An Illustrated Guide to LLVM

or: an introduction to building simple and not-so-simple compilers with Rust and LLVM

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What?

A library for building compilers

Formerly "Low level virtual machine"

- Compiler *backends*
  - Code generation, optimization
  - *Not* lexing, parsing

Supports both ahead-of-time and just-in-time

Industrial-grade

- Used in industry
  - Apple
  - Google
  - Others
- Mature
  - First release in 2003
  - ~5 million LOC

Portable

Supports many systems:

- High-performance
  - x86
  - PowerPC
  - SPARC
- Embedded
  - ARM
  - PowerPC
  - SPARC
- GPUs
  - AMD GCN
  - Nvidia PTX
- Exotics
  - BPF
  - Hexagon
  - C

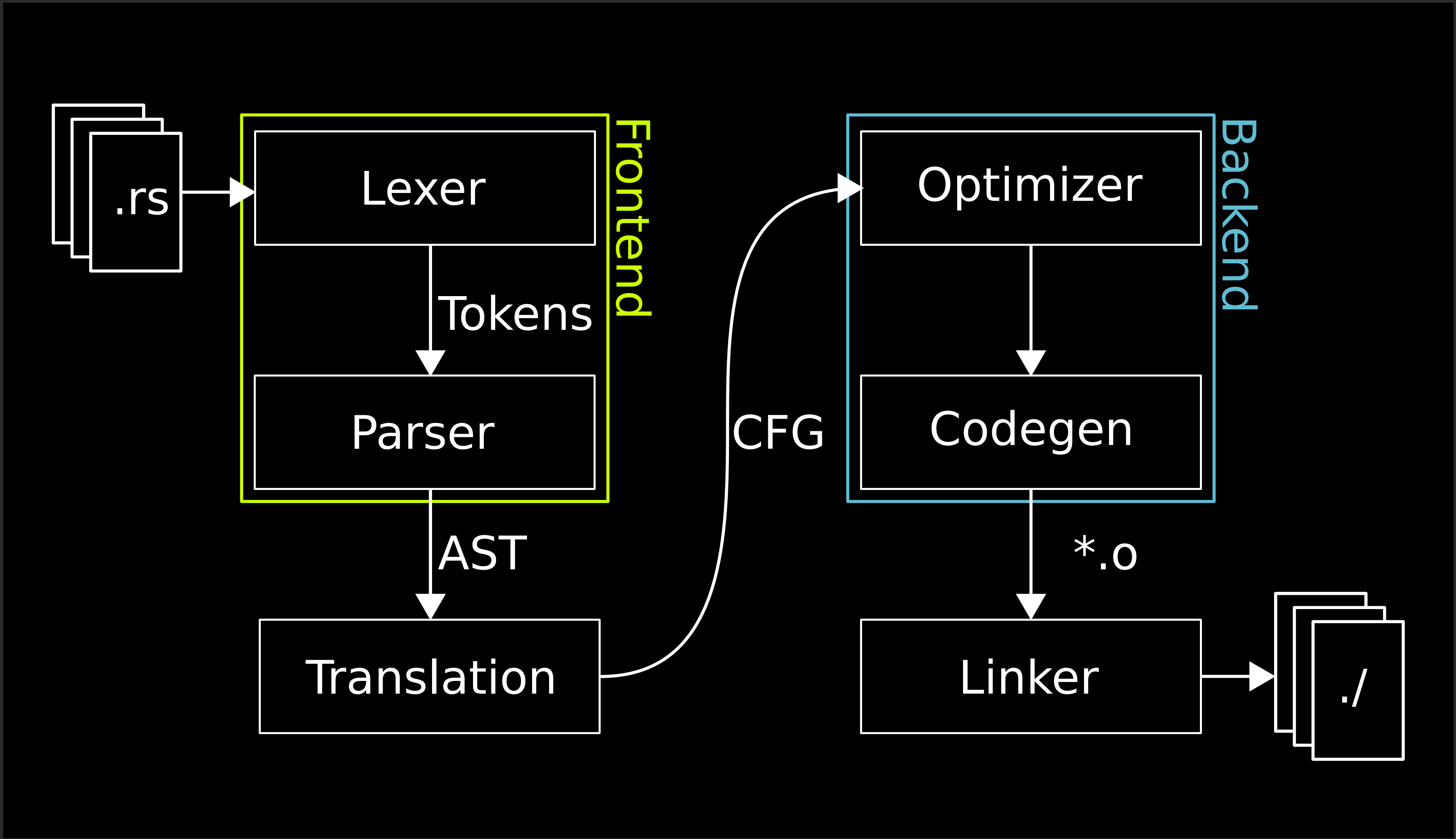
Numerous frontends

- Clang (C)
- GHC (Haskell)
- LDC (D)
- OpenJDK (Java)

