Advances in Programming Languages

Lecture 17: Traits and References in Rust

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THE UNIVERSITY *of* EDINBURGH

Topic: Programming for Memory Safety

The final block of lectures cover features used in the **Rust** programming language.

- Introduction: Zero-Cost Abstractions (and their cost)
- Control of Memory: Ownership
- Concurrency and more

This section of the course is entirely new — Rust itself is not that old — and I apologise for any consequent lack of polish.

Outline

The Rust Programming Language

The **Rust** language is intended as a tool for *safe systems programming*. Three key objectives contribute to this.

- Zero-cost abstractions
- Memory safety
- Safe concurrency

Basic References

https://www.rust-lang.org
https://blog.rust-lang.org

The "systems programming" motivation resonates with that for imperative C/C++. The "safe" draws extensively on techniques developed for functional Haskell and OCaml. Sometimes these align more closely than you might expect, often through overlap between two aims:

- Precise control for the programmer;
- Precise information for the compiler.

Review

Some basic Rust constructions.

- Rust *bindings* like `let x = 10;` are immutable by default.
- Mutability must be explicitly declared `let mut y = true;`
- Rust has conditionals, loops, and first-class functions.
- Values can be arranged in *tuples*, *structs*, *tuple structs* and labelled *enumerations*.
- Values can be decomposed with pattern matching and a discriminating `match` statement.
- Parametric polymorphism is available through generic structs, enumerations, and functions.

Zero-Cost Abstraction

All of these language features — data structures, control structures, generics — provide *abstractions* that help empower a programmer.

However, it's an important principle of Rust (and C++ before it) that all of these can readily be compiled down to simple executable code with no overhead to maintaining the abstraction.

Several of the constraints in the language are there to help with this: default immutability, strict type-checking, checked pattern-matching, restricted for, monomorphisation of generics, ...

These constraints also mean that Rust is not C. It's much more strict on the programmer — which might be judged a cost — but with the benefit of certain behavioural guarantees and potentially more aggressive optimisation from an informed compiler.

