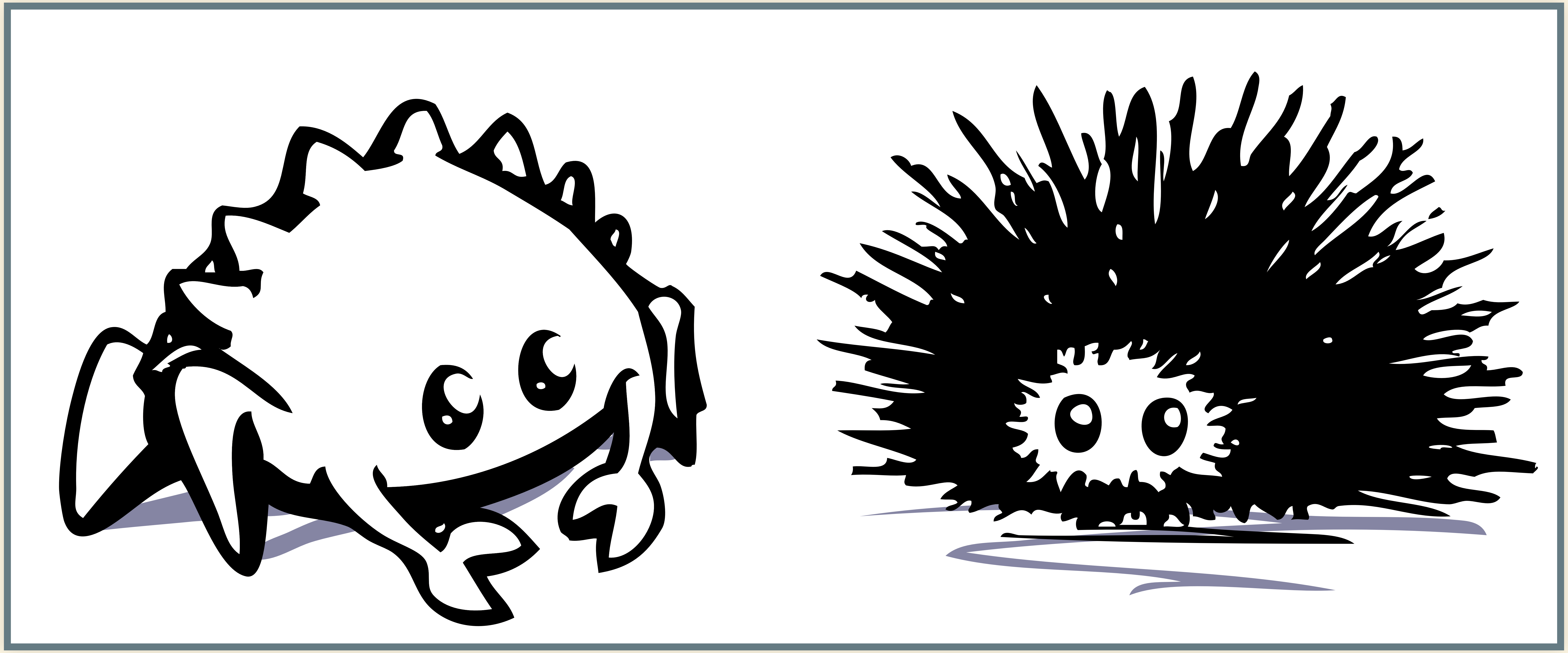
LECTURE 27

Theory and Design of PL (CS 538)

April 29, 2020



Safe and Unsafe Rust

PLEASE COMPLETE COURSE EVALS!

AGENDA

CREDITS: MARK MANSI

- Developed first version of these slides
- Graduate student in our department
- Active in Rust development

> *If you want to know more, talk to Mark!*

FOUNDATIONS

- What does Rust actually guarantee?
- Introducing `unsafe`
- Unsafety and Invariants
- Using Abstraction

GETTING STARTED WITH *UNSAFE* RUST

- Working with raw pointers
- Allocating and deallocating memory
- Links to further reading

WHAT DOES RUST *GUARANTEE?*

GOAL: FEW BUGS, FASTER PROGRAMS

- Avoid doing non-sensical or wrong things…
- … and find out when we do.
- Enable compiler optimizations.

LANGUAGE SPEC

Defines allowed, disallowed, and unspecified behaviors.

- Examples of disallowed:
  - dereference `null` pointer
  - have a `bool` that is not `true` or `false`
  - access array out of bounds
- Examples of unspecified:
  - In C/C++: `a = f(b) + g(c)`
  - which is first: `f` or `g`?

