RUST: A COUSIN OF C++ WITH BETTER MEMORY PROTECTION

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CS4414 Lecture 27

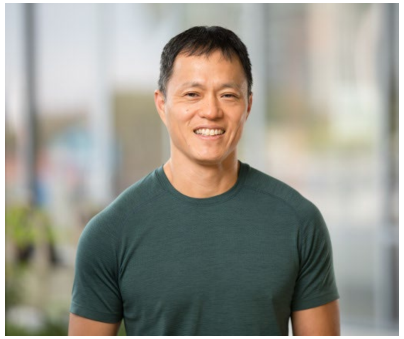
IDEA MAP FOR TODAY

Many attacks exploit weak memory protection

C++ is built on C… and C is fundamentally unsafe

Rust idea	How well does it work?	What are the criticisms of Rust?

Today's entire lecture borrows heavily from a lecture open-sourced by Prof. Wu-chang Feng at Portland State University, where they use Rust as their systems programming language



C++ IS DEEPLY CONNECTED TO C

After templates are expanded and constexpr is resolved, C++ "transforms" to a C program for compilation. The template language is a true programming language with compile-time loops, conditional statements, function calls. Yet it reduces to "plain old C."

Thus, many weaknesses of C translate to vulnerabilities in C++

To compensate we use logical reasoning to ensure safety and Valgrind as a debugging tool (but Valgrind is very slow)

C (THE GOOD PARTS)

Efficient code especially in resource-constrained environments

Direct control over hardware such as network interfaces and GPUs

Performance over safety

- Memory managed manually ("wrap" C++ pointers to improve safety)
- No periodic garbage collection (instead, each call to **free** incrementally updates the heap)
- Favored by advanced programmers: total control

BUT…

Even with this help, both C and C++ make it very easy to make mistakes involving misuse of pointers.

C also has issues with type coercion (C++ fixes them!):

- Integer promotion/coercion errors (where the code specifies the size of an integer, but then uses it in a way inconsistent with the size)
- Unsigned vs. signed errors (in C, conversions back and forth are legal and won't even trigger a warning… C++ will warn)
- Integer casting errors (easy to misunderstand the rules)

AND… IN BOTH C AND C++…

Memory pointer errors are very easy to make

- Dereferencing a null pointer
- Buffer overflows, out-of-bound access (no array-bounds checking)
- Format string errors in printf or std::cout
- Dynamic memory errors (Memory leaks, use-after-free (dangling pointer), double free of a pointer)

All of these can cause software crashes and security vulnerabilities.

EXAMPLE: C-STYLE POINTERS IN C OR C++

Lightweight, low-level control of memory

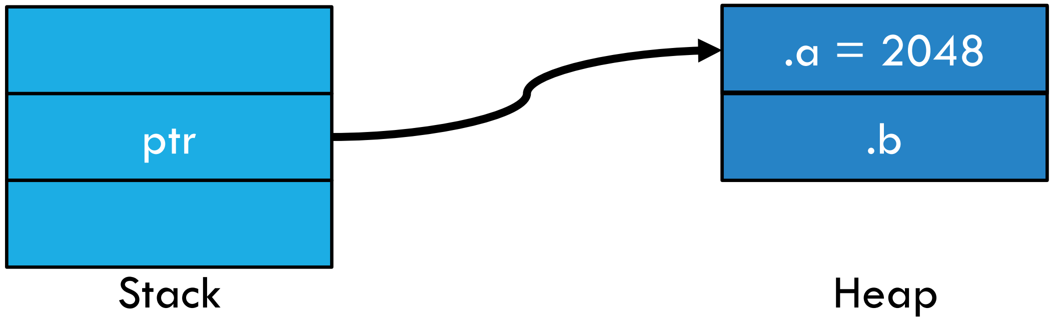
```
typedef struct { int a; int b; } Dummy;

void foo() {
    Dummy *ptr = (Dummy *) malloc(sizeof(struct Dummy));
    ptr->a = 2048;
    free(ptr);
}
```