Outline

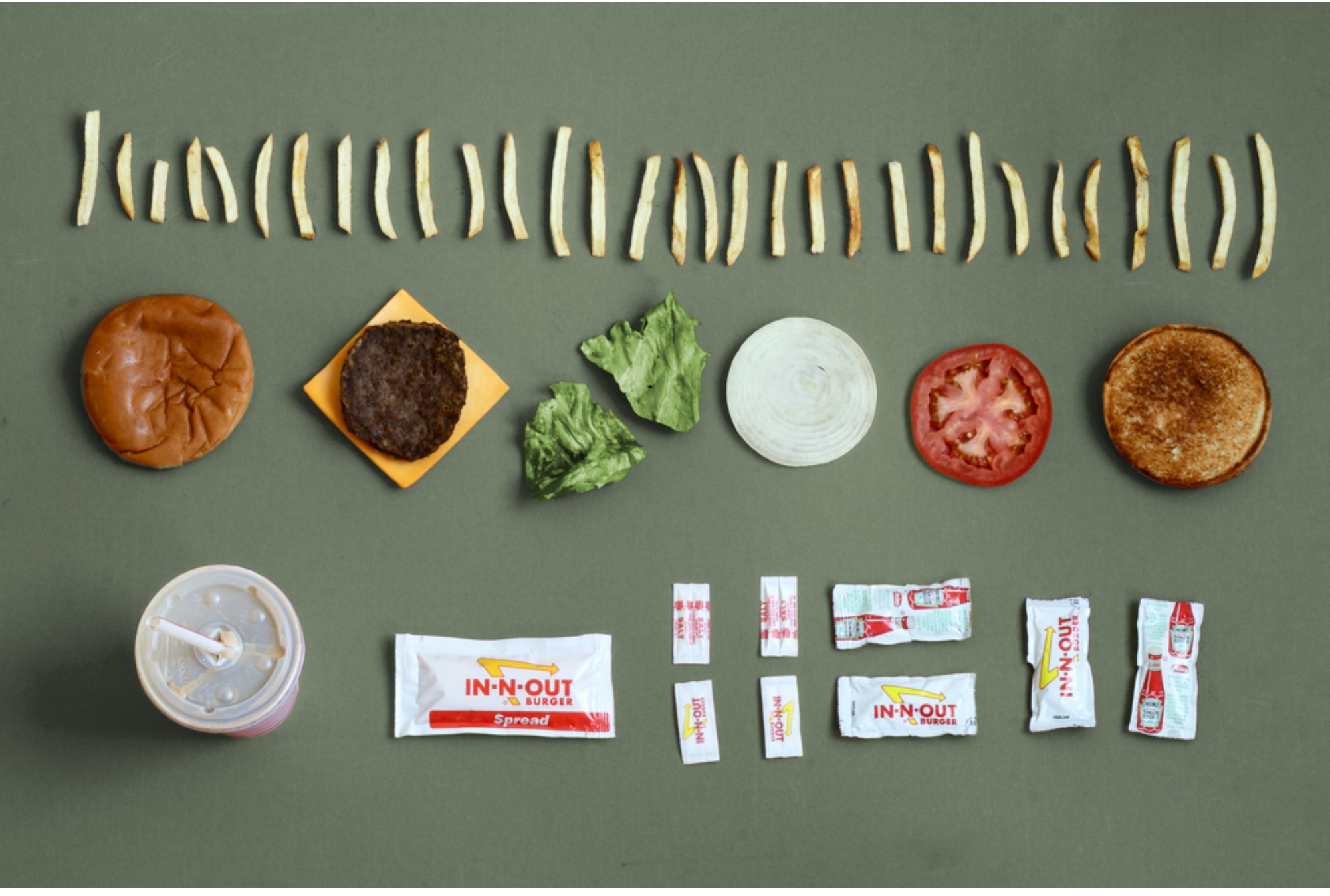
Rust's Object Model

The meaning of "objects" and "classes" can differ quite substantially between different programming languages. Generally, concepts of "object" bring together in a single construction a range of helpful abstractions. These might include, for example: data, operations, state, identity, references, namespaces, aggregation, inheritance, polymorphism, . . .

Rust doesn't really have an object model. Instead, it provides many of these abstractions as individual components, from which you might pick and choose to build your own abstractions.

This does align with the zero-cost principle: you need not pay any potential cost of the features you don't use.

A *deconstructed object model*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Structs

The basic Rust struct datatype provides a named record structure with selectors, as with the fields of an object.

```
struct Point {
  x: f64,
  y: f64,
}

let p = Point { x: 1.0, y: -2.5 };
let (a,b) = p;

let mut q = Point { x: 0.0, y: 0.0 };
q.x = q.x + 3.4;
```

Method Call Syntax

Methods for values of a struct type are declared with impl.

```
struct Point { x: f64, y: f64 }

impl Point {
    fn origin_distance (self) -> f64 {
        ( self.x * self.x + self.y * self.y ).sqrt()
    }

    fn flip(self) -> Point {
        Point { x: self.y, y: self.x }
    }
}

let p = Point { x: 2.4, y: 3.5 };
println!("{}", p.flip().origin_distance());      // Prints 4.2438...
```

Static Methods

Methods don't have to be attached to a value.

```
struct Point { x: f64, y: f64 }

impl Point {
    fn x_axis (v: f64) -> Point {
        Point { x: v, y: 0.0 }
    }

    fn y_axis (v: f64) -> Point {
        Point { x: 0.0, y: v }
    }
}

let p = Point::x_axis(1.2);
println!("{}", p.flip().origin_distance());      // Prints 1.2
```

Traits

With a trait we can declare a method suite to be implemented.

```
trait HasDistance {
    fn origin_distance (self) -> f64;
    fn xy_axis_distance (self) -> (f64,f64);
}

impl HasDistance for Point {
    fn origin_distance (self) -> f64 {
        ( self.x * self.x + self.y * self.y ).sqrt()
    }

    fn xy_axis_distance (self) -> (f64,f64) {
        ( self.y, self.x )
    }
}
```