UNDEFINED BEHAVIOR (UB)

there are no restrictions on the behavior of the program.

Compilers are not required to diagnose undefined behavior (although many simple situations are diagnosed),

and the compiled program is not required to do anything meaningful.

IMPLICATIONS OF UB

- Correct programs don't invoke UB
- UB can be hard to debug
- Compilers can assume no UB when optimizing

EXAMPLE FROM C++

```
char *p = "I'm a string literal";
p[3] = 'x';
```

ISO C++ forbids mutating string literals (ISO C++ §2.13.4p2)

EXAMPLE FROM C++

```
char *p = nullptr;
p[3] = 'x'; // Program is allowed to eat laundry here
```

Deferencing an invalid pointer is forbidden (ISO C §6.5.3.2p4)

SAFETY IN RUST

"Safety" means no UB

- Memory safety
  - e.g. accesses are to valid values only
  - e.g. prohibiting mutable aliasing pointers
- Thread safety
  - e.g. mutable aliasing state
- Enforced by type system

NO UB IN SAFE RUST

```
let x = Vec::new(); // Empty Vec
println!("Out of bounds: {}", x[2]); // Panic, not UB!
```

```
fn foo() -> &usize {
    let x = 3;
    &x // Return reference to stack variable (allowed in C)

    // Doesn't compile (borrow checker error), not UB!
}
```

UB IN (UNSAFE) RUST

- Dereferencing null, dangling, or unaligned pointers
- Reading uninitialized memory
- Breaking the pointer aliasing rules
- Producing invalid primitive values:
  - dangling/null references
  - null `fn` pointers
  - a `bool` that isn't `true` or `false`

MORE UB IN (UNSAFE) RUST

- Producing invalid primitive values:
  - an undefined enum discriminant
  - a `char` outside the ranges `[0x0, 0xD7FF]` and `[0xE000, 0x10FFFF]`
  - A non-utf8 `str`
- Unwinding into another language
- Causing a data race

WHAT DOES RUST *NOT* GUARANTEE?

EXAMPLE

```
struct Foo(Option<Arc<Mutex<Foo>>>);

impl Drop for Foo {
    /// Implement a destructor for `Foo`
    fn drop(&mut self) {
        // <do some clean up>
    }
}
```

EXAMPLE (CONTINUED)

```
fn do_the_foo_thing() {
    let foo1 = Arc::new(Mutex::new(Foo(None)));
    let foo2 = Arc::new(Mutex::new(Foo(None)));

    // Reference cycle
    foo1.lock().unwrap().0 = Some(Arc::clone(&foo2));
    foo2.lock().unwrap().0 = Some(Arc::clone(&foo1));

    // `foo1` and `foo2` are never dropped!
    // Memory never freed. Foo::drop never called. No UB!
}
```

SAFE RUST CAN STILL...

- Panic ("graceful" crashing)
- Deadlock (two threads both waiting for each other)
- Leak of memory and other resources (never freed back to the system)
- Exit without calling destructors (never clean up)
- Integer overflow (`MAX_INT + 1`)

A DILEMMA

EXAMPLE

In my program (Rust):

```rust
/// Read from file `fd` into buffer `buf`.
fn read_file(fd: i32, buf: &mut [u8]) {
    let len = buf.len();
    libc::read(fd, buf.as_mut_ptr(), len);
}
```

In `libc` (C):

```c
ssize_t read(int fd, void *buf, size_t count) {
    // oops bug accidentally overflows `buf`
}
```

RESTORING SAFETY

Compiler error: no unsafe C from safe Rust!

```
/// Read from the file descriptor into the buffer.
fn read_file(fd: i32, buf: &mut [u8]) {
    let len = buf.len();
    libc::read(fd, buf.as_mut_ptr(), len); // Compile error!
}
```

Ok, but how do we call C libraries or the OS?

`unsafe`

- Sometimes need to do something potentially unsafe
  - system calls
  - calls to C/C++ libraries
  - interacting with hardware
  - writing assembly code
  - …

> *Compiler can’t check these: Be careful!*

EXAMPLE

```rust
/// Read from the file descriptor into the buffer.
fn read_file(fd: i32, buf: &mut [u8]) {
    let len = buf.len();
    unsafe {
        libc::read(fd, buf.as_mut_ptr(), len);
    }
}
```

Rust compiles, but C code may do something bad: Be careful!

WHAT DOES `unsafe` MEAN?

