COMP 737011 - Memory Safety and Programming Language Design

Lecture 0: Course Introduction

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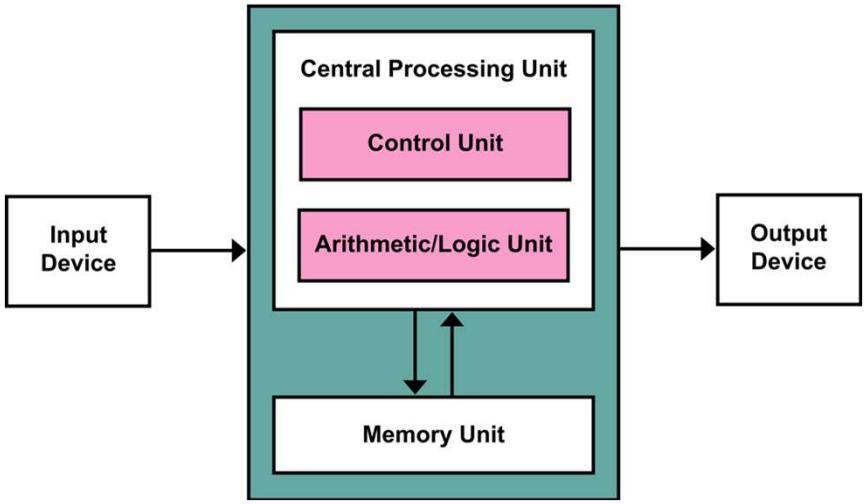
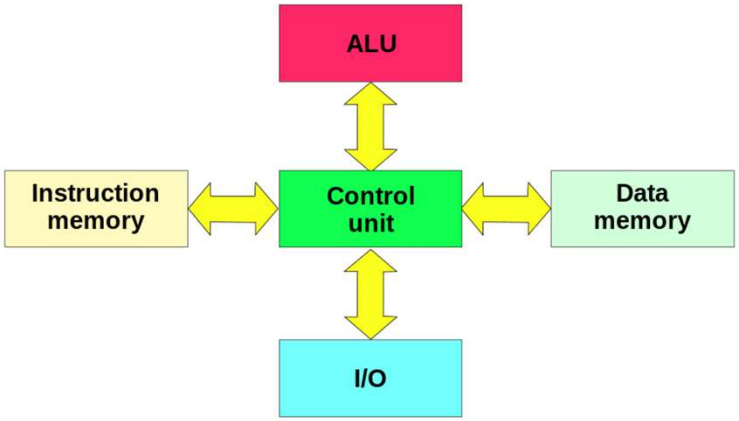
Computer Architecture

- von Neymann Architecture
  - Instructions and data share the same memory unit
  - Widely used
- Harvard Architecture
  - Instructions and data are separated
  - Mainly used in DSP or microcontrollers