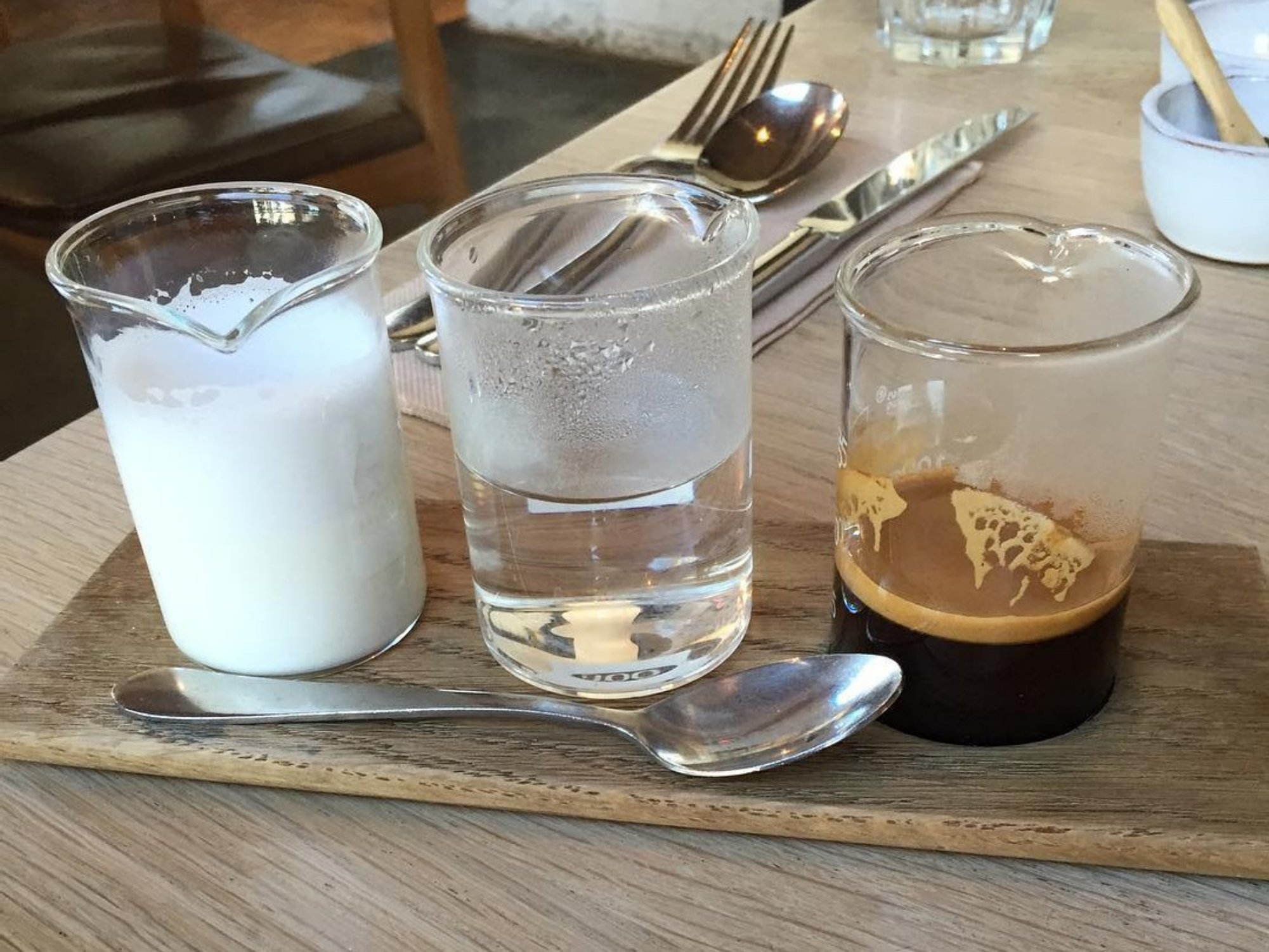
Trait Inheritance

With trait *inheritance* we declare that a trait extends one or more others.

```
trait HasDistance {
    fn origin_distance (self) -> f64;
    fn xy_axis_distance (self) -> (f64,f64);
}

trait Has3Distance : HasDistance {
    fn z_axis_distance (self) -> f64;
    fn xyz_axis_distance (self) -> (f64,f64,f64);
}

trait SpaceTime : HasDistance + HasTime {
    fn spacelike (self) -> bool;
    fn timelike (self) -> bool;
}
```



Standard Traits

Some traits common to many data or numerical types.

Eq	Can be tested for equality with ==.
Ord	Can be tested for order with <, >, <= and >=.
Default	Has some given default value.
Hash	Provides a hash function.

Typically these also assume properties which are not checked by the compiler — for example, that == is an equivalence relation.

The #[derive(...)] *attribute* prompts the compiler to automatically generate implementations for standard traits like these.