"AUDIT `unsafe` BLOCKS"

From `libstd` `Vec`. Consider `set_len`:

```
pub struct Vec<T> {
    buf: RawVec<T>,
    len: usize,
}

impl Vec {
    /// Sets the length of the vector to `new_len`.
    pub fn set_len(&mut self, new_len: usize) {
        self.len = new_len;
    }
}
```

“AUDIT `unsafe` BLOCKS”

```
fn main() {
    let mut my_vec = Vec::with_capacity(0); // empty vector
    my_vec.set_len(100);

    my_vec[30] = 0; // UB!
}
```

Huh?!? UB in safe Rust? How?

unsafe fn

```rust
impl Vec {
    /// Sets the length of the vector to `new_len`.
    pub unsafe fn set_len(&mut self, new_len: usize) {
        self.len = new_len;
    }
}
```

Can only be called in an unsafe block!

But why is it possible in the first place?

UB AND INVARIANTS

- *Language Invariant*: something assumed by Rust
  - breaking a language invariant is (by definition) UB
  - e.g. `bool` is always `true` or `false`
  - e.g. all references are valid to dereference

UB AND INVARIANTS

- *Program Invariant*: something that is always true according to the *program spec*
  - e.g. the server must write results to the log before responding to the client
- *In the presence of* `unsafe`, breaking program invariants can break lang. invariants, leading to UB

UB AND INVARIANTS

```
pub struct Vec<T> {
    buf: RawVec<T>, // `unsafe` in `RawVec`
    len: usize,
}
```

UB AND INVARIANTS

`unsafe`: someone promises to uphold invariants!

"Promise" is called a *proof obligation*.

UB AND INVARIANTS

```rust
fn read_file(fd: i32, buf: &mut [u8]) {
    let len = buf.len();

    // `read_file` promises to respect buffer length
    unsafe {
        libc::read(fd, buf.as_mut_ptr(), len);
    }
}
```

```rust
// Caller of `set_len` promises to uphold `Vec` invariants!
pub unsafe fn set_len(&mut self, new_len: usize) {
    self.len = new_len;
}
```

DIFFERENT USES OF `unsafe`

Whose job to check?

- `unsafe { ... }` blocks
  - Enclosing function is responsible
- `unsafe fn`
  - Caller responsible when calling function
  - Impl. responsible when calling other `unsafe`
- `unsafe trait` and `unsafe impl`
  - Implementor is responsible

HOW TO PLAY WITH FIRE 🔥

SAFE ABSTRACTIONS

Idea: Abstraction hides `unsafe`

- Users of the abstraction have no way to cause UB
- Language features make unsafe parts inaccessible
  - Private struct/enum fields
  - Private modules/types
- Use `unsafe` to expose dangerous interfaces
- Can reason about correctness modularly

EXAMPLE: `Vec`

Using only *safe* methods of `Vec`, it is *impossible* to cause UB, even though `Vec` uses `unsafe` internally.

- The safe methods of `Vec` all uphold invariants.
- Methods that could violate invariants are `unsafe` (e.g. `set_len`)

EXAMPLE: READING FILES

```
fn main() -> std::io::Result<()> {
    // Open: call libc and OS. Safely!
    let file = File::open("foo.txt")?;
    let mut buf_reader = BufReader::new(file);
    let mut contents = String::new();
    // Read: call libc and OS. Safely!
    buf_reader.read_to_string(&mut contents)?;
    assert_eq!(contents, "Hello, world!");
    Ok(())

    // Close: call libc and OS. Safely!
}
```

`File`, `BufReader` are safe abstractions that uphold invariants about files, memory, etc.

CAUTION: FIRE IS HOT

RUST HAS LOTS OF INVARIANTS

- Variance
- Rust ABI
- Memory layout of types
  - Zero-sized types, uninhabited types
  - `#[repr(C)]` and `#[repr(packed)]`
- Type-based optimizations
- Reordering, memory coherence, and optimizations
- Many more in the Rustonomicon