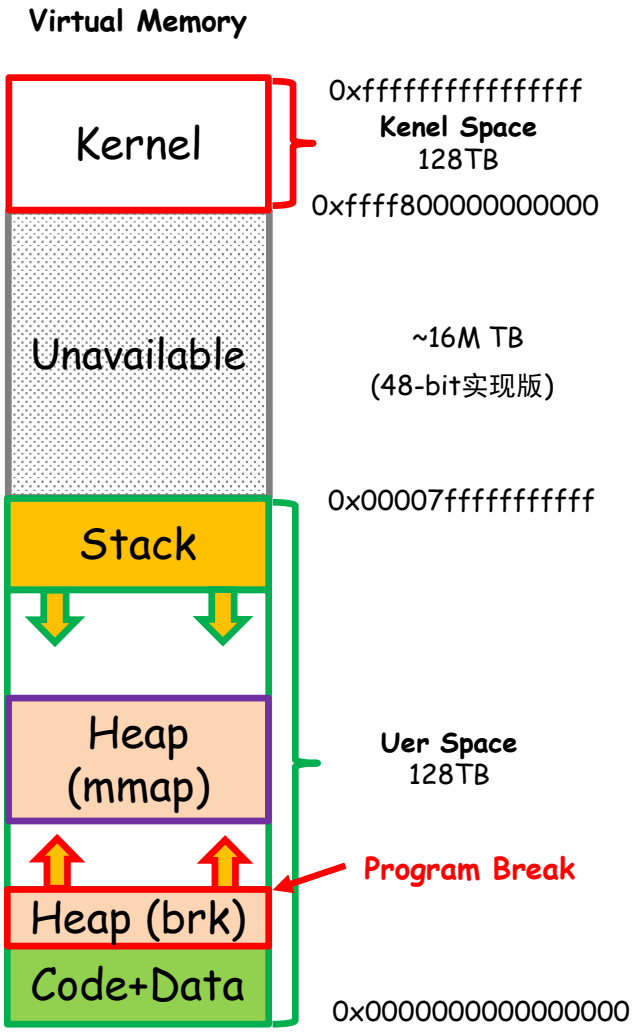
von Neymann Architecture



Harvard Architecture

Operating System

- Multi-process
  - Concurrently executed
  - May or may not share the same address space
  - An OS kernel for global control
  - Syscall for executing kernel code
- Process Memory Layout
  - Kernel space (ring 0)
    - Kernel code + data
    - Kernel runtime
  - User space (ring 3)
    - User code + data
    - User runtime: stack + heap



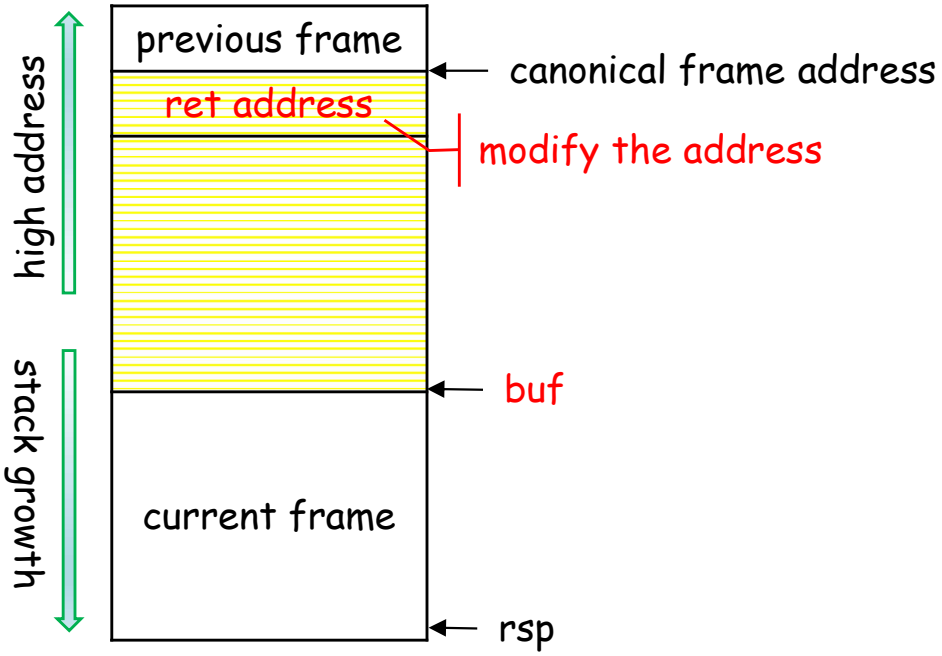
Memory Safety Issues

- Types of bugs:
  - Buffer overflow
  - Dangling pointer
  - Concurrency issue
- Consequence:
  - Data integrity
  - Code integrity
  - Control-flow integrity
  - …