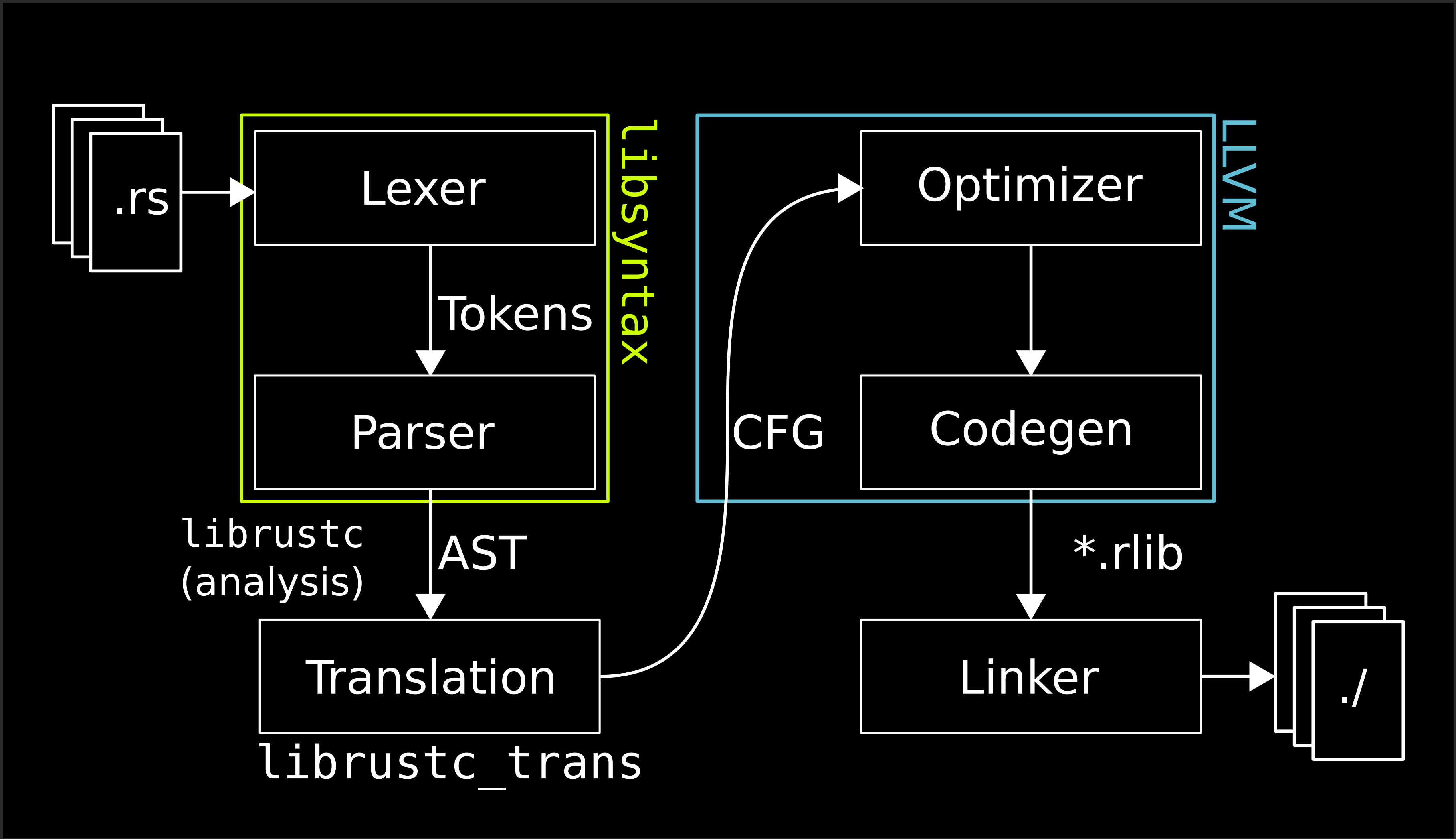
.. and of course `rustc`.

How?