PRACTICAL FIRE TWIRLING 101

EXAMPLE: `Vec`

- Caution: will ignore lots of concerns
- Can find real implementation on GitHub

FIRST: RAW POINTERS

`*const T` and `*mut T`

- Like C pointers
- Not borrow checked, `unsafe` to dereference
- Utilities in `std::ptr`
- Helpful tools in libstd
  - `NonNull`

impl Vec

```
pub struct Vec<T> {
    buf: RawVec<T>,
    len: usize,
}

pub struct RawVec<T> {
    ptr: *mut T, // ptr to allocated space
    cap: usize, // amount of allocated space
}
```

impl Vec

```
pub fn new() -> Vec<T> {
    Vec {
        buf: RawVec::new(), // initially, no allocation
        len: 0,
    }
}
```

impl RawVec

```rust
pub fn new() -> Self {
    RawVec {
        ptr: ptr::null_mut(), // null ptr, safe to construct
        cap: 0,
    }
}
```

impl Vec

```
pub fn pop(&mut self) -> Option<T> {
    if self.len == 0 {
        None  // empty vector
    } else {
        unsafe {
            self.len -= 1;  // decrement length
            let addr = self.buf.ptr.offset(self.len);

            // raw ptr read at index `val`
            let val = ptr::read(addr);

            Some(val)
        }
    }
}
```

impl Vec

```
pub fn push(&mut self, value: T) {
    // Are we out of space?
    if self.len == self.buf.cap {
        self.buf.double(); // alloc more space
    }

    // put the element in the `Vec`
    unsafe {
        // compute address of end of buffer
        let end = self.buf.ptr.offset(self.len);
        ptr::write(end, value); // write data to raw pointer
        self.len += 1; // increase length
    }
}
```

impl RawVec

```rust
pub fn double(&mut self) {
    unsafe {
        let new_cap = self.cap * 2 + 1; // new capacity

        // alloc more memory with system heap allocator
        let res = if self.cap > 0 {
            heap::realloc(NonNull::from(self.ptr).cast(),
                          self.cap, new_cap)
        } else {
            heap::alloc(new_cap)
        };
        // ...
    }
}
```

impl RawVec

```rust
pub fn double(&mut self) {
    unsafe {
        // ...
        match res {
            Ok(new_ptr) => { // update pointer and capacity
                self.ptr = new_ptr.cast().into();
                self.cap = new_cap;
            }
            Err(AllocErr) => { // handle out of memory
                out_of_memory();
            }
        }
    }
}
```

OTHER `unsafe` TOOLS

- Type memory layout: `#[repr(...)]`
- Mixed-language projects
  - `extern fn`
  - Strings, variadic fns (e.g. `printf`), `extern` types
  - rust-bindgen
  - cbindgen

EXTRA RESOURCES

- The Rustonomicon
- Ralf Jung's Blog
- Alexis Beingessner
  - Notes on Type Layouts and ABI
  - Only in Rust
  - The Kinds of Implementation-Defined

EXTRA EXTRA RESOURCES

- Various IRLO discussions:
  - UB and uninitialized memory
  - What do “memory safety”/“thread safety” mean?
  - Taming UB in LLVM
- Guide to UB

WHERE WE'VE BEEN

FIRST HALF: HASKELL

- Pure, functional language
- Rich type system
  - Algebraic datatypes
  - Polymorphism and typeclasses
- Monads and effects

SECOND HALF: RUST

- Safe, imperative language
- Ownership: memory management without GC
- Borrowing: control aliasing at all costs
- “Fearless concurrency”

DIFFERENT, YET SIMILAR

- Very strong compile-time checks
  - Haskell: typechecking
  - Rust: ownership and borrowing
- Rich type systems
  - Algebraic datatypes, sums and products
  - Typeclasses and traits
  - Rust: Mutable and immutable references
- Functional (features)
  - Closures, iterators
  - Patterns: map, fold, etc.

CORE LANGUAGES

- Simply typed lambda calculus
  - Model of functional languages
- While language
  - Model of imperative languages
- Process calculus
  - Model of message-passing languages

LANGUAGE DESIGN IS REALLY HARD

WHAT REALLY MATTERS?

- It turns out, a lot
- PL design is still a obscure art
  - Not clear how to teach design
  - Requires wisdom, and a ton of experience
- Graydon Hoare has good thoughts on this
  - Original inventor of Rust
  - Also invented Monotone, before Git

CORE TECHNICAL CONCERNS

- Literally “what works”
  - How fast is the code?
  - How fast is the compiler?
  - How well does it scale?
  - How compact is the code?
  - Can we build a lazy language?

TRADEOFFS AND WEIGHTING

- Can't have the best of all worlds
  - Peak performance
  - Correctness
  - Compilation speed
  - Language complexity
  - ...
- How to balance these tradeoffs?

QUALITY OF IMPLEMENTATION

- Languages involve implementation
  - How many bugs are in the compiler?
  - How quickly are bugs fixed?
  - How many people are working on tooling?
  - How is the effort funded?
  - Where are the engineers coming from?
  - Deliver quality on schedule?
  - How is the project managed and organized?