Buffer Overlfow

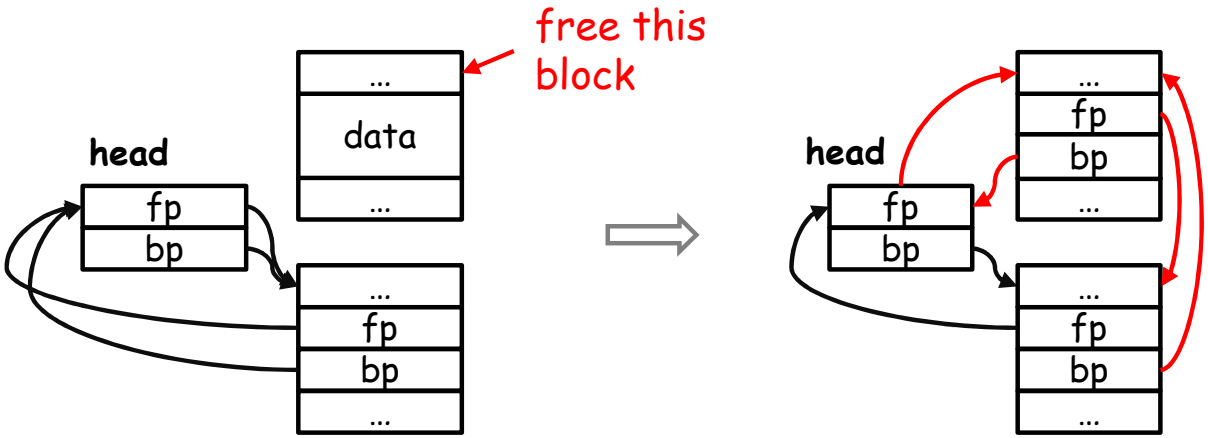
- Write beyond the allocated memory address
- Can happen either on stack or heap

```
char buf[64];
read(STDIN_FILENO, buf, 160);
if(strcmp(buf,LICENCE_KEY)==0){
    write(STDOUT_FILENO,
        "Key verified!\n", 14);
}else{
    write(STDOUT_FILENO,
        "Wrong key!\n", 11);
}
```



Dangling Pointer

- Heap are managed with linked lists
- Effects of free a memory slot on heap via free()
  - The memory is not reclaimed by the OS
  - The memory is add to a free list
  - The pointer still points to the address
- Write to a dangling pointer could breach the list



Concurrency Issue

- Race condition or data race
- How to attack the following program?

```
if (!access("/tmp/X", W_OK)) {
    /* the real user ID has access right */
    f = open("/tmp/X", O_WRITE);
    write_to_file(f);
}
else {
    /* the real user ID does not have access right */
    fprintf(stderr, "Permission denied\n");
}
```

