Bounded generics over constants in Rust

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Context: What is a type?

On this snippet

```
String myString = "Hello, World!";
```

`String` is the type of `myString` and as such, it determines:

- The operations on which `myString` could be used.
- The values `myString` could take.
- The type of `"Hello, World!"` (it should be `String`).

To be more general:

A type system is a syntatic method for proving the absence of certain program behaviors by classifying phrases according to the kinds of values they compute

Context: The Rust programming language

Rust is a systems programming language focused on safety, speed and concurrency. It is sponsored by Mozilla.

However, Rust is not your typical language:

- It does not have garbage collection nor pointer arithmetic, but it is memory safe.
- It is blazingly fast (as fast as C++), but it has high-level features:
  - Pattern matching
  - Traits
  - Higher order functions
- It features concurrency without data races.

Context: Rust's type system

Rust's type system is based on the ML type system. As such it has:

- Static type checking (i.e., programs are checked for safety during compilation).
- Type inference (i.e., type annotations are not always needed).
- Polymorphism via traits and generics.
- Enums and Structs.

It also takes care of memory safety

- Rust encodes the lifetime of each variable in its type.
- For each variable, Rust only allows one of the following:
  - One mutable reference.
  - Several inmutable references.

The problem: Functions over arrays

In Rust, Arrays (being stack allocated) must be statically sized.

As a consequence, this code compiles

```
fn add_arr(a: &[f64; 3], b: &[f64; 3]) -> [f64; 3] {
    let mut result = [0.0; 3];
    for i in 0..3 {
        result[i] = a[i] + b[i];
    }
    result
}
```

The problem: Functions over arrays

In Rust, Arrays (being stack allocated) must be statically sized.

But this code does not

```rust
fn add_arr(a: &[f64; N], b: &[f64; N]) -> [f64; N] {
    let mut result = [0.0; N];
    for i in 0..N {
        result[i] = a[i] + b[i];
    }
    result
}
```

The solution: Generics over constants

Generics are a way of archieving polymorphism based on parametrizing types. For example

- `Vec<T>` is the type of vectors of elements of type T
- `Vec<bool>` is the type of vectors of booleans
- `Vec<i32>` is the type of vectors of integers

We could allow the same pattern letting constant values be parameters

- `[bool; N]` is the type of arrays of booleans and size N
- `[bool; 0]` is the type of arrays of booleans and size 0
- `[bool; 1]` is the type of arrays of booleans and size 1

We only use constants because Rust's type checking is static.

The solution: Generics over constants

In general, a type `Foo` parametrized by a constant `C` of type `T` would be written as

```
Foo<const C: T>
```

In a similar fashion, a function `bar` parametrized by a constant `C` of type `T` would be written as

```
fn bar<const C: T> (args) -> ReturnType { ... }
```

Is important to say that the dispatch mechanism in Rust is static.

On compilation, generic functions and generic types are specialized on demand.

The solution: Arrays as const-generic types

With generics over constant values, we can write functions for any array size

```
fn add_arr<const N: usize> (a: &[f64; N], b: &[f64; N])
-> [f64; N] {
        let mut result = [0.0; N];
    for i in 0..N {
        result[i] = a[i] + b[i];
    }
    result
}
```

However, this is only a partial solution...

The problem: Dynamic check of static bounds

Consider the following generic function

```
fn <const N: usize> head(a: [f64; N]) -> Option<f64> {
    if N > 0 {
        Some(a[0])
    } else {
        None
    }
}
```

The restriction `N > 0` is checked at runtime even though `N` will not change after compilation

The solution: Bounded generics over constant values

Given that now constants are valid parameters. Rust's type checker could take care of checking properties over them.