Precise memory layout

Lightweight reference

Destruction



... ISSUE: ERRORS GO UNDETECTED

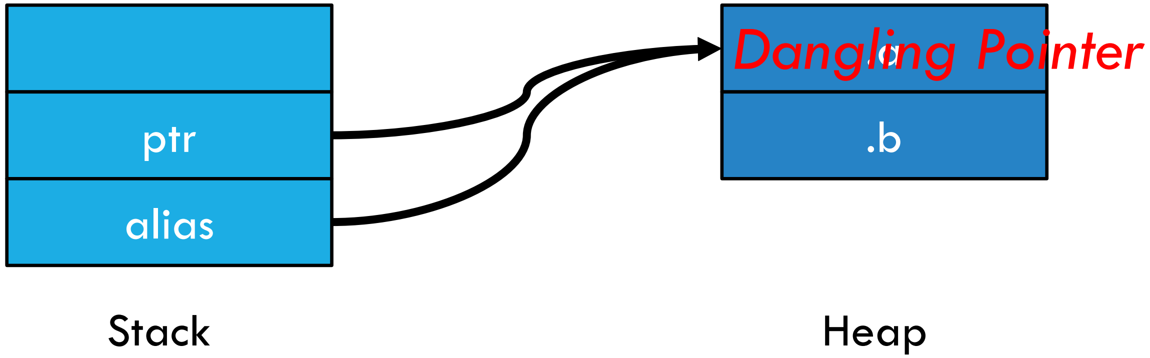
```
typedef struct { int a; int b; } Dummy;

void foo() {
    Dummy *ptr = (Dummy *) malloc(sizeof(struct Dummy));
    Dummy *alias = ptr;
    free(ptr);
    int a = alias.a;
    free(alias);
}
```

Use after free (`int a = alias.a;`)

Double free (`free(alias);`)

Aliasing ✚ *Mutation*



THESE ISSUES ARE ALL SOLVED BY MANAGED LANGUAGES, BUT THEY ARE OFTEN SLOW

Java, Python, Ruby, C#, Scala, Go…

All of them restrict direct access to memory with run-time management of memory via garbage collection. But…

- They pay a high overhead for tracking pointer use and array-index safety
- Performance can be unpredictable due to GC (bad for real-time systems)
- Limited concurrency (global interpreter lock typical)
- In some cases a VM is required (like for Python)
- Need more memory and CPU power (i.e. not bare-metal)

REQUIREMENTS FOR SYSTEM PROGRAMMING

The language must be fast and have minimal runtime overhead

Developer should be able to visualize every action the entire system is performing and gain control over everything.

We often <u>need</u> direct memory access, but wish it was memory-safe

RUST

Rust is named after a fungus that is robust, distributed, and parallel.
It is also a subsequence of "robust".

RUST

From the official website (http://rust-lang.org):

Rust is a true system programming language.

- No runtime requirement (runs fast)
- Control over memory allocation/destruction.
- Guarantees memory safety

Created by Monzilla to address severe memory leakage and corruption bugs in Firefox. First stable release in 5/2015

RUST OVERVIEW

Performance, as with C or C++, similar look and feel as C++

- Rust compiles to object code for bare-metal performance

Supports memory safety

- Programs cannot dereference pointers that have been freed
- Out-of-bound array accesses not allowed

Relatively low overhead

- Compiler checks to make sure rules for memory safety are followed
- Zero-cost abstraction in managing memory (i.e. no garbage collection)

RUST OVERVIEW

How is this done? Like C++, much occurs at compile time!

- Advanced type system
- Novel language features to prevent memory and pointer issues

But there is a cost

- *Cognitive cost* to programmers who must think more about rules for using memory and references as they program
- *Less control* of the kind needed for ML and HPC programming

MORE ON THIS LAST POINT (1)?

Recall fast word-count. Sagar first turned every file into std::strings, but then discarded most of the strings. A wasteful design.

Ken had a layer that operated directly on data in character buffers. This uses pointers to ascii chars in arrays.

In Rust, pointer logic like what Ken did is much harder to implement because the compiler perceives it as unsafe. Inserting safety checks for every pointer dereference is similarly wasteful.