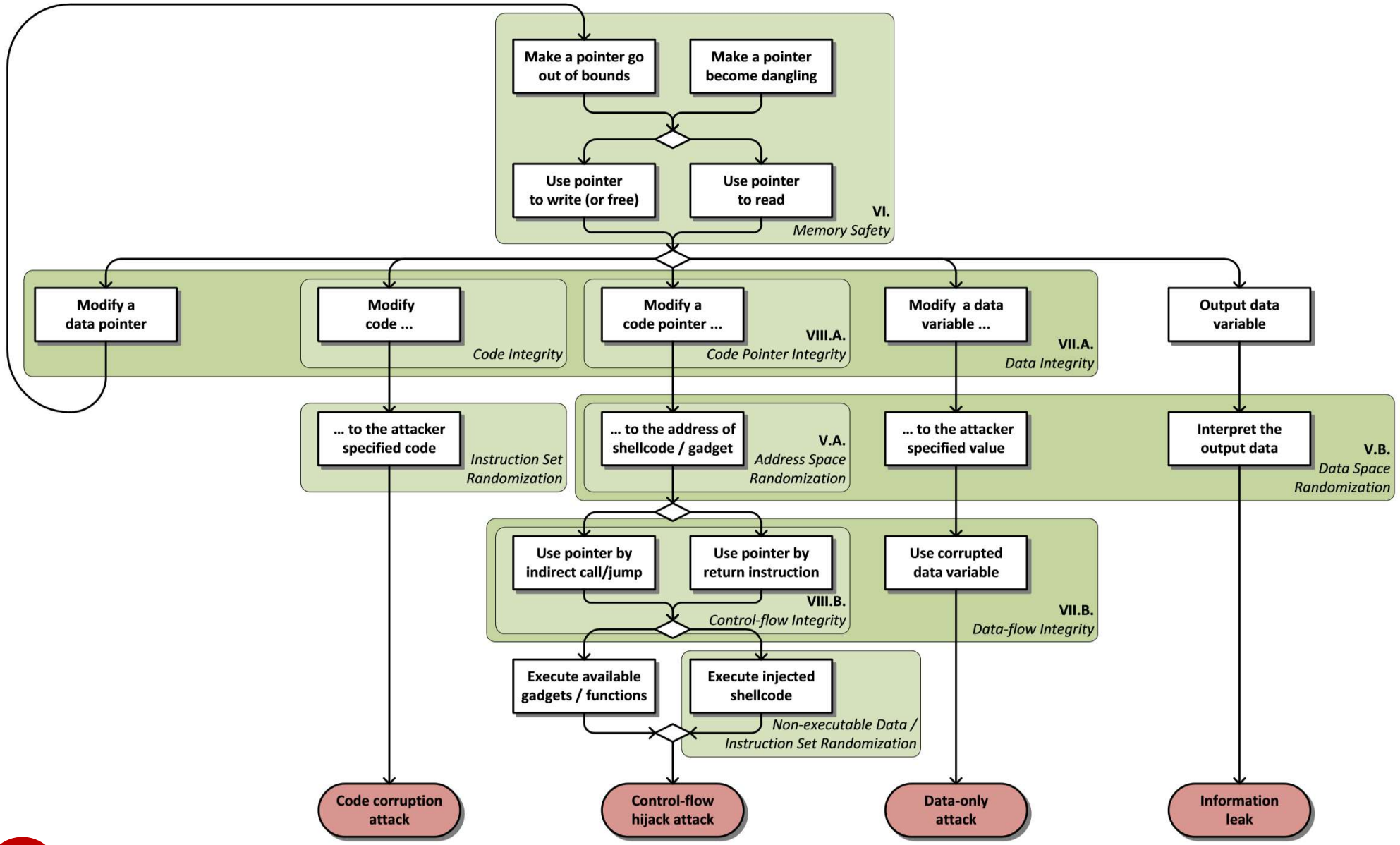
- Another thread modifies /tmp/X concurrently
  - Before access(/tmp/X, W_OK)), the file /tmp/X is indeed /tmp/X
  - After access(/tmp/X, W_OK), change /tmp/X to /etc/passwd (via symbolic link)

Top 25 Dangerous Software Errors

Rank	ID	Name	Score	2020 Rank Change
[1]	CWE-787	Out-of-bounds Write	65.93	+1
[2]	CWE-79	Improper Neutralization of Input During Web Page Generation ('Cross-site Scripting')	46.84	-1
[3]	CWE-125	Out-of-bounds Read	24.9	+1
[4]	CWE-20	Improper Input Validation	20.47	-1
[5]	CWE-78	Improper Neutralization of Special Elements used in an OS Command ('OS Command Injection')	19.55	+5
[6]	CWE-89	Improper Neutralization of Special Elements used in an SQL Command ('SQL Injection')	19.54	0
[7]	CWE-416	Use After Free	16.83	+1
[8]	CWE-22	Improper Limitation of a Pathname to a Restricted Directory ('Path Traversal')	14.69	+4
[9]	CWE-352	Cross-Site Request Forgery (CSRF)	14.46	0
[10]	CWE-434	Unrestricted Upload of File with Dangerous Type	8.45	+5
[11]	CWE-306	Missing Authentication for Critical Function	7.93	+13
[12]	CWE-190	Integer Overflow or Wraparound	7.12	-1
[13]	CWE-502	Deserialization of Untrusted Data	6.71	+8
[14]	CWE-287	Improper Authentication	6.58	0
[15]	CWE-476	NULL Pointer Dereference	6.54	-2
[16]	CWE-798	Use of Hard-coded Credentials	6.27	+4
[17]	CWE-119	Improper Restriction of Operations within the Bounds of a Memory Buffer	5.84	-12
[18]	CWE-862	Missing Authorization	5.47	+7
[19]	CWE-276	Incorrect Default Permissions	5.09	+22
[20]	CWE-200	Exposure of Sensitive Information to an Unauthorized Actor	4.74	-13
[21]	CWE-522	Insufficiently Protected Credentials	4.21	-3
[22]	CWE-732	Incorrect Permission Assignment for Critical Resource	4.2	-6
[23]	CWE-611	Improper Restriction of XML External Entity Reference	4.02	-4
[24]	CWE-918	Server-Side Request Forgery (SSRF)	3.78	+3
[25]	CWE-77	Improper Neutralization of Special Elements used in a Command ('Command Injection')	3.58	+6

