A Low Level Language with Precise Integer Types

Ian Shehadeh IRHSHEADEH@SMCM.EDU
Department of Math and Computer Science
St. Mary's College of Maryland
St. Mary's City, Maryland, USA

Abstract

We present *Howlite* a language targeting RISC-V, with a similar level of abstraction to C. Howlite uses a single scalar type, *integer*, which allows users to specify exactly the set of values allowed. Collection types are checked with a simple, structural bi-directional type checker.

Keywords: programming language

1 Introduction

Memory safety in systems programming languages has garnered a lot of attention in the last several years. A compiler that enforces strict rules on object's lifetime and mutability is helpful in large projects, especially when security is a top concern. Checking these properties at compile time allows the compiler to omit parts of its runtime, like a garbage collector, while providing similar gaurentees.

These innovations in language design fail to directly address a class of problems where direct memory manipulation is essential. These problems force the programmer to fully disable the compiler's checks, or encourage awkward solutions which trade clarity for small guarentees.

Howlite aims to address these problems. Howlite is not a language to write a web server, it is not for writing applications, it isn't even a language for writing programming languages. It is a language for writing a single module for a very specific data structure, wrapped in a python library. It is a language for writing a boot loaded, or the entrypoint to a kernel. The compiler does not impose strict requirements on how the programmer manages memory, or accesses data. Instead, the type systems gives a rich set of tools, allowing one to set their own constraints.

2 Syntax

```
func boundedAdd(a: u32, b: u32): u32 {
  if U32_MAX - a > b {
    U32_MAX
  } else {
    a + b
  }
}
```

Listing 1: Addition without Overflow

Howlite's syntax prioritizes familiarity, ease of parsing, and clarity. The syntax should be familiar, someone unfamiliar with the language should be able to immediately grasp the programmer's intent, event if they do not understand every line. In a similar vein, the programmer should be guided towards writing code that is easily legible by others. We approach this issue by providing language constructs that clearly express intent. For example, flow control constructs, like if statements may have a value. This allows the programmer to clearly show a variable's value is the result of some condition. In order to make tooling easier to write, we prioritize createing an unambigous grammar, with no constructs that require unbounded look-ahead.

2.1 Familiarity

Howlite code should be recognizable to C programmers. For this reason, we use curly braces ("{" and "}") to denote blocks of code. We use familiar imperative keywords: "if", "else", and "while", and mathmatical expressions follow typical infix notation. Howlite differs from C in that it requires a sigil character or keyword before beginning a new construct. Types do not lead in variable assignments or functions. Instead we use the "let" or "func" keywords, respectively. This simplifies parsing, since we know what type of statement or expression will follow, similarly, type ascriptions are always prefixed with `:`. These keywords and symbols were decided by surveying popular languages during design. For example, "let", and `:` come from TypeScript, while "func" is a keyword in Go.

2.2 Clarity

TODO

3 Type Checking

Howlite's implements a simple bi-directional type checker [Dunfield and Krishnaswami (2020)]. Every node in the AST is given a type. An AST node's type is typically derived from it's children's types, through a process called *synthesis*, we call these types *synthesized types*. Many constructs in the language must be ascribed types by the programmer: variables declared with "`let`", function parameters, and return values. Types which are declared explicitly are called *assumed* types.

```
let a: Uint32 = 1;
```

Listing 2: Simple Let statement

Here, `Uint32` is the assumed type of `x`. Where ever `x` is referenced, we can consider it of type `Uint32`. The literal `1` has no assumed type. Instead, we synthesize a type for `1` by following a set of rules. For literals, this rule is simple: *for a literal scalar N the synthesized type is* $\{N\}$. As expressions grow, synthesizing types becomes more complicated.

3.1.1 Typechecking an AST

To better illustrate this process, we'll walk through synthesizing a tree.

```
func average(x : 0..10, y : 0..10, z : 0..10) : 0..10 {
  (x + y + z) / 3
}
```

The function parameters: `x`, `y`, and `z` have each been given the assumed types `UInt32`. An assumed type is analogous to the the statement "no matter the value of `x`, we can always assume it is a `UInt32`". The function's assumed return type is `UInt32`. This allows any caller to treat the expression `average(a, b, c)` as a `UInt32`, even if the operations performed by the function are unknown. An assumed type is a promise; it allows the references to entity to *assume* the type of that entity, without knowing anything else about it.

To illustrate how these assumed types interact with synthesized types, we'll manually type check the function.