MORE ON THIS LAST POINT (2)?

Think about our lectures on SIMD, where we needed to control layout of data structures in memory to ensure that the alignment rules for data would be “visible” to the C++ compiler, and used templates + inlining + constexpr to preserve code elegance.

In Rust it can be hard or impossible to get the same kinds of guarantees. Rust lacks C++’s template “language”.

RUST IS ALSO AT ODDS WITH DIRECT-MAPPED GPU MEMORY, DMA AND RDMA

Device-mapped memory and mapped files can be exposed, but Rust protects accessing that memory with costly overheads.

All forms of direct memory transfers from network, disk or GPU are inherently unsafe, as are shared segments and VM page remapping: features advanced C++ developers often use.

RUST'S TYPE SYSTEM

RUST TYPES LOOK MUCH LIKE C/C++ TYPES

Primitive types

- `bool`
- `char` (4-byte unicode)
- `i8/i16/i32/i64/isize`
- `u8/u16/u32/u64/usize`
- `F32/f64`

Numeric types specified with width. The Unicode char default might surprise some C or C++ developers.

C TYPES HAVE SOME IDIOSYNCRASIES.

C "overloads" integers to get Booleans. Can create ambiguity: an integer isn't limited to just 0 or 1.

- True, False, or Fail? 1, 0, -1? Misinterpretations lead to security issues
- Example: In the PHP is a widely used C library for web programming. In it, strcmp returns 0 for both equality *and* failure!

C++ offers a true Boolean type. If you use it, this can't occur

C, C++ ARRAY TYPE

In Rust, arrays stored with their length `[T; N]`

- Allows for both compile-time and run-time checks on array access via `[]`

C

```
void main() {
     int nums[8] = {1,2,3,4,5,6,7,8};
     for ( x = 0; x < 10; i++ )
          printf("%d\n",nums[i]);
}
```

Rust

```
fn main() {
    let nums = vec![1,2,3,4,5,6,7,8];
    for x in 0..10 {
        println!("{}",nums[x]);
    }
}
```

```
7
8
thread 'main' panicked at 'index out of bounds: the len is 8 but the index is 8',
note: Run with `RUST_BACKTRACE=1` for a backtrace.
```

Program ended.

RUST AND BOUNDS CHECKING

But…

- Checking bounds on every access adds overhead

```
fn main() {
    let nums = vec![1,2,3,4,5,6,7,8];
    for x in 0..10 {
        println!("{}",nums[x]);
    }
}
```

- Arrays typically accessed via more efficient iterators to allow compile time checking, avoid runtime overheads
  - Can use x86 `loop` instruction

```
fn main() {
    let nums = vec![1,2,3,4,5,6,7,8];
    for num in &nums {
        println!("{}",num);
    }
}
```

RUST IS VERY CAUTIOUS ABOUT COERSIONS

In C code, you can cast any integer to an unsigned integer of the same size, or back. C++ doesn't allow this… except when compiling C

-1 casts to 2147483648 (largest uint32). Is this what a developer intended? The C specification just says this is an "undefined" cast!

A European rocket once veered wildly off course, then exploded because one module used unsigned int, but another used signed int.

RUST VS C TYPING ERRORS

C has confusing implicit integer casts and promotion

-1 > 0U

2147483647U < -2147483648

Rust's type system prevents such comparisons

```
void main() {
    unsigned int a = 4294967295;
    int b = -1;
    if (a == b)
        printf("%u == %d\n",a,b);
}

mashimaro <~>  9:44AM % ./a.out
4294967295 == -1
```

```
fn main() {
    let a:u32 = 4294967295;
    let b:i32 = -1;
    if a == b {
        println!("{} == {}", a, b);
    }
}
```

```
rustc 1.15.1 (021bd294c 2017-02-08)
error[E0308]: mismatched types
 --> <anon>:4:13
  |
4 |     if a == b {
error: aborting due to previous error
```