Compiler structure



rustc



.rs
Lexer
Tokens
Parser
libsyntax
librustc
(analysis)
AST
Translation
librustc_trans
Optimizer
LLVM
CFG
Codegen
*.rlib
Linker
./

Talking to LLVM

IR goes in..

```
fn add(x: i32, y: i32) -> i33 {
    (x as i33) + (y as i33)
}
```

```
target triple = "x86_64-unknown-linux"

define external i33 @add(i32 %x, i32 %y) nounwind readnone {
    %xe = sext i32 %x to i33
    %ye = sext i32 %y to i33
    %result = add i33 %x, %y
    ret i33 %result
}
```

..code comes out

```
     .text
     .globl add
add:
     movsxd rcx, edi
     movsxd rax, esi
     add rax, rcx
     ret
```

More complex

Testing the Collatz conjecture:

```
fn collatz(x: u32) -> bool {
    if x == 1 {
        return true;
    }

    let next = if x % 2 == 0 {
        x / 2
    } else {
        (3 * x) + 1
    }
    collatz(next)
}
```

`collatz(u32)` in IR

```
define "fastcc" i1 @collatz(i32 %x) {
    %finished = icmp eq i32 %x, 1
    br i1 %finished, label %Base, label %Continue
Base:
    ret i1 1

Continue:
    %next = alloca i32
    %odd = urem i32 %x, 2
    %odd1 = trunc i32 %odd to i1
    br i1 %odd1, label %Odd, label %Even
```

`collatz(u32)` continued

```
Odd:
    %halved = udiv i32 %x, 2
    store i32 %halved, i32* %next
    br label %Recurse
Even:
    %larger = mul i32 %x, 3
    %larger1 = add i32 %larger, 1
    store i32 %larger1, i32* %next
    br label %Recurse

Recurse:
    %nextval = load i32, i32* %next
    %result = musttail call i1 @collatz(i32 %nextval)
    ret i1 %result
}
```

SSA

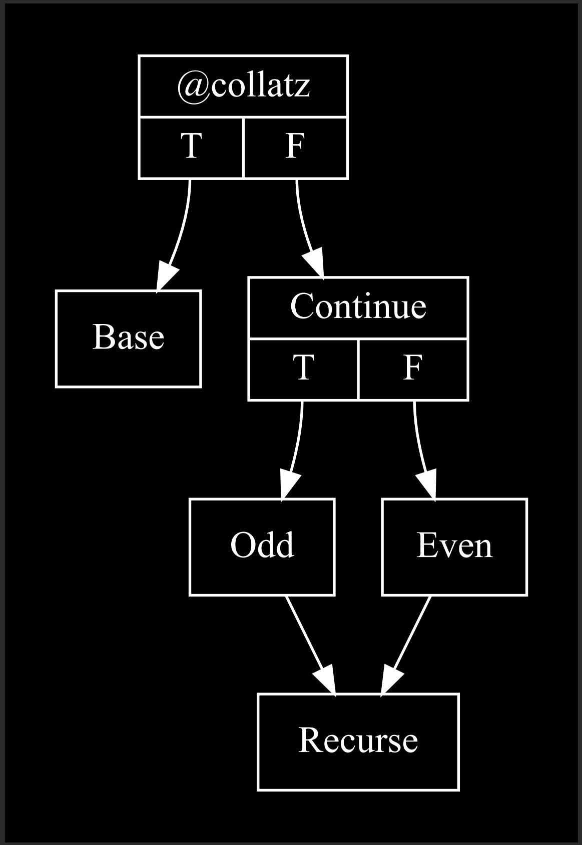
Why not this?

```
    %nextval = %halved
    br label %Recurse
Even:
    // ...
    %nextval = %larger1
Recurse:
    // use nextval
```

Single static assignment

- Every value has exactly one assignment
- Allows the system to work with a true CFG

Control flow graph



Native format for optimization.

Speaking Merthese

Token	Action
m	Print "merth"
e	Print "\n"
r	Print " "
t	Print random [a-z] [0, 13.4) times
h	Jump to after the next 'h'
_	Do nothing