If `P: bool` is a boolean expression depending on a constant `C`, we can restrict `C` as a parameter

```
// A generic type over a bounded constant
Foo<const C: T> with P
// A generic function over a bounded constant
fn bar<const C: T> (args) -> ReturnType with P { ... }
```

Now, the type checker enforces that any instance of `Foo` and `bar` over a constant satisfies `P`

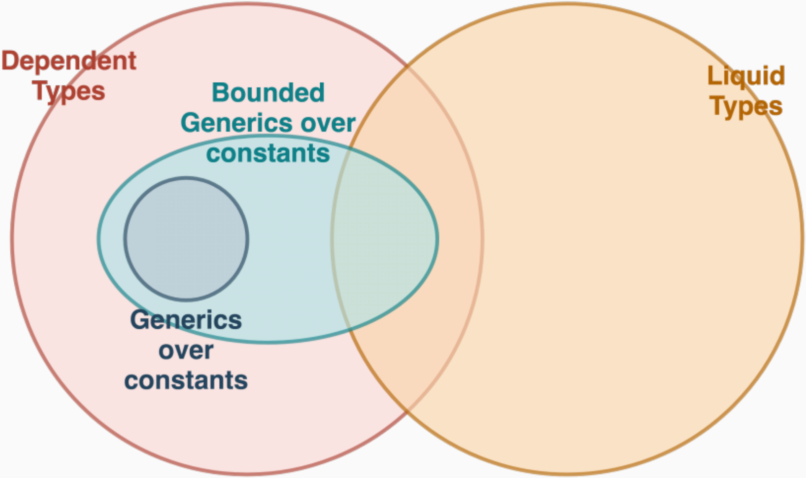
The solution: Static check of static bounds

Now, we can write static bounds over constant parameters.

```
fn <const N: usize> head(a: [f64; N]) with {N > 0} -> f64 {
    a[0]
}
```

Given that the bound `N > 0` is checked during compilation and not in runtime, this code is not just shorter, it is also faster.

Related work: Generics over values in theory



Related work: Languages with dependent types

There are already languages with dependent types:

- Haskell: A general purpose pure functional programming language.
  - It supports dependent types using extensions.
  - It has a liquid version.
- Idris: A general purpose pure functional programming language with dependent types.
- Coq: An interactive theorem prover written in OCaml.
- Agda: An interactive theorem prover written in Haskell.

In 2018, there were around 15 papers about those languages and dependent types in POPL, OOPSLA, PLDI and ICFP.

Related work: Rust Status Quo

The Rust community is already working on an implementation of generics over constants. However, this implementation still needs:

- A mechanism to determine when two constant expressions are equal.
- A mechanism to add bounds over constant parameters.
- A mechanism to determine when two bounds are equal.

Road Ahead: What needs to be done

We want to:

- Provide an unification algorithm for constant expressions to determine type equality on generic types over constants.
- Modify the parser and the subsequent compiler stages to add the `with` syntax.
- Provide unification for boolean arithmetic expressions to determine type equality on bounded generic types over constants.
- Integrate this changes into Chalk, the PROLOG interpreter written in Rust, as it will be integrated into the type checking process.

Road Ahead: Unification

Rust compilation has several stages

`Rust` → `AST` → `HIR` → `MIR` → `miri` → `LLVM IR` → `Machine Language`

The unification algorithm for constant expressions can be implemented in

- HIR or AST: Some constants could be in external libraries.
- MIR: Control flow would make unification too complex.
- miri: A simple unification algorithm could be done.

We are still deciding which alternative is better.

Validation

We will

- Provide formal verification of the unification algorithm either by hand or using a proof assistant (Coq).
- Compare the capabilities of Rust with this new set of features against other dependently typed languages.
- Seek to integrate this work into Rust during 2019.

Schedule

Thesis 1:

- Literature review: Weeks 1 to 8
- Unification design: Weeks 9 to 12
- Unification implementation: Weeks 12 to 16
- Document writing: Weeks 14 to 16

Thesis 2:

- `with` syntax implementation: Weeks 1 to 3
- Unification for boolean expressions: Weeks 3 to 5
- Verification: Weeks 5 to 7
- Document writing: Weeks 5 to 11