

# **CSC2/455 Software Analysis and Improvement Introduction**

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Sreepathi Pai

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URCS

# Outline

Classical Compiler Analysis

Program Analysis

Fundamental Issues

Administrivia

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# An example program

```
#include <stdio.h>

int main(void) {
    int N = 10000;
    int sum = 0;

    for(int i = 1; i < N; i++) {
        sum += i;
    }

    if(sum > 0) {
        printf("%d: %x\n", sum, sum);
    } else {
        printf("sum is zero\n");
    }

    return 0;
}
```

# Compiled with gcc -O0

```
main:
    pushq   %rbp
    movq   %rsp, %rbp
    subq   $16, %rsp
    movl   $10000, -4(%rbp)
    movl   $0, -12(%rbp)
    movl   $1, -8(%rbp)
    jmp    .L2
.L3:
    movl   -8(%rbp), %eax
    addl   %eax, -12(%rbp)
    addl   $1, -8(%rbp)
.L2:
    movl   -8(%rbp), %eax
    cmpl   -4(%rbp), %eax
    jl    .L3
    cmpl   $0, -12(%rbp)
    jle   .L4
    movl   -12(%rbp), %edx
    movl   -12(%rbp), %eax
    movl   %eax, %esi
    leaq   .LC0(%rip), %rdi
    movl   $0, %eax
    call   printf@PLT
    jmp    .L5
.L4:
    leaq   .LC1(%rip), %rdi
    call   puts@PLT
.L5:
    movl   $0, %eax
    leave
    ret
```

## Compiled with gcc -O1

```
main:
    subq    $8, %rsp
    movl    $9999, %eax
.L2:
    movl    $49995000, %ecx
    movl    $49995000, %edx
    leaq   .LC0(%rip), %rsi
    movl    $1, %edi
    movl    $0, %eax
    call   __printf_chk@PLT
    movl    $0, %eax
    addq   $8, %rsp
    ret
```

The compiler:

- Eliminated the for loop
  - Replaced it with the value computed
- Eliminated the else part of the if/then
  - Because it would never execute

## How did it do that?

How do you think the compiler did this?

# Compilers today

- GNU Compiler Collection (GCC)
- LLVM
  - Many proprietary compilers based on LLVM
- Visual Studio
- Proprietary compilers
  - Intel `icc`
  - NVIDIA/Portland Group



# DSL Compilers today

- DSL: Domain Specific Languages
- OpenAI Triton
  - Used to generate high performance matrix multiply for PyTorch
- IREE
  - Compiles ONNX ML models to high performance code
- Microsoft CCL
  - Generates high performance communication primitives for ML

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## Analysis (and Verification)

- How many times will this loop execute?
- Will this condition always be true?
- Is this value always a constant?
- Are there bugs in a given piece code?
  - NULL pointer dereferences?
  - Data races (in concurrent code)?
- Is this code correct (according to some specification)?

# Properties

- Safety properties
  - Informally, “something bad will never happen”
  - Formally, a property that is always true
- Liveness properties
  - Informally, “something good will eventually happen”
  - Formally, a property that will eventually be true
- Other properties:
  - All allocated memory is freed
  - All open files are closed

# Program Analysis Tools today

- (Synopsys) Coverity
- GrammaTech CodeSonar
- Facebook Infer
- Frama-C
- PVS-Studio
- Microsoft SLAM
- Lots of others...

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## What does this Python program do?

```
for i in range(n):  
    print("boom!")
```

## Strategy: Run (or Interpret) the program

- Running the program and observing what it does is a perfectly reasonable way of analyzing a program
  - Maybe run it in a simulator/VM or interpreter
- What problems do you anticipate with this strategy?



## Some potential problems

- Too long
- Infinite loop (aka non-termination)
- Number of inputs may be infinite!
  - Behaviour may depend on input

## What does this program do?

```
def collatz(n): # n is a positive integer
    while n > 1:
        print(n)
        if n % 2 == 0:
            n = n // 2 # integer division
        else:
            n = 3 * n + 1

    for i in range(n):
        print("boom!")
```

## Some runs: $n=5$

5  
16  
8  
4  
2  
1  
boom!

## Some runs: $n=12$

12

6

3

10

5

16

8

4

2

1

boom!

## Analyzing this program

- This program will print only 1 boom!
- *If* the loop terminates
  - Only if  $n$  is always reduced to 1
  - Is it always? (\$500 reward!)
- Can we determine if the loop terminates?
  - For any  $n$ ?
  - For a fixed  $n$ ?

# Undecidability: The Halting Problem

- In general, an algorithm cannot determine if a program will terminate on a given input
- What does this imply for program analysis?
  - End of this course?

# Program Analysis

- Program analysis needed for optimization (“making programs faster”)
  - Reducing number of operations
  - Substituting cheaper operations
  - Increasing parallelism of operations
- Also need for verification (“security”)
  - Will this program crash for any input?
  - Will this program leak memory? (`malloc` but no corresponding `free`)
  - Will this program read another user’s files?
  - Can a program be subverted to obtain root access?
- Computers everywhere, such questions far more important now!
  - 4.4B people have smartphones!

