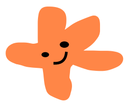
C*

Also written as `cstar` and pronounced **Sea Star**.



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Introduction

C* is a general-purpose systems programming language. It is between the level of C and Zig on a semantic level, and syntactically it also borrows a lot from Rust (pun intended). It is meant primarily for programs that would otherwise be implemented in C for the speed, simplicity, and explicitness of the language, but want a few simple higher-level language constructs, more expressiveness, and some safety, but no so many overwhelming language features and implicit costs like in Rust, C++, or Zig.

It has manual memory management (no GC) and uses LLVM as its primary codegen backend, so can be optimized as well as C, or even better in cases. All of C*'s higher-level language constructs are zero-cost, meaning none of those features give it any overhead over C, which often lead to a highly-optimized style where in C you would take less efficient shortcuts (e.x. function pointers and type-erased generics) and use dangerous constructs like `goto`. In the future, it may also have a C backend so that it can target any architecture where there is a C compiler.

While a general-purpose language, C* will probably have the most advantages when used in systems and embedded programming. It's expressivity and high-level features combined with its relative simplicity, performance, and explicitness is a perfect match for many of these low-level systems and embedded programs.

Language Features

This will contain a high-level overview of the important features of C*, but for a more in-depth explanation of things, see The C* Language section.

Expression Oriented

C* is highly-expression oriented. Unlike C, where many things are only statements, most things in C* are expressions. Things like:

- Statements evaluate to the unit type `()`.
- Blocks evaluate to their last expression, which could be a statement (and thus `()`) or a trailing expression (with no `;)
- Functions and closures themselves.
- `if`, `if/else`, `match` are all expressions.
- `for` evaluates to the `break` value, which is usually `()`.

Postfix Everything

Most unary operators and keywords can be used postfix as well.

- `.if {}`
- `.if {} else {}`
- `.match {}`
- `.for {}`
- `.*` for dereference
- `.&` for pointer to
- `.&mut` for mutable pointer to
- `.!` for negation
- `.@()` for builtins, like as (casting), size_of, etc.
  - `.@cast(T)`: convert to `T`, like an int to float cast, or an int widening cast
  - `.@ptr_cast<T>()`: cast a pointer like `*T` to `*U`
  - `.@bit_cast<T>()`: reinterpret the bits, like from `u32` to `f32`
  - `.@size_of()`: size of a type
  - `.@align_of()`: alignment of a type
  - `.@call(func)`: call a function or closure in a unified syntax

Combined with everything being an expression, `match`, and having methods, this makes it much easier to write things in a very fluid style.

Furthermore, and perhaps most importantly in practice, this makes autocompletion vastly better, because an IDE can narrow done what you may type next based on the type of the previous expression. This can't be done with postfix operators and functions (rather than methods). You get to think in one forward direction, rather than having to jump from some prefix things to some postfix things.

Algebraic Data Types

C* has `struct`s for product types and `enum`s for sum types. This is very powerful combined with pattern matching. `enum`s in particular, which are like tagged unions, are much safer and correct compared to C unions. These data types are also fully zero-cost; there is no automatic boxing, and the safe performance as C can be easily be achieved. Sometimes even better, because the layout of compound types is unspecified in C*.

For example, you can do this to make a copy-on-write string.

```
struct String {
    ptr: *u8,
    len: usize,
}

struct StringBuf {
    ptr: *u8,
    len: usize,
    cap: usize,
}

enum CowString {
    Borrowed(String),
    Owned(StringBuf),
}
```

Pattern Matching

Instead of having a `switch` statement like in C, C* has a generalized `match` statement, which can be used to match many more expressions, including integers (like in C), `enum` variants, dereferenced pointers, slices, arrays, and strings. Also, there is no fall-through, but `match` cases can be combined explicitly.