RUST VS C TYPING ERRORS

Same or different?

```c
void main() {
    char a=251;
    unsigned char b = 251;
    printf("a = %x\n", a);
    printf("b = %x\n", b);

    if (a == b)
        printf("Same\n");
    else
        printf("Not Same\n");
}
```

```
mashimaro<> % ./a.out
a = fffffffb
b = fb
Not Same
```

```rust
fn main() {
    let a:i8 = 251;
    let b:u8 = 251;

    if a == b {
        println!("Same");
    } else {
        println!("Not Same");
    }
}
```

```
rustc 1.15.1 (021bd294c 2017-02-08)
error[E0308]: mismatched types
 --> <anon>:5:13
  |
5 |     if a == b {
error: aborting due to previous error
```

RUST VS C TYPING ERRORS

201 > 200?

```c
#include <stdio.h>
void main() {
    unsigned int ui = 201;
    char c=200;
    if (ui > c)
        printf("ui(%d) > c(%d)\n",ui,c);
    else
        printf("ui(%d) < c(%d)\n",ui,c);
}
```

```
mashimaro <~> 12:50PM % ./a.out
ui(201) < c(-56)
```

```rust
fn main() {
    let ui:u32 = 201;
    let c:i8 = 200;
    if ui > c {
        println!("ui({}) > c({})",ui,c);
    } else {
        println!("ui({}) < c({})",ui,c)
    }
}
```

```
rustc 1.15.1 (021bd294c 2017-02-08)
error[E0308]: mismatched types
 --> <anon>:4:13
  |
4 |     if ui > c {
```

RUST VS C TYPING ERRORS

In Rust, casting is allowed via the “as” keyword

- Follows similar rules as C
- But, warns problem before performing the promotion with sign extension. C++ does this too, but because C code can be pulled in so easily…

```c
#include <stdio.h>
void main() {
  char c=128;
  unsigned int uc;
  uc = (unsigned int) c;
  printf("%x %u\n",uc, uc);
}
```

```
mashimaro <~>  1:24PM % ./a.out
ffffff80 4294967168
```

```rust
fn main() {
    let c:i8 = 128;
    let uc:u32 = c as u32;
    println!("uc = {}", uc);
}
```

```
rustc 1.15.1 (021bd294c 2017-02-08)
warning: literal out of range for i8, #
default
 --> <anon>:2:16
  |
2 |     let c:i8 = 128;
uc = 4294967168
```

RUST VS C TYPING ERRORS

C has issues with unchecked underflow and overflow

- Silent wraparound in C caught by runtime check in Rust

```
void main() {
    unsigned int a = 4;
    a = a - 3;
    printf("%u\n",a-2);
}
mashimaro <~>  9:35AM % ./a.out
4294967295
```

```
fn main() {
    let mut a:u32 = 4;
    a = a - 3;
    println!("{}", a - 2);
}
```

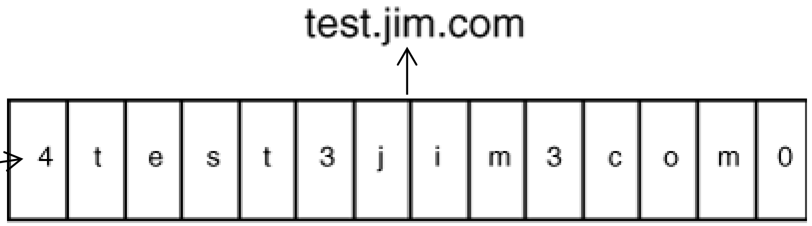
```
rustc 1.15.1 (021bd294c 2017-02-08)
thread 'main' panicked at 'attempt to subtract with overflow',
stack backtrace:
```

EXAMPLE: A FAMOUS C VULNERABILITY

DNS parser vulnerability discussed in B&O, Chapter 2

- `count` read as byte, then `count` bytes concatenated to `nameStr`

```
  char *indx;
  int count;
  char nameStr[MAX_LEN]; //256
...
  memset(nameStr, '\0', sizeof(nameStr));
...
  indx = (char *)(pkt + rr_offset);
  count = (char)*indx;
  while (count){
    (char *)indx++;
    strncat(nameStr, (char *)indx, count);
    indx += count;
    count = (char)*indx;
    strncat(nameStr, ".“, sizeof(nameStr) – strlen(nameStr));
  }
  nameStr[strlen(nameStr)-1] = '\0';
```



What if count = 128?

