;
    }
    if (!isdigit(*cp) && *cp != '.') break;
    }
}
```c
int __nss_hostname_digits_dots( ... ) {
    ...
    size_needed = sizeof(*host_addr) + sizeof(*h_addr_ptrs) + strlen(name) + 1;
    *buffer = (char*)malloc(size_needed);
    ...
    35 lines of code ...
    host_addr = (host_addr_t*)*buffer;
    h_addr_ptrs = (host_addr_list_t*) ((char*)host_addr + sizeof(*host_addr));
    h_alias_ptr = (char**)((char*)h_addr_ptrs + sizeof(*h_addr_ptrs));
    name = (char*)h_alias_ptr + sizeof(*h_alias_ptr);
    ...
    if (isdigit(name[0])) {
        for (cp=name; ; ++cp) {
            if (*cp == '\0') {
                if (*--cp == '.') break;
                if ((af == AF_INET) ? inet_aton(name, host_addr) : inet_pton(af, name, host_addr))
                    result_buf->h_name = strcpy(hostname, name);
                goto done;
            }
        }
        if (!isdigit(*cp) && *cp != '.') break;
    }
}
```
Impact of this C bug

• Discovered by Qualys researchers in 2015 during a routine code audit of the Gnu standard C libraries
  – affects nearly all Linux code that performs host lookups
• Initially classified as low-severity (rare crash)
• Qualys then demonstrated that they could use it gain complete remote control over nearly any Linux networking application.
• Eventual conclusion: Nearly all Linux systems were vulnerable to complete remote compromise for over a decade.
High-level Take-aways

• C/C++ code contains many “unsafe” features that invite disaster:
  – unconstrained pointer arithmetic
  – unstructured control-flows
  – unchecked datatype casting (programmer casts are blindly trusted)
  – in-lined assembly code
• About 25% of all highest severity bugs in history have been “buffer errors”.
• The world’s most mission-critical software (e.g., operating systems) consist of hundreds of millions lines of C code.
  – No human can comprehend, much less comprehensively debug/audit that.
• Most of the software crashes you experience are a direct result of the unsafe design of C/C++. 
Java: A Type-safe, Imperative Language

• Find two bugs:

```java
import java.io.*;
import java.util.*;

class Summation {
    public static void main(String[] args) {
        List list = new LinkedList();

        for (int i=0; i<args.length; ++i)
            list.add(args[i]);

        int sum = 0;
        while (!list.isEmpty())
            sum += ((Integer)list.remove(1)).intValue();

        System.out.println(sum);
    }
}
```
Java: A Type-safe, Imperative Language

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        System.out.println(sum);
    }
}
```

1. **Cast Exception!**
   - The code attempts to cast `Integer` to `int` directly, which is a type-safe language feature.

2. **OutOfBounds Exception!**
   - The list index `1` is used to remove an element, but the list might be empty, causing an `IndexOutOfBoundsException`.
A Real-world Java Bug

```java
/**
 * Handles XML content
 */
public class XStreamHandler implements ContentTypeHandler {

    public String fromObject(Object obj, String resultCode, Writer out) throws IOException {
        if (obj != null) {
            XStream xstream = createXStream();
            xstream.toXML(obj, out);
        }
        return null;
    }

    public void toObject(Reader in, Object target) {
        XStream xstream = createXStream();
        xstream.fromXML(in, target);
    }

    protected XStream createXStream() {
        return new XStream();
    }

    ...  
```
/**
 * Handles XML content
 */
public class XStreamHandler implements ContentTypeHandler {

    public String fromObject(Object obj, String resultCode, Writer out) throws IOException {
        if (obj != null) {
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        return null;
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    public void toObject(Reader in, Object target) {
        XStream xstream = createXStream();
        xstream.fromXML(in, target);
    }

    protected XStream createXStream() {
        return new XStream();
    }

    ...
Impact of this bug

• Discovered in Apache Struts library in 2017
  – Representational State Transfer (REST) plug-in
• Eventually identified as the root cause of the famous Equifax breach
  – Private financial data of over 150 million people stolen
  – One of the largest cybercrimes in history
  – Cost Equifax at least $650 million in fines (plus reputation loss, private settlements, etc.)
Problems with Java

• Every Java cast operation is potentially unsafe
  – Some casts are non-obvious (example: deserialization)
  – Even the obvious casts are so pervasive that they form a huge attack surface
• Some typecasting issues can be solved with Generics, but not all (e.g., list emptiness check)
• Problems:
  – Many forms of unsafe dynamic code-loading
  – Massive runtime library, whose foundations are mostly written in C
  – Inexpressive type system $\rightarrow$ code duplication $\rightarrow$ inconsistencies $\rightarrow$ bugs
Goals of Functional Languages

• In an “Advanced” Programming Language:
  – The compiler should tell you about typing errors in advance (not at runtime!)
  – The language structure should make it difficult to write programs that might crash (no unsafe casts!)
  – 80% of your time should be spent getting the program to compile, and only 20% on debugging
  – should be tractable to create a formal, machine-checkable proof of correctness for mission-critical core routines, or even full production-level apps
In OCaml…

• You almost never need to cast anything
  – The compiler figures out all the types for you
  – If there’s a type-mismatch, the compiler warns you

• OCaml is fast
  – Somewhere between C (fastest) and Java (slow)
  – Hard to measure precisely. (So-called “language benchmarks” typically call underlying math libraries that aren’t even implemented in the languages being tested!)

• Functions are “first-class”:
  – you can pass them around as values, assign them to variables, ...
  – you can SAFELY build them at runtime

• But: The syntax and coding style is very weird if you’ve only ever programmed in imperative languages!
OCaml: Getting Started

• OCaml programs are text files (*.ml)
  – Write them using any text editor (e.g., Notepad)
  – Unix: Emacs has syntax highlighting for ML/OCaml
  – Windows: I use Vim (www.vim.org)

• Installing OCaml (see course website)
  – Unix: pre-installed on the department Unix machines
  – Windows: Self-installers for native x86 and for Cygwin

• Two ways to use OCaml:
  – The OCaml compiler: ocamlc (compile *.ml to binary)
  – OCaml in interactive mode (use OCaml like a calculator)
  – Demo...