Traits and Generics

Where a type parameter <T> appears in a declaration, it can usually be given a *trait bound* in the form <T:Trait>.

```
fn is_in_positive_quadrant<T:HasDistance> (p:T) -> bool {
    let (x,y) = p.xy_axis_distance();
    x >= 0.0 && y >= 0.0
}

struct HashTable <K:Eq+Hash,V> { ... }

impl <K:Eq+Hash,V> HashTable <K,V> {
   fn new () -> HashTable<K,V> { ... }
}

let ht : HashTable<(i32,i32),Point> = HashTable::new();
```

More About Traits

Methods in traits are *statically dispatched* — which code is executed is fixed by the static type of the value for which the method is invoked.

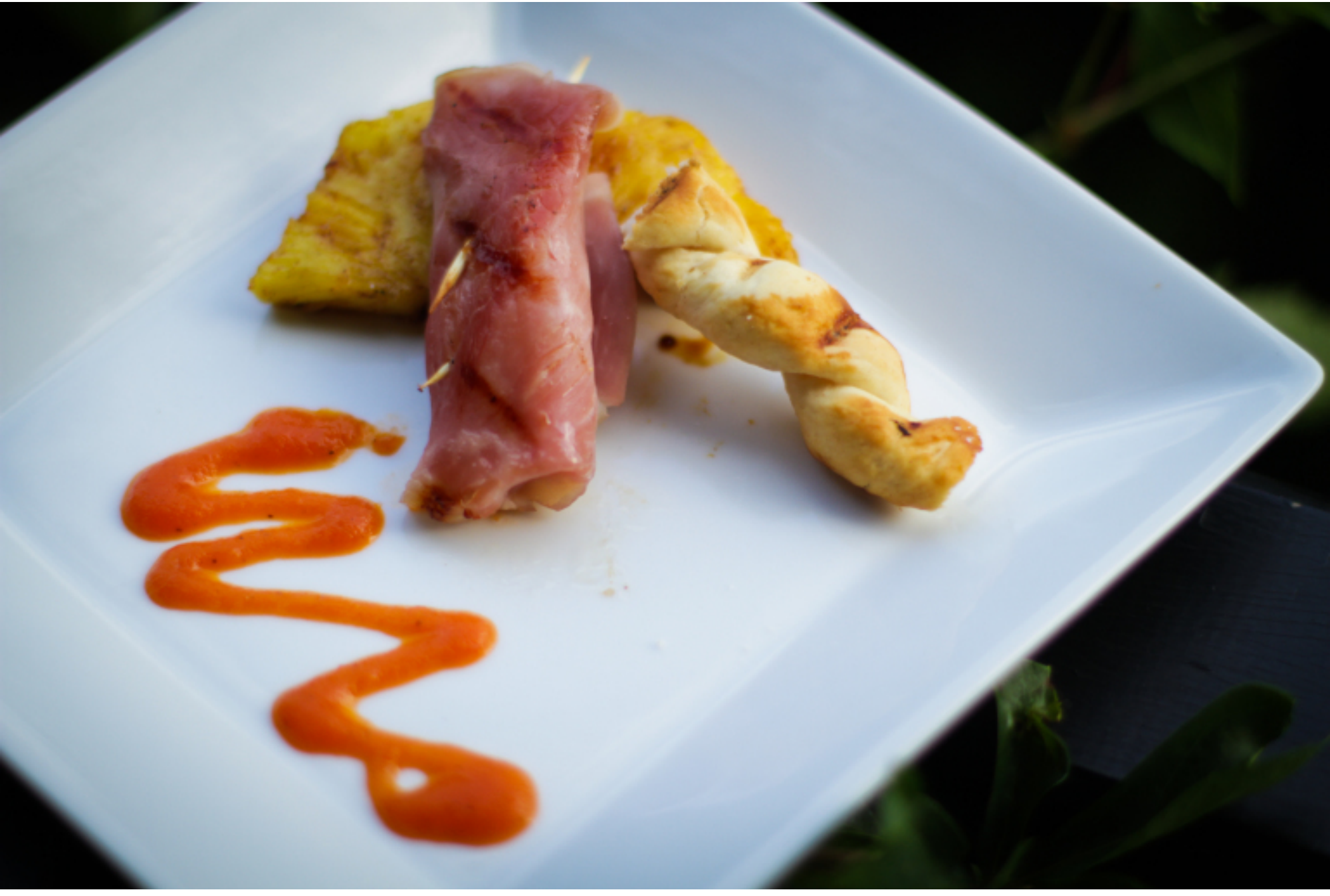
It is possible to arrange for dynamic dispatch, where the code chosen depends on the runtime type of a value, but this is not the default.