Furthermore, just like you can destructure to pattern match in a `match` statement, you can also do the same as a general statement, like in a `let`. It's like an unconditional `match`.

```
let cow = CowString::Borrowed("🐄");
let len = match cow {
    Borrowed(s) => s.len(),
    Owned(s) => s.len(),
};
let String {ptr, len} = "🐄";
```

Note that string literals are of the `String` type similarly defined as above, and you can redeclare/shadow variables like `len`.

Generics

C* supports generic types and values, but they are at this point unconstrained. That is, they are like C++'s concept-less templates. They are always monomorphic, except when the exact same code can be shared (no boxing ever). They are not currently higher-kinded. Types and functions can be generic over both types and values, like this:

```
enum Option<T> {
    None,
    Some(T),
}

enum ShortVec<T, N: u8> {
    Inline {
        array: [T; N],
        len: u8,
    },
    Allocated {
        ptr: Option<*T>,
        len: usize,
        cap: usize,
    },
}

fn short_vec_len<T, N: u8>(v: *ShortVec<T, N>): usize {
    v.match {
        Inline {len, _} => len.@cast(),
        Allocated {len, _} => len,
    }
}
```

Non-Null Pointers

C* has pointers, `*T` and `*mut T`, but they are always non-null valid pointers. To express nullability, use `Option<*T>`, which uses the `0` pointer representation for the `None` variant. Nullability can also be nested with `Option`, like `Option<Option<*T>>`, which can't easily be done in C with nullable pointers.

Monadic Error Handling

There are no exceptions in C*, just like C. It uses return values for error handling, similarly to C. But C* has much better support for this using the `Option` and `Result` types.

The definitions of these types are:

```
struct Option<T> {
    None,
    Some(T),
}

struct Result<T, E> {
    Ok(T),
    Err(E),
}
```

That is, `Option` represents an optional value, and `Result` represents either a successful `Ok` value or an error `Err` value.

There is special syntactic support for using these two monadic types for error-handling using the `.?` postfix operator in `try` blocks:

```
struct IndexError {
    index: usize,
}

fn get_by_index<T>(a: *[T], i: usize): Result<T, IndexError> {
    if (i < a.len()) {
        Ok(a[i])
    } else {
        Err(IndexError {index: i})
    }
}

struct IndexPair {
    first: usize,
    second: usize,
}

fn get_two_by_index<T>(a: *[T], i: usize, j: usize): Result<T, IndexError> try {
    let first = try {
        get_by_index(a, i).?
    };
    let second = get_by_index(a, j).?;
    IndexPair {first, second}
}
```

This desugars to

```
fn get_two_by_index<T>(a: *[T], i: usize, j: usize): Result<T, IndexError> {
    let first = try {
        get_by_index(a, i).match {
            Ok(i) => i,
            Err(e) => return Err(e),
        }
    };
    let second = get_by_index(a, j).match {
        Ok(i) => i,
        Err(e) => return Err(e),
    }
    Ok(IndexPair {first, second})
}
```

As you can see, without the try `.?` operator and `try` blocks, doing all the error handling with just `match` quickly becomes tedious. This is also kind of like a monadic `do` notation, except it is in C* limited to just the monads `Option<T>`, and `Result<T, E>` (over `T`).

Note also that `try` blocks can be specified at the function level as well as normal blocks.

Uncatchable Panics

While monadic error-handling with `Option` and `Result` is usually superior, there are still cases where you have unrecoverable errors (maybe you don't want to handle out of memory conditions), or where you'd rather just end the program than handle the error. In this case, you can `panic`, which will print an error message and immediately `abort`.

To do this with an `Option` or `Result`, you can just call `.unwrap()`, which will panic if it was `None` or `Err` and return the `Some` or `Ok` value.

There is no language-supported unwinding. `abort` is immediately called after a panic, and only the OS cleans things up. Nothing is stopping you from calling `setjmp` and `longjmp` from C, but no unwinding of `defer` statements is done, and it may result in undefined behavior. There is no undefined behavior, however, in a normal panic because you just simply `abort`.