https://cwe.mitre.org/top25/archive/2021/2021_cwe_top25.html

Eternal War in Memory



Laszlo Szekeres, *et al.* "Sok: Eternal war in memory." *IEEE Symposium on Security and Privacy*, 2013.

Methods to Protect Memory Safety

- Developers are human, so errors cannot be avoided
- Preventing bugs by programming language design.
  - Type safety, smart pointer, *etc.*
- Preventing bugs by testing
  - Address sanitizer, fuzz, symbolic execution, etc
- Preventing attack during runtime
  - Stack canary, shadow stack, *etc.*

Availability Issue

- Types of bugs:
  - Stack overflow
  - Heap exhaustion
  - Memory leakage
- Consequence:
  - Unexpected termination
  - May not be easy to recover
- This course also considers availability issues because it is closely related to memory safety

Rust Language for Memory Safety

- A system programming language focusing on:
  - Memory safety
  - Concurrency safety
  - Efficiency
- Timeline
  - Personal project started in 2006 by Mozilla employee Graydon Hoare.
  - Self-hosting since 2011
  - First stable version was released in 2015

Why Rust?

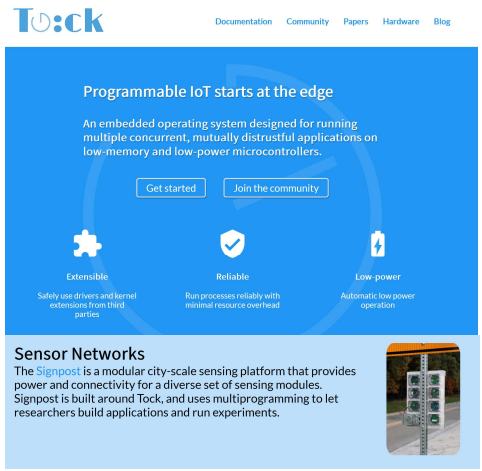
- State-of-the-art language for memory safety
- Most favorable according to stackoverflow
- Many large companies turn to Rust

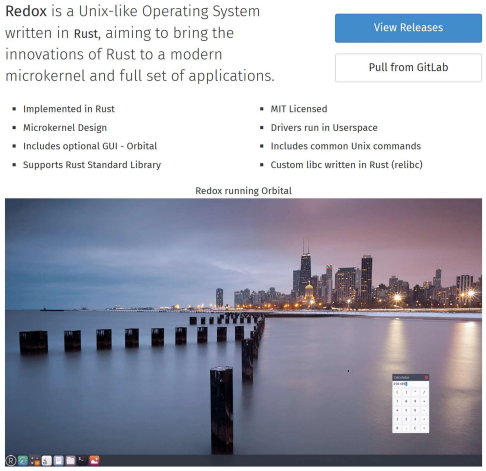
Using Rust in Windows

Security Research & Defense / By MSRC Team / November 7, 2019 / Memory Safety, Rust, Safe Systems Programming Languages, Secure Development

This Saturday 9th of November, there will be a keynote from Microsoft engineers Ryan Levick and Sebastian Fernandez at RustFest Barcelona. They will be talking about why Microsoft is exploring Rust adoption, some of the challenges we've faced in this process, and the future of Rust adoption in Microsoft. If you want to talk with some of the people working on how Microsoft is evolving its code practices for better security, be sure to attend the keynote and talk to Ryan and Sebastian afterwards!