Planning

Primitive operations

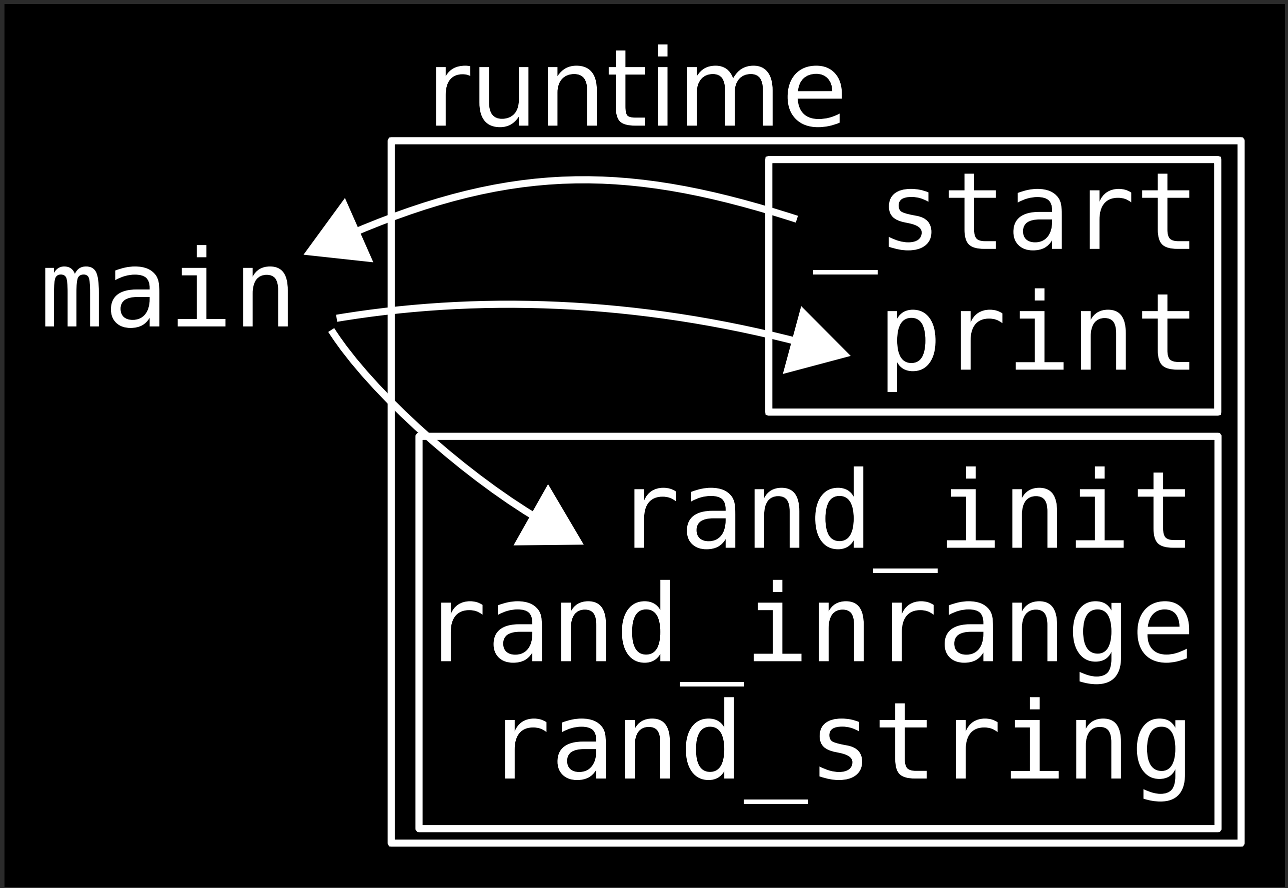
- Print string
  - `fn print(s: *mut u8, len: u8)`
- Random integer
  - `fn rand_inrange(max: u8) -> u8`

These are not supported by any CPU..

Runtime library

- Statically linked
  - Better optimization (inlining!)
  - Self-contained
- Written in IR
  - Because we can
  - More portable

Program structure



`_start`

- Initialize RNG
  - Open `/dev/urandom`
  - Read bytes
  - Close file
- Call `main`
- `exit(0)`

We need to do syscalls

```
extern fn syscall(nr: i64, ...) -> i64;
```

```
define private i64 @syscall2(i64 %nr, i64 %p1, i64 %p)
          inlinehint {
     %1 = call i64 asm sideeffect "syscall",
               "={rax},{rax},{rdi},{rsi}"
               (i64 %nr, i64 %p1, i64 %p2)
     ret i64 %1
}
```

- RAX: nr
- RDI: p1
- RSI: p2
- Result: RAX

```
extern fn open(path: *mut u8, flags: c_int) -> c_int
```

```
@__NR_open = private constant i64 2

define private i32 @open(i8 *%path0, i32 %flags0) {
    %nr = load i64, i64* @__NR_open
    %path = ptrtoint i8* %path0 to i64
    %flags = zext i32 %flags0 to i64
    %out0 = call i64 @syscall2(i64 %nr, i64 %path, i64 %flags)
    %out = trunc i64 %out0 to i32
    ret i32 %out
}
```

Turns out syscalls are boring.
Back to `_start`.

```
declare void @main()
define void @exit(i32 %code) noreturn {}

define void @_start() noreturn {
    // initialize RNG
    call void @main()
    call void @exit(i32 0)
    unreachable
}
```

Feels like C: declare external functions, glue them together.