Sign extended then used in strncat

Type mismatch in Rust

```
char *strncat(char *dest, const char *src, size_t n);
```


http://www.informit.com/articles/article.aspx?p=686170&seqNum=

ANOTHER C VULNERABILITY

2002 FreeBSD `getpeername()` bug (B&O Ch. 2)

- Kernel code to copy hostname into user buffer
  - `copy_from_kernel()` call takes signed `int` for size from user
  - `memcpy` call uses unsigned `size_t`
- What if adversary gives a length of "-1" for his buffer size?

```
#define KSIZE 1024
char kbuf[KSIZE]
void *memcpy(void *dest, void *src, size_t n);

int copy_from_kernel(void *user_dest, int maxlen){
    /* Attempt to set len=min(KSIZE, maxlen) */
    int len = KSIZE < maxlen ? KSIZE : maxlen;
    memcpy(user_dest, kbuf, len);
    return len;
}
```

Type mismatch in Rust

`(KSIZE < -1)` is false, so `len = -1`

`memcpy` casts `-1` to $2^{32}-1$

Unauthorized kernel memory copied out

RUST'S OWNERSHIP & BORROWING

~~Aliasing~~ ✚ ~~Mutation~~

Compiler enforced:

Every resource has a unique *owner*.

Others can *borrow* the resource from its owner (e.g. create an *alias*) with restrictions

Owner *cannot* free or mutate its resource while it is borrowed.

No need for runtime Memory safety Data-race freedom

OWNERSHIP AND LIFETIMES

There can be only one "owner" of an object at a time.

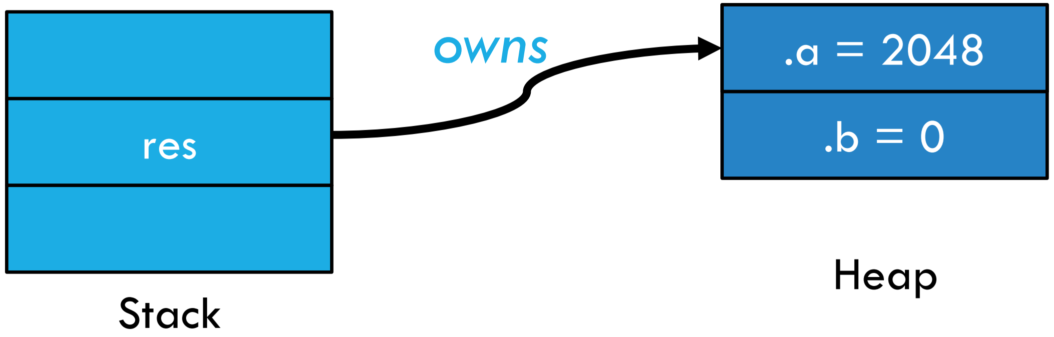
- When the "owner" of the object goes out of scope, its data is automatically freed
- Can not access object beyond its lifetime (checked at compile-time)

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy {
                                a: 0,
                                b: 0
                            });
    res.a = 2048;
}
```

Memory allocation

Resource owned by res *is freed automatically*



ASSIGNMENT CHANGES OWNERSHIP

```rust
//#[derive(Clone)]
struct Point { x: i32, y: i32 }

fn main() {
    let a = Point { x: 1, y: 2};
    let b = a;

    println!("{}, {}", a.x, a.y);
}
```

http://is.gd/pZKiBw

```
rustc 1.15.1 (021bd294c 2017-02-08)
error[E0382]: use of moved value: `a.x`
 --> <anon>:8:24
  |
6 |     let b = a;
  |         - value moved here
7 |
8 |     println!("{}, {}", a.x, a.y);
  |                        ^^^ value used here after move
  |
```

OWNERSHIP TRANSFERS IN FUNCTION CALLS

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy {
                        a: 0,
                        b: 0
                   });
    take(res);
    println!("res.a = {}", res.a);
}

fn take(arg: Box<Dummy>) {
}
```

Compiler Error. If you plan to use res again, must employ "borrow" semantics, not "move" semantics!