# Mission Impossible?

- No general technique to analyze programs
  - Many different approaches
- We will study many of these
  - Basic
  - Advanced
  - Recent advances



# Roadmap of the course: Part I

- Dataflow Analysis (DFA)
  - Mostly used in compilers
  - Automatic, fast, and approximate
- You'll construct the “mid-end” of a compiler for a subset of the C language
  - Introduces you to the engineering and theoretical aspects
- One specialized non-compiler tool: Oracle's Soufflé

## Some topics from part I

- How do we represent programs for analysis?
- Analyses
  - Identifying expressions that have the same value
  - Detecting the last use of a variable
  - Recognizing that an expression has already been computed
  - Determining code that is always executed
  - Identifying unused code
  - etc.

# Program Analysis: Part II

- Abstract Interpretation (AI)
  - Automatic, slower, and approximate
  - Specialized tools: Facebook Infer, many others
- Model Checking
  - Automatic, fast (but not as fast as DFA), and precise
  - Can be intractable
  - We'll look at CBMC, perhaps also Spin
- Symbolic Execution
  - Automatic, fast, and precise
  - Can be intractable
  - We'll look at KLEE and maybe Angr
- Deductive Techniques
  - Manual to semi-automated, as fast as you think, and precise
  - Essentially involves writing proofs
  - We'll look at (Microsoft) Dafny

## Some things program analysis makes possible

- Fast Javascript
  - pioneered by Google's V8
- Safe in-kernel execution of user-provided code
  - Linux eBPF
  - pioneered by Sun's DTrace
- Safe systems programming languages
  - Rust
- Airplanes in the sky
  - Remember Boeing 737 MAX?

## Where program analysis is being used

- Compilers
- Program security industry
  - Conventional programs
  - Programs on “blockchain”

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# People

- Instructor: Dr. Sreepathi Pai
  - E-mail: [sree@cs.rochester.edu](mailto:sree@cs.rochester.edu)
  - Office: Wegmans Hall 3409
  - Office Hours: Monday 15:30 to 16:30 (or by appointment)
- TAs:
  - Jingyu Qiu
  - Office Hours: Thursday 16:00 to 17:00, Wegmans 2215

# Places

- Class: Meliora 224
  - M,W 1025–1140
- Course Website
  - <https://cs.rochester.edu/~sree/courses/csc-255-455/spring-2025/>
- Blackboard
  - Announcements, Discussions
- Gradescope
  - Assignments, Homeworks, Grades, etc.



# References

- Three textbooks
  - Aho, Lam, Ullman, Sethi, *Compilers: Principles, Techniques and Tools*
  - Cooper and Torczon, *Engineering a Compiler*
  - Rival and Yi, *Introduction to Static Analysis: An Abstract Interpretation Perspective*, MIT Press, 2020
- This course requires a lot of reading!
  - Books and materials have been placed on reserve
  - Some online, some in Carlson Library

# Grading

- Homeworks: 15%
- Assignments: 70% (5 to 6)
- Exams: 15%
- Graduate students should expect to read a lot more, and work on harder problems.

There is no fixed grading curve. See course website for grade scale.

See course website for late submissions policy.

## Academic Honesty

- Unless explicitly allowed, you may not show your code to other students
- You may discuss, brainstorm, etc. with your fellow students but all submitted work must be your own
- All help received must be acknowledged in writing when submitting your assignments and homeworks
- All external code you use must be clearly marked as such in your submission
  - Use a comment and provide URL if appropriate
- If in doubt, ask the instructor
- It is a violation of course honesty to make your assignments on GitHub (or similar sites) public

All violations of academic honesty will be dealt with strictly as per UR's Academic Honesty Policy.

# Code Generation Tools

- Tools like CoPilot, ChatGPT are best not used
  - unfortunately these tools are hard to avoid
- Unless otherwise stated, you are free to use "AI" tools to do your assignments (e.g. ChatGPT, Co-pilot, etc.) provided you follow the rules below. Not following the rules below will be treated as a honesty code violation.
  - Please put a comment at the top in each file that includes AI-generated material (include auto-completions) indicating what system was used, like "`# AI: ChatGPT`"
  - If this is a system like ChatGPT, include the *full* transcript as a comment at the end of the source file.
  - If this was a system like Co-pilot which and you used prompts, leave the prompts in the source code.

## Instructor/TA expectations about generated code

- Note that the TAs and I will only help you debug AI-generated code at our discretion.
- Also note that compiler engineering requires good programming skills, and you should use this class to develop them

# Course Goals

- Write your own compilers
- Modify existing compilers
- Read about new analyses (in research papers)
- Create new analyses
- Use analysis tools and frameworks

# Where are they now?

- Class alumni have gone on to careers in compilers
- Industry
  - NVIDIA
  - Cray/HPE
  - Texas Instruments
  - Qualcomm
  - Microsoft
  - and others to work on compilers.
- Graduate school
  - UIUC
  - Utah
  - Cornell
  - and others.