Putting trait bounds on generic functions doesn't change the fact that during compilation these are replaced by multiple monomorphic versions.

A *marker trait* is one that doesn't require any methods at all, but serves to record some useful property of a type. These might be recognized specially by the compiler, or describe something that the programmer wishes to indicate but cannot directly express in the language.

For example, the Sized trait indicates types whose size in memory is fixed and known at compile time.

Outline



Passing Structures

```
fn difference (a:Point,b:Point) -> Point {
    Point { x: (b.x-a.x), y: (b.y-a.y) }
}

let p = Point { x:1,  y:5 };
let q = Point { x:8,  y:3 };

let r = difference(p,q);          // r is now Point { x:7, y:-2 }
```

Boxing Structures

```
fn difference (a:Box<Point>,b:Box<Point>) -> Box<Point> {
    Box::new (Point { x: (b.x−a.x), y: (b.y−a.y) })
}

let p = Box::new(Point { x:1, y: 5 });
let q = Box::new(Point { x:8, y: 3 });

let r = difference(p,q);
let s = ∗r;                          // s is now Point { x:7, y:−2 }
```

Vectors on the Heap

```
fn total (v:Vec<i32>) -> i32 {
    let mut accum = 0;
    for x in v { accum = accum + x };
    accum
}

let a = vec![1,5,8,3];          // a : Vec<i32>

let t = total(a);               // t is now 17
```

When to Deallocate?

In Most Languages

Values explicitly passed around, whether small or large, have a lifetime exactly as long as their bindings stay in scope. They can be placed in stack-allocated memory which is released when they go out of scope. If they are large, though, it may be costly to pass them around.

Values allocated on the heap are cheaper to pass by reference in and out of functions. However, when can the heap space be released?

In C, the user has to manage this explicitly. In Java or OCaml the runtime system has a garbage collector.

Getting this right is important: not just to avoid wasting space, but also for *memory safety* — not reading or writing heap areas after deallocation.

When to Deallocate?

In Rust

Rust uses *move semantics*: the *ownership* of values passes from one binding to the next; through assignment, function call and return.

The lifetime of a value, whether on the stack or the heap, can be tracked precisely through the lifetimes of its bindings.

The compiler does this statically, guaranteeing memory safety without programmer intervention or a runtime garbage collector.

Move Semantics

```
fn difference (a:Point,b:Point) -> Point {
    Point { x: (b.x-a.x), y: (b.y-a.y) }
}

let p = Point { x:1,  y:5 };
let q = Point { x:8,  y:3 };

let r = difference(p,q);          // r is now Point { x:7, y:-2 }
                                  // p and q are no more

let s = difference(q,p);          // Error: use of moved value

let t = difference(r,r);          // Error: use of moved value
```

Move Semantics

```
fn difference (a:Box<Point>,b:Box<Point>) -> Box<Point> {
    Box::new (Point { x: (b.x−a.x), y: (b.y−a.y) })
}

let p = Box::new(Point { x:1, y: 5 });
let q = Box::new(Point { x:8, y: 3 });

let r = difference(p,q);
let s = ∗r;                          // s is now Point { x:7, y:−2 }
                                     // p, q and r are no more

let t = difference(q,p);             // Error: use of moved value
let u = ∗r                           // Error: use of moved value
```

Move Semantics

```
fn imean (v:Vec<i32>) -> i32 {
    let mut accum = 0;

    for x in v { accum = accum + x };

    accum / ( v.len() as i32 )    // Error: use of moved value
}

let a = vec![1,5,8,3];            // a : Vec<i32>

let m = imean(a);                 // Hoping for 4 here
```

Clone and Copy Traits

```
fn imean (v: Vec<i32>) -> i32 {
    let mut accum = 0;

    for x in v.clone() { accum = accum + x };

    accum / ( v.len() as i32 )    // This now works
}

let a = vec![1,5,8,3];            // a : Vec<i32>

let m = imean(a);                 // We do get 4 here
```

Clone and Copy Traits

The Clone trait provides an explicit clone() method to duplicate a value. A value and its clone have separate ownership.

Types with the marker trait Copy are always assigned by cloning; Clone is a supertrait of Copy, so all types marked Copy also implement Clone.