Ownership is moved from res to arg

arg is out of scope and the resource is freed automatically

MUTABILITY: A STATIC FORM OF LOCKING

By default, Rust variables are immutable (read only)

- Usage checked *at compile time*

mut is used to declare a resource as mutable.

```
fn main() {
    let a: i32 = 0;
    a = a + 1;
    println!("{}" , a);
}
```

http://is.gd/OQDszP

```
fn main() {
    let mut a: i32 = 0;
    a = a + 1;
    println!("{}" , a);
}
```

```
rustc 1.14.0 (e8a012324 2016-12-16)
error[E0384]: re-assignment of immutable variable `a`
 --> <anon>:3:5
  |
2 |     let a: i32 = 0;
  |         - first assignment to `a`
3 |     a = a + 1;
  |     ^^^^^^^^^ re-assignment of immutable variable

error: aborting due to previous error
```

```
rustc 1.14.0 (e8a012324 2016-12-16)
1
Program ended.
```

BORROWING

You cannot borrow mutable reference from immutable object

- Or mutate an object immutably borrowed

You cannot borrow more than one mutable reference (to support atomicity)

- You can borrow an immutable reference many times

There cannot exist a mutable reference and an immutable one simultaneously (removes race conditions)

The lifetime of a borrowed reference should end before the lifetime of the owner object does (removes use after free)

BORROWING EXAMPLE (&)

You cannot borrow mutable reference from immutable object

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let res = Box::new(Dummy{a: 0, b: 0});

    res.a = 2048;

    let borrower = &mut res;
}
```

Error: Resource is immutable (points to `res.a = 2048;`)

Error: Cannot get a mutable borrowing of an immutable resource (points to `&mut res`)

BORROWING EXAMPLE (&)

You cannot mutate an object immutably borrowed

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy{
                    a: 0,
                    b: 0
                });
    take(&res);
    res.a = 2048;
}

fn take(arg: &Box<Dummy>) {
    arg.a = 2048;
}
```

Resource is returned from arg to res

Resource is immutably borrowed by arg from res

Compiler Error: Cannot mutate via an immutable reference

Resource is still owned by res. No free here.

BORROWING EXAMPLE (&MUT)

You cannot borrow more than one mutable reference

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy{a: 0, b: 0});

    take(&mut res);
    res.a = 4096;

    let borrower = &mut res;
    let alias    = &mut res;
}

fn take(arg: &mut Box<Dummy>) {
    arg.a = 2048;
}
```

~~Aliasing~~ + *Mutation*

Mutably borrowed by arg from res but returned when take completes.

Multiple mutable borrowings are disallowed

Returned from arg to res

IMMUTABLE, SHARED BORROWING (&)

You can borrow more than one immutable reference

- But, there cannot exist a mutable reference and an immutable one simultaneously

Aliasing ✚ ~~Mutation~~

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy{a: 0, b: 0});
    {
        let alias1 = &res;
        let alias2 = &res;
        let alias3 = alias2;
        res.a = 2048;   // struck through on slide
    }
    res.a = 2048;
}
```

USE-AFTER FREE IN C OR C++

```c
void some_dumb_function(){
    int *used_after_free = malloc(sizeof(int));

    /* ... after use */
    free(used_after_free);


    /* what the... */
    printf("%d", *used_after_free);
}
```

Memory allocated to int

Then freed

Then used after free

If these calls are far away from each other, this bug can be very hard to find.

RUST PREVENTS THIS!