Defer

To aid in resource handling, C* has a `defer` keyword. `defer` defers the following statement or block until the function returns, but will run it no matter where the function returns from (but not `panic` s/ `abort` s) (actually, the `defer` will run when its block exits, but its easier to just think about function blocks first).

For example, you can use this to ensure you correctly clean up resources in a function:

```
extern "C" fn open(path: *u8, flags: i32): i32;
extern "C" fn close(fd: i32): i32;

fn open_file_in_dir(dir: *[u8], filename: *[u8]): Result<i32, String> try {
    let mut path = Vec.new(Mallocator());
    defer path.free();
    try {
        if (dir.len() > 0) {
            path.extend(dir).?;
            path.push(b'/').?;
        }
        path.extend(filename).?;
        path.push(0).?;
    }.map_err(fn(_) "alloc error").?;

    let path = path.as_ptr();
    let fd = open(path, O_RDWR).match {
        -1 => Err("open failed"),
        fd => fd,
    }.?;
    defer println(f"opened {fd}");
    return fd;
}
```

In this example, you have to allocate a path to store the directory and filename you combine, and then open that path and return the file descriptor if it was successful. You have to clean up the memory allocation, though, and do that while still handling all the allocation errors and the open error. The latter can be done elegantly with `try` and `.?`, but if you mix in the `path.free()`, you'd have to run it before every error return, which means you have to duplicate it and not use `.?` anymore.

Instead, you can use `defer` for this. No matter where you return from the function, it will run its statement right before that. You can also use `defer` for any statement, not just resource cleanup, like logging for example.

However, sometimes you want to cancel a `defer`:

```
struct FilePair {
    fd1: i32,
    fd2: i32,
}

fn open_two_files(path1: *[u8], path2: *[u8]): Result<FilePair, String> try {
    let fd1 = open_file_in_dir(b"", path1).?;
    close: defer close(fd1);
    let fd2 = open_file_in_dir(b"", path2).?;
    close: defer close(fd2);
    println(f"opened {fd1} and {fd2}");
    undefer close;
    FilePair {fd1, fd2}
}
```

In this example, you want open two files and return them if successfull. If only one is successful, though, that's an error and you should close the first one before returning the error. In order to do that cleanly, you can use the `undefer` keyword, which cancels an earlier labeled `defer`, in this case labeled `close`.

`defer` and `undefer` are actually syntax sugar for something a bit more low-level and wordy:

```
fn open_two_files(path1: *[u8], path2: *[u8]): Result<FilePair, String> try {
    let fd1 = open_file_in_dir(b"", path1).?;
    let close1 = {fd1} fn() close(fd1);
    let close1 = close1.@defer());
    let fd2 = open_file_in_dir(b"", path2).?;
    let close2 = {fd1} fn() close(fd1);
    let close2 = close2.@defer());
    println(f"opened {fd1} and {fd2}");
    let close = [close2, close1];
    close.undo();
    FilePair {fd1, fd2}
}
```

That is, `.@defer()` places the closure on the stack and returns a `Defer` struct, which can be undone with `Defer.undo()` (`[Defer].undo()` just maps `Defer.undo()` over the array). `Defer.undo()` sets a bit in the `Defer` struct that it's been undone. Then when the stack unwinds, any none-undone `Defers` on the stack are run.

Comparison to Destructors

In many other languages, destructors are used for resource handling instead of defer. This is more uniform, automatic, and safe, since destructors run automatically when dropped out of scope. If you have destructors, though, you also need moves in order to do what we can do with `undefer`, but then you also need ownership, which C* doesn't track. Furthermore, `defer` is a lot more explicit and flexible. All the resource cleanup is written explicitly so there are no hidden costs, which most programmers coming from C will prefer. And since you can put any statement in a `defer`, it's much more flexible than destructors.