This blog describes part of the story of Rust adoption at Microsoft. Recently, I've been tasked with an experimental rewrite of a low-level system component of the Windows codebase (sorry, we can't say which one yet). Instead of rewriting the code in C++, I was asked to use Rust, a memory-safe alternative. Though the project is not yet finished, I can say that my experience with Rust has been generally positive. It's a good choice for those looking to avoid common mistakes that often lead to security vulnerabilities in C++ code bases.





https://insights.stackoverflow.com/survey/2021

Key Idea of Rust

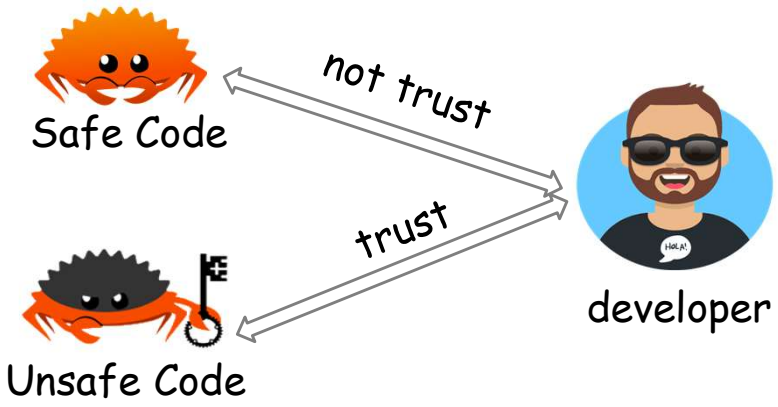
- Security zones of Rust Code:
  - unsafe code: dereference raw pointer, FFI, etc
  - safe code: without undefined behaviors
- Interior safety: developers should
  - avoid using unsafe code as best as they can
  - wrap unsafe code into safe APIs so that they can use safe APIs instead

```
let mut num = 5;
let r1 = &num as *const i32;
let r2 = &mut num as *mut i32;
unsafe {
  println!("r1 is: {}", *r1);
  println!("r2 is: {}", *r2);
}
```

Dereference raw pointers

```
unsafe fn dangerous() {
  let address = 0x012345usize;
  let r = address as *const i32;
}
unsafe {
  dangerous();
}
```

Call unsafe functions



Objective of This Course

- Practice the skills in research and solving problems.
- After this course, the student shall
  - understand the issues related to memory safety and can demonstrate them
  - know some basic ideas and tools for solving memory safety problems
  - understand the advanced features of Rust

Tentative Schedule

Week	Subject		In-class Practice
1	Problems related to Memory-Safety	Buffer Overflow	Attack Experiment
2		Memory Allocation	Coding Practice
3		Memory Exhaustion	Attack Experiment
4		Dangling Pointers	Attack Experiment
5		Concurrent Memory Access	Coding Practice
6	Rust Programming Language	Rust Ownership-based Memory Management	Coding Practice
7		Rust Generics and Traits	Coding Practice
8		Rust Concurrency Programming	Coding Practice
9		Rust Compiler Theory	Tool Experiment
10		Rust Compiler Techniques	Tool Experiment
11	Advanced Topic for Memory Safety	Effectiveness of Rust	Discussion
12		Testing and Fuzzing	Tool Experiment
13		Address Sanitizer	Tool Experiment
14		Static Program Analysis	Tool Experiment
15		Symbolic Execution	Tool Experiment
16		Isolation of Unsafe Code	Discussion
17		Code Search and Recommendation	Coding Practice
18	Course Exam	Project Report	

Grading

- In-class Practice: Max 60%
  - 10-15 experiments
  - 6% for each experiment
  - You may get all the marks by doing 10 experiments
  - Submit simple experiment reports on elearning
  - Due: T+1 week
- Discussion: 10%
  - Two classes
- Project: 30%
  - 20min presentation
    - one paper or multiple papers
  - PPT file is required for submission

Notice

- Plagiarism or cheating will not be tolerated
  - You cannot copy any sentence or paragraph
  - Rephrase it or "*quote it*"
- Hard due date of assignments