The lifetime of a borrowed reference should end before the lifetime of the owner object does

USE AFTER FREE CAUGHT BY RUST AT COMPILE-TIME

Unique ownership, borrowing, and lifetime rules easily enforced

```
fn main() {
    // This binding lives in the main function
    let name = String::from("Hello world!");
    let mut name_ref = &name;
    {
        let newname = String::from("Goodbye!");
        name_ref = &newname;
    }
    println!("name is {}", &name_ref);
}
```

```
rustc 1.15.1 (021bd294c 2017-02-08)
error: `newname` does not live long enough
  --> <anon>:8:5
   |
7  |         name_ref = &newname;
   |                     ------- borrow occurs here
8  |     }
9  |     println!("name is {}", &name_ref);
10 | }
   | - borrowed value needs to live until here
error: aborting due to previous error
```

DANGLING POINTER IN C

Famous scoping issues example (B&O Ch 3, Procedures)

```
int* func(int x) {
      int n;
      int *np;
      n = x;
      np = &n;
      return np;
}
```

Local variable is allocated in stack,
a temporal storage of function.

Reference returned, but variable now out
of scope (dangling pointer)

What does `np` point to after function returns?

What happens if `np` is dereferenced after being returned?

http://thefengs.com/wuchang/courses/cs201/class/08/invalid_ref.c

CAUGHT BY RUST AT COMPILE-TIME

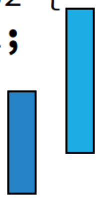
Ownership/Borrowing rules ensure objects are not accessed beyond lifetime

```rust
fn a_dumb_function() -> &i32 {
    let local_variable: i32;

    &local_variable
}

fn main() {
    let raw_pointer = a_dumb_function();

    *raw_pointer = 123;
}
```



borrowed pointer cannot outlive the owner!!

http://is.gd/3MTsSC

```
rustc 1.15.1 (021bd294c 2017-02-08)
error[E0106]: missing lifetime specifier
 --> <anon>:1:25
  |
1 | fn a_dumb_function() -> &i32 {
  |                         ^ expected lifetime parameter
  |
  = help: this function's return type contains a borrowed value,
  = help: consider giving it a 'static lifetime

error: aborting due to previous error
```

SEEMS LIKE RUST WINS EVERY TIME! BUT IT ISN'T SO SIMPLE!

C/C++

Haskell/Python

more control,
less safety

less control,
more safety

Rust

more control,
more safety

RUST OWNERSHIP AND BORROWING CAN BE ANNOYING!

```rust
fn main() {
    let mut v = vec![];

    v.push("Hello");

    let x = &v[0];

    v.push("world");

    println!("{}", x);
}
```

v is an owner of the vector

By taking a reference to v[0], x borrows the vector from v

now v cannot modify the vector
because it lent the ownership to x

http://is.gd/dEamuS

CONCURRENCY & DATA-RACE FREEDOM

```
struct Dummy { a: i32, b: i32 }

fn foo() {
    let mut res = Box::new(Dummy {a: 0, b: 0});

    std::thread::spawn(move || {
        let borrower = &mut res;
        borrower.a += 1;
    });

    res.a += 1;
}
```

Spawn a new thread

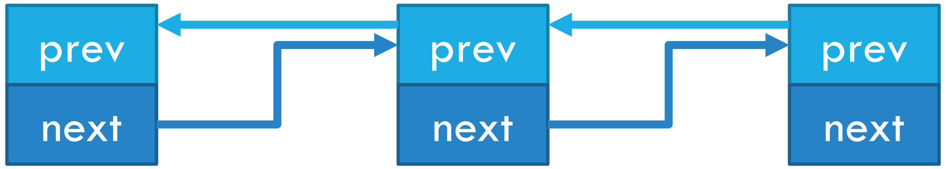
res is mutably borrowed

Error: res is being mutably borrowed

MUTABLY SHARING

Mutably sharing is *inevitable* in the real world.

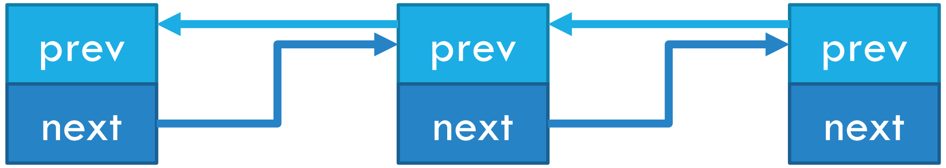
Example: mutable doubly linked list




```
struct Node {
    prev: option<Box<Node>>,
    next: option<Box<Node>>
}
```

We require two mutable pointers to the middle mode. This is the essential feature of a list!