Basic types like bool and i32 implement Copy; they have *copy semantics*.

```
let v = 2;
let w = v+v;
let u = 2+2;

fn difference (a:Point,b:Point) -> Point {
    Point { x: (b.x−a.x), y: (b.y−a.y) }
}
```

Complete Deconstruction

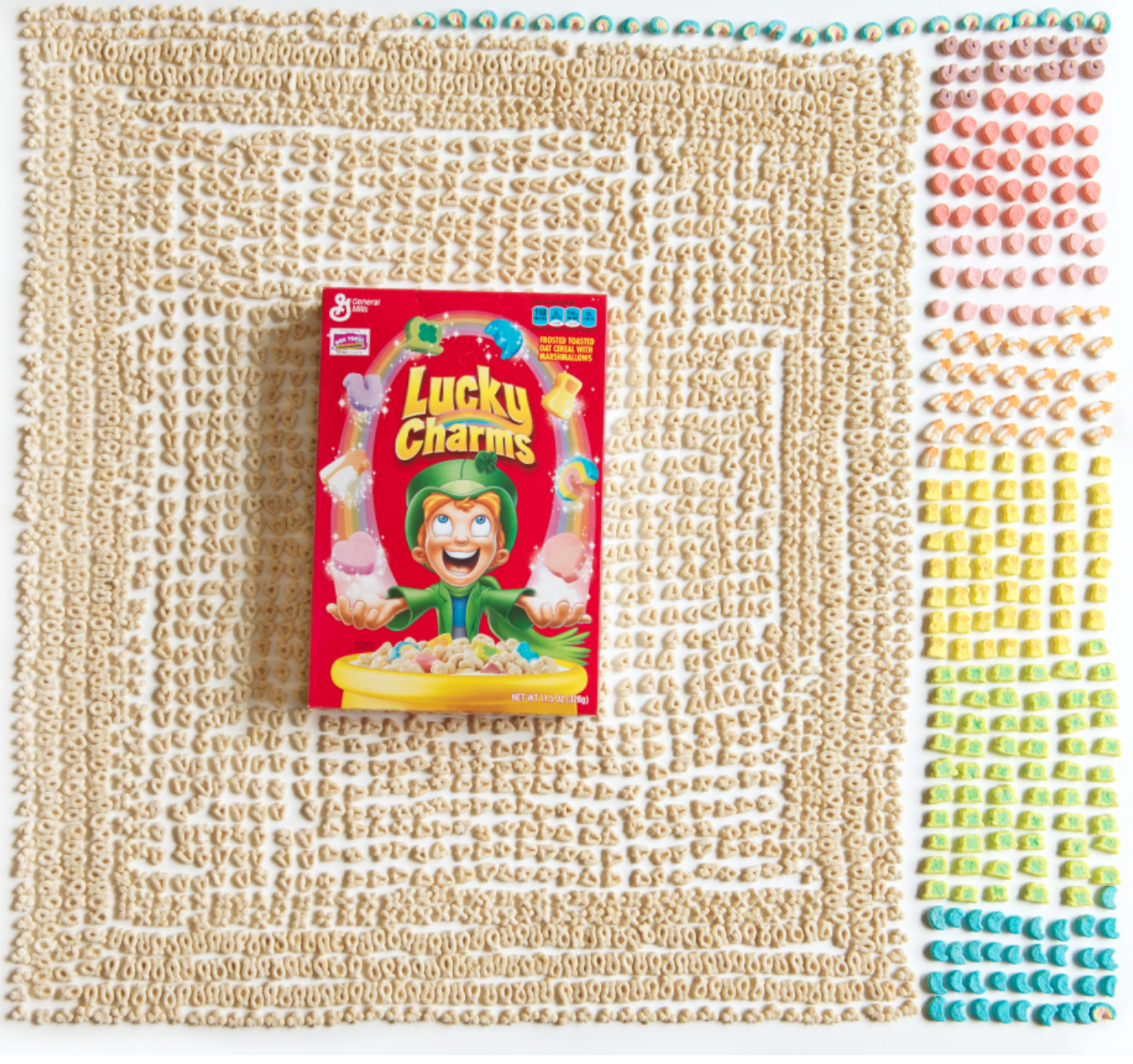
We've now taken apart almost everything that makes an object.

We can put structures on the heap and have the compiler track exactly when to allocate memory and when to free it, with no runtime cost.