Writing some Rust

Skeleton

```
extern crate llvm_sys as llvm;

fn main() {
    unsafe {
        LLVM_InitializeNativeTarget();
        LLVM_InitializeNativeAsmPrinter();
        LLVM_InitializeNativeAsmParser();

        let ctxt = LLVMContextCreate();
        /* Use ctxt */
        LLVMContextDispose(ctxt);
    }
}
```

Create `main`

```
declare void @main()
```

```
let main_name = b"main\0".as_ptr() as *const _;
let main_module =
        LLVMModuleCreateWithNameInContext(main_name, ctxt);

let ty_void = LLVMVoidType();
let ty_fn_main = LLVMFunctionType(ty_void,
                 /* ParamTypes */ ptr::null_mut(),
                 /* ParamCount */ 0,
                 /* IsVarArg   */ 0);
let main_function = LLVMAddFunction(main_module,
                                    main_name,
                                    ty_fn_name);
```

Emitting IR

```
fn LLVMPrintModuleToFile(M: LLVMModuleRef,
                         Filename: *const c_char,
                         ErrorMessage: *mut *mut c_char)
                         -> LLVMBool

fn LLVMPrintModuleToString(M: LLVMModuleRef) -> *mut c_char
```

Could we use `io::Write` instead?

Dropping to C++

```
extern "C" typedef int (*cb_t)(const void *, size_t, void *);

class raw_callback_ostream : public llvm::raw_ostream {
    cb_t callback;
    void *callback_data;

public:
    raw_callback_ostream(cb_t cb, void *cb_data) { /* ... */ }

private:
    void write_impl(const char *p, size_t sz) override {
        callback(p, sz, callback_data);
        offset += sz;
    }
};
```

A C function to expose it:

```
extern "C" void PrintModuleIR(LLVMModuleRef M,
                              cb_t cb,
                              void *cb_data) {
    raw_callback_ostream out(cb, cb_data);
    out << *llvm::unwrap(M);
}
```

Rust adapter from `Write` to callbacks

```
extern "C" fn module_ir_printer<W>(src: *const u8,
                                   size: libc::size_t,
                                   state: *mut libc::c_void)
                                   -> libc::c_int
        where W: std::io::Write {
    let (src, out) = unsafe {
        (slice::from_raw_parts(src, size),
         &mut *(state as *mut W))
    };
    let _res = out.write_all(src);
    0
}
```

Safe wrapper

```
fn dump_module_ir<W>(module: LLVMModuleRef, mut out: W)
        where W: std::io::Write {
    unsafe {
        PrintModuleIR(module,
                      module_ir_printer::<W>,
                      &mut out as *mut W as *mut libc::c_void);
    }
}
```

Emit some IR

```
let main_function = LLVMAddFunction(main_module,
                                    main_name,
                                    ty_fn_name);
dump_module_ir(main_module, std::io::stderr());
```

```
; ModuleID = 'main'
source_filename = "main"

declare void @main()
```

Using Builders

```
let bb_main =
    LLVMAppendBasicBlockInContext(ctxt,
                                  main_function,
                                  b"\0".as_ptr() as *const _);
let b = LLVMCreateBuilderInContext(ctxt);

LLVMPositionBuilderAtEnd(b, bb_main);
LLVMBuildRetVoid(b);
LLVMDisposeBuilder(b);
```

```
define void @main() {
    ret void
}
```