Methods

C* has associated functions and simple methods, though these are largely syntactic sugar. To declare these for a type, simply write:

```
struct Person {
    first_name: String,
    last_name: String,
}

impl Hello {

    fn new(first_name: String, last_name: String): Self {
        Self {first_name, last_name}
    }

    fn say_hi1(self: Self) {
        print(f"Hi {self.first_name} {self.last_name}");
    }

    fn say_hi1(self: *Self) {
        print(f"Hi {self.last_name}, {self.first_name}");
    }

    fn remove_last_name(self: *mut Self) {
        self.last_name = "";
    }

}

fn main() {
    let mut person = Person.new("Khyber", "Sen");

    {
        person.say_hi1();
        person.&.say_hi2();
        person.&mut.remove_last_name();
        person.say_hi1();
    }
    {
        Person.say_hi1(person);
        Person.say_hi2(person.&);
        Person.remove_last_name(person.&mut);
        Person.say_hi1(person);
    }
}
```

In this example, we first declared a `struct Person`, and then an `impl` block for `Person` to define methods/associated functions for it. Note that this `impl` block can be anywhere, even in other modules.

In the `impl` block, we first declared an associated function `Person.new`, which is just a normal function but namespaced to `Person`. Similar, the other three methods are just normal functions, too, as seen when we call them explicity in the second block in `main`. But we can also use `.` syntax to call them, which just allows us to explicitly naming `Person`.

Inside an `impl` block, we can also use the `Self` type as an alias to the type being implemented. This is especially useful with generics.

Note that the `.&` and `*Self` are explicit, because wan't these kinds of things to be done explicitly. For example, `Person.say_hi1` takes `Self` by value, which means it must copy the `Person` every time. If `Person` were a much larger struct, this could be very expensive and we don't want to hide that information. Also, the difference between `.&` and `.&mut` is explicit to make mutability explicit everywhere.

Closures

In C*, you can also use anonymous closures. These are similar to normal functions, but they can "enclose" over values in the current scope.

For example,

```
impl <T, F> Option<T> {
    fn map(self: Self, f: F): F(T) {
        match self {
            None => None,
            Some(t) => Some(f.@call(t)),
        }
    }
}

fn main() {
    try {
        let a = Some("hello").map(fn(s) s.len()).?;
        let b = Some("world").map({a} fn(s) a + s.len()).?;
        let c = Some("🏳️‍⚧️").map({n: b} fn(s) n + s.len()).?;
        None.map({a.&, b.&mut, n: &mut c} fn(s) {
            print(f"{s}: {a.*}, {b.*}, {n.*}");
            n.*++;
            b.* += n.*;
        });
        print(f"{s}: {a}, {b}, {c}");
    }
}
```

These are some example of how to create closures and how to call them. In particular:

- Closures have a generic, unnamed type. So when we take a closure as a parameter, we need to use a generic (this is because closure type depend on what they capture). You can also apply a type to a function type to get its return type, like `F(T)`.
- We can call a closure using the unified calling syntax: `.@call()`. Normal function calls are `()`, and we want to be explicit when we're actually calling a closure, so `.@call()` is needed. `.@call()` also works on normal functions, though, since all functions can be implicitly converted to non-capturing closures.
- The closure syntax is very similar to function syntax, with a few differences:
  - The return expression does not have to be a block, like in normal functions; it can directly use an expression. Note that functions effectively just return a block. That's how `try` blocks work, for example.
  - Argument and return types are inferred, though they can still be specified if you want. This is because they are more local, and thus documented types are not as necessary.
  - If you want to capture variables, you specify an anonymous struct literal before the `fn`. This follows the same normal rules for struct literals, but you don't have to specify the type, since the type is anonymous. Then that struct's fields are available within the closure as variables.

The way closures are implemented are by creating an anonymous struct of the captured closure context. Then there is a method on that struct that takes the closure arguments and returns the closure body with the context struct destructured inside (so its variables are in scope). This is what is called by `.@call()`. Note that there are no indirect function calls, boxing, or allocations involved in this, but it requires the use of generics. If nothing is captured by a closure, though, then it can be cased to a function pointer: `fn(T, U): R`, which can be called indirectly and passed to C over FFI. The same is true of normal functions.