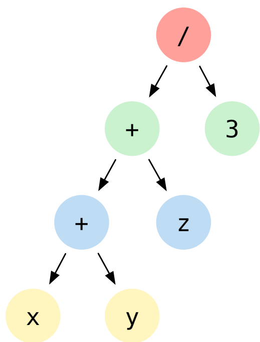
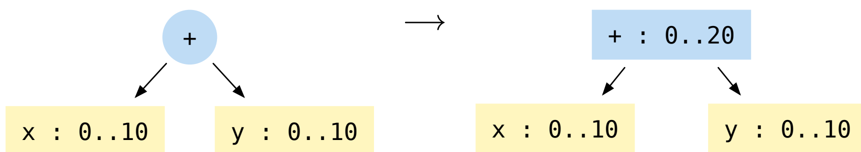


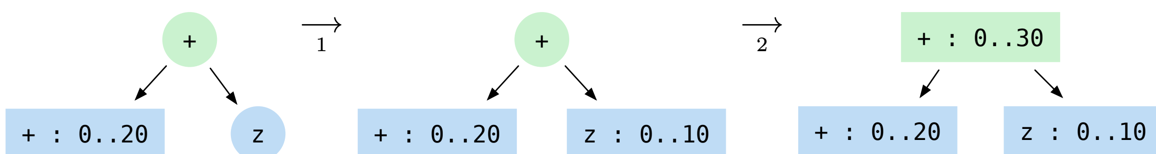
Figure 1: AST

The funtion body, `(x + y + z) / 3`, has the syntax tree seen in Figure 1. The type checker works bottom-up, left-to-right. So, we begin with the leaves of the tree: `x`, and `y`. Identifier AST node's synthesized type is the assumed type of the symbol they include. So `x` is synthesized to type `0..10` (the assumed type of `x`), and `y` is synthesized to type `0..10` (the assumed type of `y`).

This information is added to the tree, and we reference it synthesize `+`. An operator node's synthesized type is constructed by applying the given operation to the synthesized types of each operand. Types may be constructed using arithmetic operations, this process will be defined more formally in Section 3.2. For now, take for granted that `0..10 + 0..10 : 0..20`.

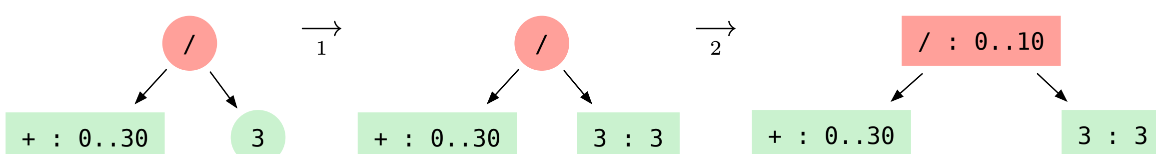


Now, we move up the tree, to synthesize the right hand side of `+`, then finally `+` itself.



In (1) we synthesize the node's type from the assumed type of `z`. In (2) we used this information, and the type of `+` to synthesize a type for `+`.

Finally, we again move up the tree, now to `/`.



Due to the the functions return value, the assumed type of the body is `0..10`. Function body's type is synthesized based on the possible return values. So the synthesized type of this function's body is the the type of `/`.

Type checking is the process of comparing assumed and synthesized types. If a synthesized is not a subset of the assumed type, then a type error is attached to that node.

3.2 Scalars

There is a single scalar type in Howlite, this simplifies the type checking by condensing many cases into a single, generic case. There are no distinct enumerable types, true boolean types, or even a unit type in the language. Instead of distinct types, we have the scalar type "Integer" (floating point number are out of scope). A scalar may be any set of Integers.

3.2.1 Synthesis of Scalars

As seen above, a scalar may be systhensized from a single value, for example the type of -5 is $\{-5\}$. We can also construct new scalars using arithmetic operations:

Given a scalar type $T = \{t_1, t_2, t_3 ... t_n\}$, where $\forall i : t_i \in \mathbb{Z}$, and a scalar type $U = \{u_1, u_2, u_3 ... u_n\}$ where $\forall j : u_j \in \mathbb{Z}$. (i.e T, U are subsets of the integers). We can construct the following types:

- $T \times U = \{tu : \forall t \in T, \forall u \in U\}$
- $T + U = \{t + u : \forall t \in T, \forall u \in U\}$
- $T - U = \{t - u : \forall t \in T, \forall u \in U\}$
- $T \div U = \{t \div u : \forall t \in T, \forall u \in U\}$

For example, given $T = \{1, 2, 3\}$ and $U = \{-5, -7\}$, we'd compute the following:

- $T \times U = \{1(-5), 2(-5), 3(-5), 1(-7), 2(-7), 3(-7))\} = \{-5, -10, -15, -7, -14, -21\}$
- $T + U = \{1 + -5, 2 + -5, 3 + -5, 1 + -7, 2 + -7, 3 + -7) = \{-4, -3, -2, -6, -5, -4\}$
- $T - U = \{1 - (-5), 2 - (-5), 3 - (-5), 1 - (-7), 2 - (-7), 3 - (-7)) = \{6, 7, 8, 9, 10\}$
- $T \div U = \{1 \div (-5), 2 \div (-5), 3 \div (-5), 1 \div (-7), 2 \div (-7), 3 \div (-7)) = \{0\}$

3.2.2 Bitwise Operations

Howlite times to do not explicitly define their size (in practice, all scalars are encoded as register-sized twos complement integers). This makes operations like bitwise not (set complement) difficult to define.