🎉🎉

Manual testing

The pieces so far

linux-x86_64.ll

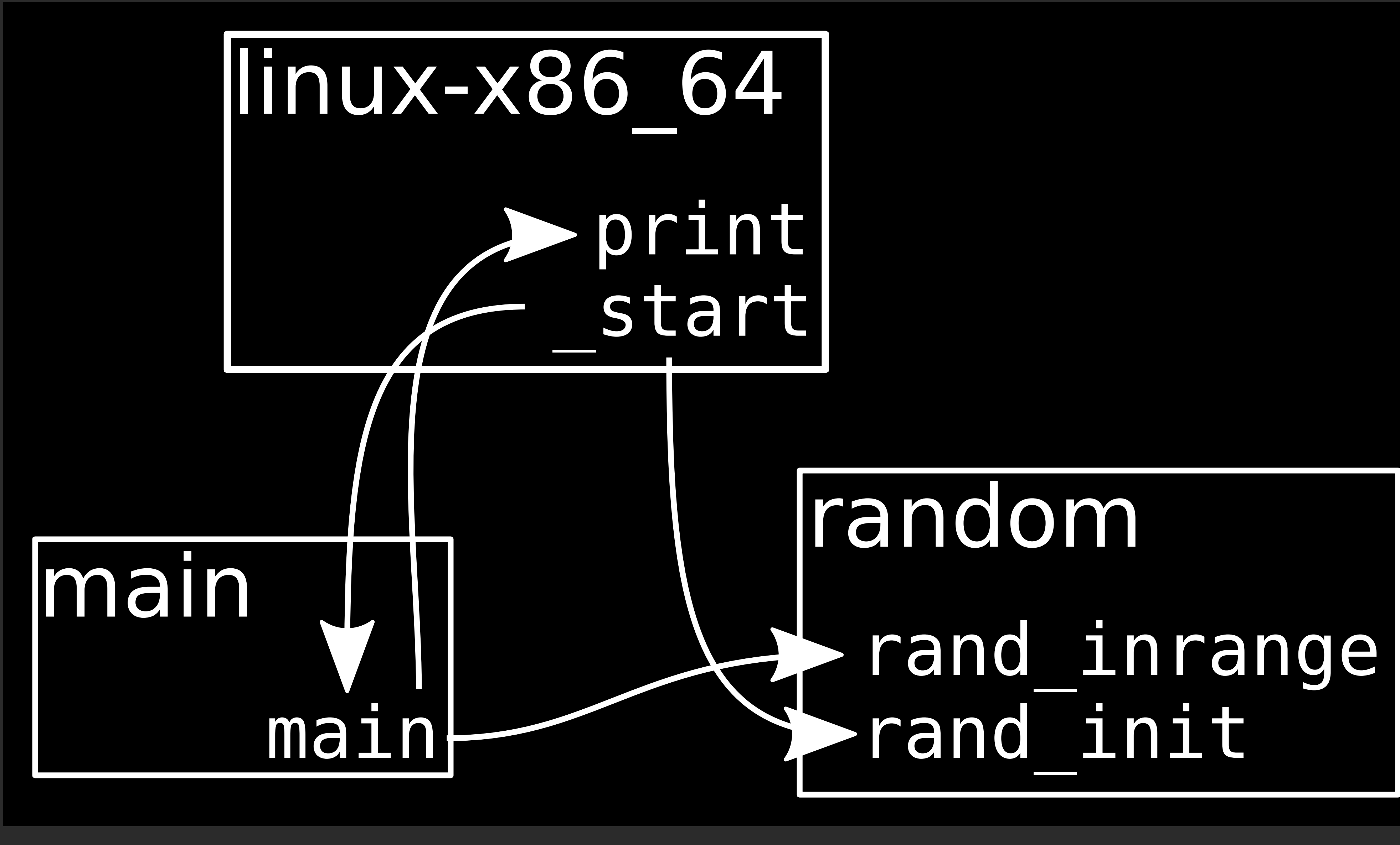
`_start` and `print` functions for x86_64 Linux