COGNITIVE LOAD

- PL is a human computer interface
- Computer side is easier to measure
- Human side is very poorly understood
  - How hard is it to work in the language?
  - How predictable/intelligible is the compiler?
  - How hard is it to understand certain features?
  - How much can a person “hold in their head”?

HUMAN/CULTURAL CONTEXT

- Languages are used by humans
  - Which libraries are better?
  - Which libraries are worse/missing?
  - How is the documentation?
- What is this language “for”? Who will want to use it?
  - Often depends on cultural context at the start

TECHNICAL CONTEXT

- What technologies does the language work with?
- Many of these are not feasible to change
  - Operating systems
  - Foreign function interface
  - Networking, databases
  - Standards: floating point, unicode, …
- How to adapt to these requirements?

WHAT'S NEXT?

LOTS OF ROOM FOR BETTER LANGUAGES

- PL features take a very long time to mature
  - Haskell has been around for 30 years
  - Rust is young, but builds on decades of PLs
- A good list of promising features

MODULES

- Most languages don't have module systems
  - Or: just use modules for namespaces
  - Mostly: combine modules by "including"
- Richer module systems in SML/OCaml
  - Decompose code into separate parts
- Fancier ways to combine whole program units
  - Functions that transform modules
  - Select between modules at run time

ERROR HANDLING

- No good solutions known, many not-so-good ones
- Exceptions
  - Who should handle exception?
  - At any moment, could jump to handler
- Return error codes
  - Programmers forget to check
- More philosophically
  - What errors should be caught?
  - What errors should simply cause a crash?
  - What is an error?

EFFECT SYSTEMS

- IO in Haskell: any kind of side-effect
- Effect systems: track specific effects
  - “This function reads a file”
  - “This function sends on network”
  - “This function prints to screen”
- In research languages, but still far to go

REFINEMENT/DEPENDENT TYPE SYSTEMS

- Even fancier type systems
- The dream: use types to encode full spec
  - "This function returns a sorted list"
  - "This function finds the minimum element"
  - "This function correctly compiles C to assembly"
- … and have the compiler check it for you
- Currently: very hard to use

SESSION TYPES

- Types for communicating processes
  - Closely related to process calculus
- Ensure that sender/receiver on same page
  - Avoid deadlocks, wrong messages, etc.
- Long studied, not yet mature

RICHER PATTERNS

- Pattern matching is nice, once you get used to it
- Currently pretty basic: name different parts of data
- Fancier matching behavior?
  - Match the first non-zero element in list
  - Match the last even number, or fail

COST/RESOURCE ANALYSIS

- Fancier types for time and space
  - Describe how long function takes to run
  - Describe how much space function uses
- Catch space leaks, or rare worst-cases

FORMALIZATION

- Languages are still implemented first
- Later on: people try to formalize (sometimes)
- Time and time again: serious design flaws
  - Compilers don't correctly compile
  - Ambiguous or unclear desired behavior
  - Type systems that don't guarantee safety
- Currently: formalization is very expensive

NEW KINDS OF HARDWARE

- Not just programming a CPU anymore
  - GPU, TPU, custom chips, etc.
- How to program these very-different platforms?
  - Would like to write just one program

WHAT ELSE IS IN PL?

IMPLEMENTATION (CS 536/701)

- How to implement languages?
  - How do interpreters and compilers work?
- How to make programs go fast?
  - Compiler optimizations? JITs?
- How to make compilers go fast?
  - Incremental compilation?
- How to implement functional languages?
- How does type checking and type inference work?

VERIFICATION (CS 703/704)

- What can even fancier type systems do?
- How to use automated solvers to verify programs?
  - SMT and Horn solvers?
  - Model checking?
- How to verify imperative programs?
- How to verify program correctness
  - At run time? Contracts and dynamic analyses
  - At compile time? Abstract interpretation

SYNTHESIS (CS 703)

- How to write programs automatically?
- How to guide solvers to find correct programs?
- How to do machine learning on open source code?

SEMANTICS (CS 704)

- How to give a more realistic operational semantics?
  - With a stack, control, etc.
- How to model concurrency mathematically?
  - Process calculus, Petri nets, …
- How to model memory on multicore machines?
  - Weak memory models
- How to design languages for mathematical proofs?
  - Theorem provers and dependent type theories
- How to model programs more mathematically?
  - Denotational semantics

THAT'S ALL, FOLKS: REMEMBER TO DO COURSE EVALS!