RUST SOLUTION: RAW POINTERS




```
struct Node {
    prev: option<Box<Node>>,
    next: *mut Node
}
```

Raw pointer

Rust allies C-style pointers too…. But now the compiler does *NOT* check the memory safety of most operations involving that pointer.

If possible, operations *wrt*. raw pointers should be encapsulated in a *unsafe* {} syntactic structure.

RUST RAW POINTERS BREAK RUST'S NORMAL MUTABILITY RESTRICTIONS

```
let a = 3;

unsafe {
    let b = &a as *const u32 as *mut u32;
    *b = 4;
}

println!("a = {}", a);
```

I know what I'm doing

Print "a = 4"

TALKING TO LIBRARIES: THE FOREIGN FUNCTION INTERFACE (FFI)

You can call code in libraries written in other languages, but the foreign functions are unsafe (e.g. libc calls)

```
extern {
    fn write(fd: i32, data: *const u8, len: u32) -> i32;
}

fn main() {
    let msg = b"Hello, world!\n";
    unsafe {
        write(1, &msg[0], msg.len());
    }
}
```

BIG DEAL?

It is, because libraries are really important.

In ML we rely on tools like LINPACK, MPI, etc. And most GEMM kernels for ML tasks mix C or C++ with GPU or host parallelism.

Even if recoded in Rust they would still be unsafe!

SO THIS TELLS US THAT RUST…

… often yields programs that actually are still unsafe!

Rust isn't some sort of magic wand. It is more like a tool that we can use to protect ourselves against certain kinds of errors

Monzilla found it super effective! But some hard-core C++ developers who play with Rust find it annoying. And people focused on host parallelism may find the compiled code slow.

WHAT ABOUT SPEED? IS RUST FAST LIKE C++, OR SLOW LIKE PYTHON?

Used correctly, Rust code performs well – potentially, better than Java and certainly better than Python. Sometimes as well as C++

Rust can do most of what we do in C++, and often at the same speed.

But it lacks templates + constexpr + inlining: C++ magic speedup

RUST (CURRENTLY) IS WEAK ON COMPILE TIME OPTIMIZATIONS

With skilled use of templates and constexpr, a C++ program can be extensively precomputed, leaving only things that must occur at runtime.

Rust has generics but nothing analogous to the C++ template language, so SIMD coding isn't feasible. There are situations where Rust might be dramatically slower than C++ (despite using the same LLVM back end as Clang).

AN UNWINABLE DEBATE!

People who love Rust aren’t going to switch back to C++

People who love C++ agree that Rust addresses many security issues (but at a cost). And they find ownership and mutability annoying, yet inadequate for even trivial data structures.

… the market adoption of Rust is good, but not overwhelming

BOTTOM LINE?

Rust genuinely is a powerful tool, but not trivial to use correctly, and limiting in important ways.

To get similar security in C++ requires systematic attention to risks, careful coding style, verification of logic, testing.

But because systems programming involves external libraries, GPUs and DMA, we sometimes have no other choice .

FURTHER READING

Haozhong Zhang "An Introduction to The Rust Programming Language"

Aaron Turon, *The Rust Programming Language,* Colloquium on Computer Systems Seminar Series (EE380) , Stanford University, 2015.

Alex Crichton, *Intro to the Rust programming language,* http://people.mozilla.org/~acrichton/rust-talk-2014-12-10/

The Rust Programming Language, https://doc.rust-lang.org/stable/book/

Tim Chevalier, "Rust: A Friendly Introduction", 6/19/2013

RESOURCES

Rust website: http://rust-lang.org/

- Rust by example: http://rustbyexample.com/
- Guide: https://doc.rust-lang.org/stable/book/
- User forum: https://users.rust-lang.org/
- Book: https://doc.rust-lang.org/stable/book/academic-research.html

Speed of Rust versus C++*: https://www.bairesdev.com/blog/when-speed-matters-comparing-rust-and-c/

* **Note: This guy never took CS4414! He means "if you code without giving it much thought"**