random.ll

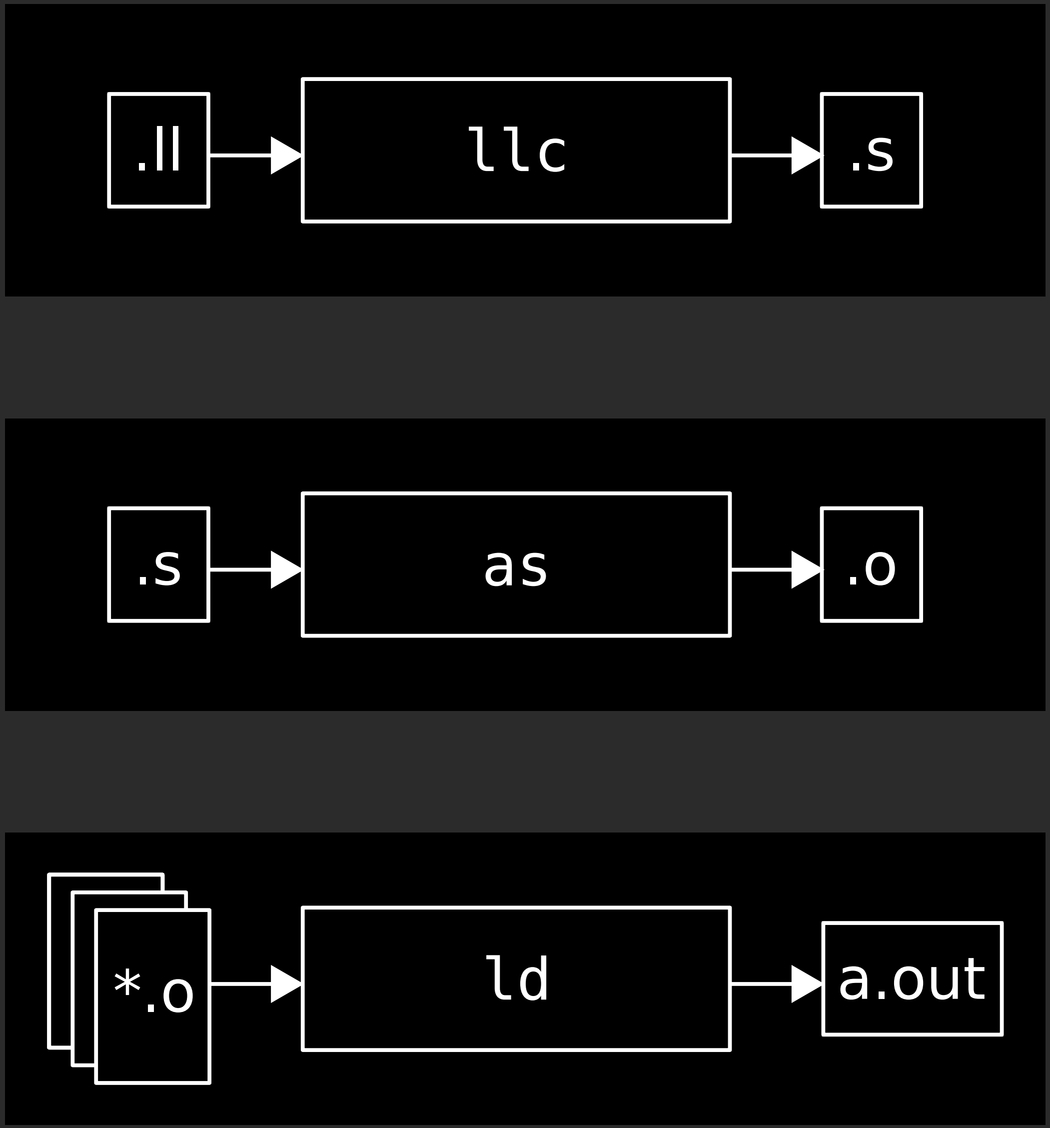
`rand_inrange` function and RNG impl

main.ll

Generated `main` function


linux-x86_64
print
_start
main
main
random
rand_inrange
rand_init

Code generation



```
llc linux-x86_64.ll
as -o linux-x86_64.o linux-x86_64.s

llc random.ll
as -o random.o random.s

llc main.ll
as -o main.o main.s

ld main.o linux-x86_64.o random.o
./a.out
```

Optimization

The generated code is inefficient!

- Less so if optimization is turned on
  - `llc -O2`
- Better: LTO
  - `llvm-link *.ll -o a.bc`
  - `llc -O2 a.bc`, etc

We can do better (but not right now)

More Rust

Using the runtime

```
let ty_void = LLVMVoidTypeInContext(ctxt);
let ty_i8 = LLVMIntTypeInContext(ctxt, 8);
let ty_i8p = LLVMPointerType(ty_i8, 0);

let param_types = [ty_i8p, ty_i8];
let ty_rt_print = LLVMFunctionType(
        ty_void,
        param_types.as_ptr() as *mut _,
        param_types.len(),
        0);

let rt_print = LLVMAddFunction(
        llmod,
        b"print\0".as_ptr() as *const _,
        ty_rt_print);
```

```
declare void print(i8*, i8)
```

Other functions left as an exercise for the reader.

Being wrong

`LLVMVoidType` ↔ `LLVMVoidTypeInContext`

Implicit global context ↔ explicit

- Mixing contexts is *wrong* and can cause miscompilation
- Tools to help prevent bugs?

Bug swatting

- `LLVMVerifyModule`
  - Print message or abort
- Debug assertions
  - `LLVM_ENABLE_ASSERTIONS`
  - Usually not enabled in binary releases
- Manual inspection
  - As done earlier

Filling in `main`

Parsing code

```
let code: Iterator<char>;

while let Some(c) = code.next() {
    match c {
        'm' => { /* Print "merth" */ },
        'e' => { /* Print newline */ },
        'r' => { /* Print space */ },
        't' => { /* Random string */ },
        'h' => { loop { match code.next() {
            Some('h') | None => break,
            _ => continue,
        } } },
        _ => { /* Do nothing */ },
    }
}
```

m is for merth

m → print("merth", 5)

```
let b: Builder;

let v_5i8 = LLVMConstInt(ty_i8, 5, 0);
let v_merth = LLVMBuildGlobalStringPtr(
        b,
        b"merth\0".as_ptr() as *const _,
        b"MERTH\0".as_ptr() as *const _);

LLVMBuildCall(b,
              rt_print,
              [v_merth, v_5i8].as_ptr() as *mut _,
              2,
              b"\0".as_ptr() as *const _);
```

e is for newline

e → print("\n", 1)

```
let v_newline = ptr_to_const(
        llmod,
        ty_i8,
        LLVMConstInt(ty_i8, 10, 0),
        b"NEWLINE\0");

LLVMBuildCall(b,
              rt_print,
              [v_newline, v_1i8].as_ptr() as *mut _,
              2,
              b"\0".as_ptr() as *const _);
```

ptr_to_const

```
fn ptr_to_const(llmod: LLVMModuleRef,
                ty: LLVMTypeRef,
                value: LLVMValueRef,
                name: &[u8])
                -> LLVMValueRef {

    let g = LLVMAddGlobal(llmod, ty, name.as_ptr() as *const _);
    LLVMSetInitializer(g, value);
    LLVMSetGlobalConstant(g, 1 /* true */);
    LLVMConstInBoundsGEP(g, [v_const_0i8].as_ptr() as *mut _, 0)
}
```