We can pass arguments and received results, implement traits and invoke methods, move values and clone them. All runtime computation is clear and visible.

The cost, though, is that now every assignment is a transfer of ownership, and nothing can be used more than once without laboriously making a clone.

This is similar to the world of *linear type systems*


General Mills
FROSTED TOASTED OAT CEREAL WITH MARSHMALLOWS
Lucky Charms
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References and Borrowing

```
fn difference (a: &Point,b: &Point) -> Point {
    Point { x: (b.x-a.x), y: (b.y-a.y) }
}

let p = Point { x:1,  y:5 };
let q = Point { x:8,  y:3 };

let r = difference(&p,&q);      // r is now Point { x:7, y:-2 }
                                // p and q are still available

let s = difference(&q,&p);      // Borrow references again

let t = difference(&r,&r);      // Borrow two references to r
```

References and Borrowing

```
fn imean (v: &Vec<i32>) -> i32 {
    let mut accum = 0;

    for x in v { accum = accum + x };      // Just borrowing

    accum / ( v.len() as i32 )    // Works fine
}

let a = vec![1,5,8,3];                // a : Vec<i32>

let m = imean(&a);                    // We get 4 here
```

Multiple Reader Single Writer

```
fn swap (x: &mut i32, y: &mut i32) {
    let (xv, yv) = (*x, *y);

    *x = yv; *y = xv;
}

let mut a = 1;
let mut b = 5;

swap (&mut a, &mut b);          // Now a = 5 and b = 1

swap (&mut a, &mut b);          // Back to a = 1 and b = 5

swap (&mut a, &mut a);          // Borrowing error
```

Safe Systems Programming

Move semantics lets the compiler statically check the lifetime of structured values. This guarantees memory safety without runtime overhead.

Borrowing references makes it possible to live with move semantics. Borrowing mutable references, with multiple-read single-writer, makes for C-like pointer manipulation and precise control of memory.

That's the core of *safe systems programming* in Rust. So all is good, yes?

The Borrow Checker

> "Many new users to Rust experience something we like to call 'fighting with the borrow checker', where the Rust compiler refuses to compile a program that the author thinks is valid."
>
> *The Rust Programming Language*

Was it all worth it?

Rust certainly offers a lot with its aim of zero-cost abstractions and precise control of memory through ownership and borrowing.

Not everyone is convinced it's worth the cost, though.

It's also notable that Rust has an unsafe keyword, essential for providing its standard libraries, and Safe Rust sits within a larger Unsafe Rust langauge.

So is Rust code really safe? What if it uses unsafe parts? What has been proved about any of this?

ERC Project "RustBelt"

Announcement

We are very pleased to announce the awarding of a 2015 ERC Consolidator Grant for the project **"RustBelt: Logical Foundations for the Future of Safe Systems Programming"**. The project concerns the development of rigorous formal foundations for the Rust programming language (see project summary below).

The project is 5 years long and will include funding for several postdoc and PhD student positions supervised by **Derek Dreyer** at the **Max Planck Institute for Software Systems (MPI-SWS)** in Saarbruecken, Germany.

Homework

Watch This

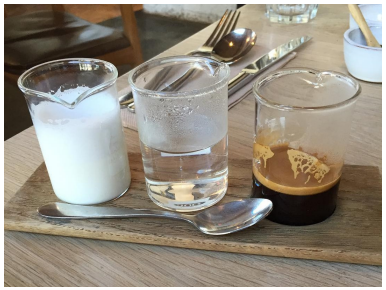
Peter O'Hearn: Reasoning with Big Code
https://is.gd/reasoning_big_code

Talk at the *Alan Turing Institute* about how Facebook is using automatic verification at scale to check code and give feedback to programmers.

Image Credits

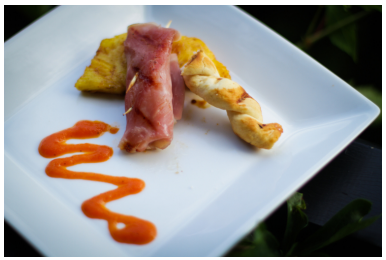
Deconstructed Burger

Things Organized Neatly, Austin Radcliffe on Tumblr



Deconstructed Coffee

Jamila Rizvi on Facebook and Instagram



Deconstructed Pizza

The Foodie Collective

Deconstructed Lucky Charms

Hello Cereal Lovers on Things Organized Neatly.