Slices

C* also has slices. These are a pointer and length, and are much preferred to passing the pointer and length separately, like you usually have to do in C.

They are implemented like this (not actually, but similarly):

```
struct Slice<T> {
    ptr: *T,
    len: usize,
}
```

But they can be written as `*[T]`. Actually, slices are unsized types, so their type is just `[T]`, but usually `*[T]` is used and that is what's equivalent to the above `Slice<T>`.

Unlike pointers like `*T`, slices can be indexed. By default, using the indexing operator, this is bounds checked for safety, but there are also unchecked methods for indexing. Usually, though, bounds checking can be elided during sequential iteration, so the performance hit is minimal, and can be side-stepped if really needed.

Slices can also be sliced to create subslices by indexing them with a range (e.x. `[1..10]` or `[1..]`). Again, this is bounds checked by default.

Strings

There are multiple types of strings in C* owing to the inherent complexity of string-handling without incurring overhead. The default string literal type is `String`, which is UTF-8 encoded and wraps a `*[u8]`. This is a borrowed slice type and can't change size. To have a growable string, there is the `StringBuf` type, but there is no special syntactic support for this owned string. `String`s are made of `char`s, unicode scalar values, when iterating (even though they are stored as `*[u8]`). `char`s have literals like `c'\n'`.

Then there are byte strings, which are just `*[u8]` and do not have to be UTF-8 encoded. String literals for this are prefixed with `b`, like `b"hello"` (and for char byte literals, a `b` prefix, too: `b'c'`). The owning version of this is just a `Box<[u8]>` (notice the unsized slice use), and the growable owning version is just a `Vec<u8>`.

Furthermore, for easier C FFI, there is also `CString` and `CStringBuf`, which are explicitly null-terminated. All other string types are not null-terminated, since they store their own length, which is way more efficient and safe. Literal `CString`s have a `c` prefix, like `c"/home"`.

And finally, there are format strings. Written `f"n + m = {n + m}"`, they can interpolate expressions within `{}`. Types that can be used like this must have a `format` method (might change). format, or f-strings, don't actually evaluate to a string, but rather evaluate to an anonymous struct that has methods to convert it all at once into a real string. Thus, f-strings do not allocate.

Imports

Instead of using a preprocessor with `#include`s like in C, C* uses imports. Each file is a module of its name, and it can be imported to use in another file/module, or specific items from that module. Short modules can also be declared inline with

```
mod name {

}
```

Structural Comments

Besides just using `//` for line comments and `///` for doc comments, `/-` can be used for a sort of structural comment. That is, it will comment out the next item, whether that be the next expression, the next line, or the next function.

C FFI

C* has no stable ABI, but can easily do C FFI by marking an item (like a function or a struct) `extern "C"`. C* constructs are automatically converted to their C equivalents:

C*	C	Notes
`()`	`void`	
`bool`	`_Bool`	
`u8`	`uint8_t`	
`i8`	`int8_t`	
`u16`	`uint16_t`	
`i16`	`int16_t`	
`u32`	`uint32_t`	
`i32`	`int32_t`	
`u64`	`uint64_t`	
`i64`	`int64_t`	
`u128`	`unsigned __int128`	
`i128`	`__int128`	
`usize`	`size_t`	
`isize`	`ssize_t`	
`uptr`	`uintptr_t`	
`iptr`	`intptr_t`	
`f16`	`_Float16`	
`f32`	`float`	
`f64`	`double`	
`f128`	`_Float128`	
`*T`	`*T`	for argument types
`Option<*T>`	`*T`	for return types
`fn(T, U): R`	`R (*)(T, U)`	

There is also an `extern "C" union {}` type available that is for FFI with C `union`s. It is unknown which variant is active, unlike `enum`s, which track that.