Consider the following C code, wich sets the n'th bit of a 16-bit field to zero:

```
uint16_t n = 9;
uint16_t field = 0b1010101010110011;
uint16_t mask = ~(1u << n);          // = 0b1111110111111111
field &= mask                        // = 0b1010100010110011
```

Translating to Howlite:

```
let n: 9 = 9;
let field: UInt16 = 0b1010_1010_1011_0011;
let mask: UInt16 = ~(1 << n);
field = field & mask;
```

Typechecking line three proceeds as follows, we begin from the bottom and synthesize up:

1. *synthesize* `1 : 1`, through the literal synthesis rule
2. *synthesize* `n : 9`, by using the variable's assumed type
3. *synthesize* `1 << n : 1(2⁹)`, using arithmetic synthesis rules

Now, we have the expression `(1 << n) : 0b1000000000`. Bitwise not of `0b1000000000` is `0b0111111111`.

Now, taking the intersection of `field` and `mask`:

$$\begin{array}{rr} \text{field}: & 1010101010110011 \\ \text{mask}: & 0111111111 \\ \& & 0010110011 \end{array} \quad (1)$$

Because `mask`'s synthesized type is only defined up to the 10′th bit, we accidentally clear the last 6 bits of `field`.

Listing 3: Example: Working with Masks

To compensate for the lack of explicitly sized integers, we define scalar *universe* types: `Pad8<{T : 0..0xff}>`, `Pad16<{T : 0..0xffff}>`, `Pad32<{T : 0..0xffffffff}>`, `Pad64<{T : 0..0xffffffffffffffff}>`. We define equivalent types for signed integers: `Sign8<{T : -0x80..0x7F}>`, `Sign16<{T:  -0x8000..0x7fff}>`, `Sign32<{T : -0x80000000..0x7fffffff}>`, `Sign64<{T : 0x8000000000000000..-0x7fffffffffffffff}>`.

For any type `A : PadN<{T}>`, where `N` is `8`, `16`, `32`, or `64`, and `T` is some subtype of $0..(2^N - 1)$, we define bitwise not as all elements of $0..(2^N - 1)$ which are not included in T; more formally: $\sim A = \{x : \forall x \in \mathbb{N}, x < 2^N, x \notin T\} = 0..(2^N - 1) \setminus T$.

Similarly, for any type `B : SignN<{T}>`, where `N` is `8`, `16`, `32`, or `64`, and T is some subtype of $-(2^{N-1})..(2^{N-1} - 1)$, we define bitwise not as all elements of $-(2^{N-1})..(2^{N-1} - 1)$ not in T: $\sim B = \{x : \forall x \in \mathbb{Z}, x \notin T, -(2^{N-1}) < x < 2^{N-1} - 1\}$

3.2.3 Universes, Registers, and Overflow

During code generation, the intermediate values in an expression must be stored somewhere. Ideally, they're kept in a CPU register. But, the synthesized type of a particular expression may not fit into a single register. For example, on a 32-bit machine, if `x` is of type `UINT32`, then `x + 1` is of type `0..0x100000000`. Many systems programming languages do not check these operations. Some languages check overflow at runtime, and a small set check at compile time.

Howlite does not prevent overflow, but instead defines overflow in the type system. For a given scalar universe type, with a size of N bits, the following reductions are defined:

If a scalar type T has the minimum and maximum values $T_{\min}$, and $T_{\max}$, then we define the canonical form C of T

- If $T_{\min} \geq 0$ and $T_{\max} < 2^N$, then $C = T$
- If $T_{\min} \geq 0$ and $T_{\max} \geq 2^N$, then $C = \{t, o : t \in T, t < 2^N, o \in \mathbb{N}, o < T_{\max} - 2^N\}$
- TODO differentiate between signed and unsigned universe types.
- If $-(2^{N-1}) \leq T_{\min} < 0$ and $T_{\max} < 2^{N-1}$, then $C = T$
- If $T_{\min} < -(2^{N-1}) < 0$ and $T_{\max} < 2^{N-1}$, then $C = \{t, o : t \in T, -(2^{N-1}) \leq t < 2^{N-1}, o \in \mathbb{N}, 2^N + T_{\min} \leq o < 2^{N-1}\}$
- If $-(2^{N-1}) \leq T_{\min} < 0$ and $2^{N-1} \leq T_{\max}$, then $C = \{t, o : t \in T, -(2^{N-1}) \leq t < 2^{N-1}, o \in \mathbb{Z}, o < T_{\max} - 2^N\}$
- If $T_{\min} < -(2^{N-1}) < 0$ and $2^{N-1} \leq T_{\max}$, then $C = \{t, o, p : t \in T, -(2^{N-1}) \leq t < 2^{N-1}, o \in \mathbb{Z}, o < T_{\max} - 2^N, p \in \mathbb{N}, 2^N + T_{\min} \leq o < 2^{N-1}\}$

An example of this kind of operation, on 32-bit hardware:

```
let arr: &[UInt8; 0..100];
let x: Pad8<{0..100}> = 100;
while x >= 0 {

  x = x - 1;
  // x : 0..100 | 0xff
  // because x may be zero, and 0 - 1 is 0xff
  // INVALID
  if (arr[x]) {
    break
  }
}
```

References

Dunfield, J. and Krishnaswami, N. (2020) *Bidirectional Typing*, doi: 10.48550/arXiv.1908.05839