Examples

GCD

Here is how you write simple algorithms like GCD in C*:

```
fn gcd(a: i64, b: i64): i64 {
    fn gcd(a: u64, b: u64): u64 {
        match b {
            0 => b,
            _ => gcd(b, a % b),
        }
    }(a.abs(), b.abs()).@cast(i64)
}
```

Systems Programming

Here is an example program in C* for part of a simple HTTP/1.0 server, equivalent to part0 of hw3 in Jae's OS class (https://gist.github.com/RyanLee64/957cf2336d9cea168839f549f99f8916). It showcases many of C*'s notable features, like enums, methods, generics, defer, expression-orientedness, postfix operators, pattern matching, closures, monadic error handling, and byte, c, and format strings.

That code (the ported part) is ~230 LOC, while the C* below is only ~80 LOC, and it is more correct in error handling and edge cases, faster in places (though IO dominates here), and the business logic stands out more (while less important things like errors, resource cleanup, allocations, and string handling stay in the background). That is, C* allows you to be simulatenously more expressive while still staying correct and explicit, and the performance is just as good if not better.

```
enum Status {
    Ok,
    NotImplemented,
    BadRequest,
    // rest skipped for brevity
}

struct RequestLine {
    method: *[u8],
    uri: *[u8],
    version: *[u8],
}

impl RequestLine {
    fn check(self: *Self): Result<(), Status> try {
        let Self {method, uri, version} = self.*;
        match (method, version) {
            (b"GET", b"HTTP/1.0" | b"HTTP/1.1") => {},
            _ => Err(Status.NotImplemented).?,
        }
        if uri.starts_with(b'/').! || uri.equals(b"/..") || uri.contains(b"/../") {
            Err(Status.BadRequest).?;
        }
    }
}

fn main(): Result<(), AnyError> try {
    let (port, web_root) = std.env.argv().match {
        [_, port, web_root] => (port.parse<u16>().?, web_root),
        [program, ...] => Err(f"usage: {program} <server_port> <web_root>").?,
    };
    let server_socket = Socket.new(PF_INET, SOCK_STREAM, IPPROTO_TCP).?;
    defer server_socket.&.close();
    server_socket.&.bind(SocketAddr {
        family: AF_INET,
        addr: InetAddr {
            addr: INADDR_ANY.to_be(),
        },
        port: port.to_be(),
    }).?;
    server_socket.&.listen(5).?;
    let mut request_line_buf = Vec.new();
    defer request_line_buf.free();
    let mut line_buf = Vec.new();
    defer line_buf.free();
    loop try {
        let client_socket = server_socket.&.accept().?;
client_socket_close:
        defer client_socket.&.close();
        let mut client_stream = fdopen(client_socket.fd, c"r").?;
        undefer client_socket_close; // stream (`FILE *` in C) takes ownership
        defer client_stream.&.close();
        let line_or_status = try {
            // read and parse request line
            let line = client_stream.&mut.read_line(buf.&mut)
                .map_err(fn(_) Status.BadRequest).?
                .split(fn(b) " \t\r\n".contains(b)).match {
                    [method, uri, version] => RequestLine { method, uri, version },
                    _ => Err(Status.NotImplemented).?,
                };
            line.&.check().?;
            // read headers, skip them
            loop {
                client_stream.&mut.read_line(buf.&mut)
                    .map_err(fn(_) Status.BadRequest).?
                    .match {
                        "\n" | "\r\n" => break,
                        _ => {},
                    }
            }
            line
        }
        let (line, status) = match line_or_status {
            Ok(line) => (line, Status.Ok),
            Err(status) => (RequestLine { method: b"", uri: b"", version: b"" }, status),
        };
        client_socket.write(f"HTTP/1.0 {status.code()} {status.reason()}\r\n\r\n").?;
        match line_or_status {
            Ok(_) => handle_request(web_root, line.uri, client_socket).?,
            Err(_) => client_socket.write(f"<html><body>\n<h1>{status.code()} {status.reason()}</h1>\n</body></html>").?;
        }
        eprintln(f"{client_socket.addr} \"{line.method} {line.uri} {line.version}\" {status.code()} {status.reason()}").?;
    }
}
```