- Save a byte vs `GlobalStringPtr`
- GEP: GetElementPointer
  - Inbounds: must not be out of bounds

r is for space

This space intentionally left blank.

t is for randomness

- [0, 13.4) times [a-z]
- Runtime: `rand_inrange` + `rand_string`

```
let len = rand_inrange(13.4 as i8 + 1);
rand_string(len);
```

```
let v_len = LLVMBuildCall(
        b,
        rt_rand_inrange,
        [LLVMConstAdd(
             LLVMConstFPToUI(
                 LLVMConstReal(LLVMFloatTypeInContext(ctxt),
                               13.4),
                 ty_i8),
             v_1i8)
        ].as_ptr() as *mut _,
        1,
        b"\0".as_ptr() as *const _);

LLVMBuildCall(rt_rand_string, [v_len]);
```

FP is slow, do it all as const for speed.

Codegen & optimization

Load runtime

```
static RT_SOURCES: &'static [&'static [u8]] = &[
    include_bytes!("../runtime/random.ll")
];

let mbuf = LLVMCreateMemoryBufferWithMemoryRange(
        code.as_ptr() as *const _,
        code.len() - 1 as libc::size_t,
        b"\0".as_ptr() as *const _,
        /* RequiresNullTerminator */ 1);

let module: LLVMModuleRef;
let err_msg: *mut i8;
LLVMParseIRInContext(ctxt, mbuf, &mut module, &mut err_msg);
/* Error checking here */
```

Platform runtime

```
static RT_TARGET_SOURCE: phf::Map<
    &'static str,
    &'static [u8]
> = ...;
```

Use `phf` for excessively efficient lookup tables (built at compile-time)

```
let target = LLVMGetDefaultTargetTriple();
RT_TARGET_SOURCES.get(target);
```

Linking

```
let main_module: LLVMModuleRef;

for module in rt_modules {
    // Destroys module
    LLVMLinkModules2(main_module, module);
}
```

Easy as `llvm-link`

Codegen

```
let triple = "x86_64-unknown-linux";
let target: LLVMTargetRef;
LLVMGetTargetFromTriple(triple, &mut target, ptr::null_mut());

let tm = LLVMCreateTargetMachine(target,
                                 triple,
                                 "", "",
                                 LLVMCodeGenLevelAggressive,
                                 LLVMRelocDefault,
                                 LLVMCodeModelDefault);
```

Get a target, make a target machine

```
let mbuf: LLVMMemoryBufferRef;
LLVMTargetMachineEmitToMemoryBuffer(tm, llmod, ty,
                                    ptr::null_mut(),
                                    &mut mbuf);

let mut w: io::Write;
let code: &[u8] = slice::from_raw_parts(
        LLVMGetBufferStart(mbuf),
        LLVMGetBufferSize(mbuf)
);
w.write_all(code);

LLVMDisposeMemoryBuffer(mbuf);
```

Emit code to memory,
write to a file.

Not pictured: linker invocation
(as subprocess)

Optimization

```
let fpm = LLVMCreateFunctionPassManagerForModule(llmod);
let mpm = LLVMCreatePassManager();

let pmb = LLVMPassManagerBuilderCreate();
LLVMPassManagerBuilderSetOptLevel(pmb, 2);
LLVMPassManagerBuilderUseInlinerWithThreshold(pmb, 225);
LLVMPassManagerBuilderPopulateModulePassManager(pmb, mpm);
LLVMPassManagerBuilderPopulateFunctionPassManager(pmb, fpm);
LLVMPassManagerBuilderDispose(pmb);
```

Pass manager wrangles optimizer passes

Including: DCE, GVN, constant propagation, LICM, loop unrolling, inlining..

Running passes

```
LLVMInitializeFunctionPassManager(fpm);

let mut func = LLVMGetFirstFunction(llmod);
while func != ptr::null_mut() {
    LLVMRunFunctionPassManager(fpm, func);
    func = LLVMGetNextFunction(func);
}

LLVMFinalizeFunctionPassManager(fpm);
```

Iterate over functions, optimizing each

```
LLVMRunPassManager(mpm, llmod);
```

LTO

- Link modules together, then optimize
  - ..retaining external symbols
- Internalize symbols first

```
let mut func = LLVMGetFirstFunction(llmod);
while func != ptr::null_mut() {
    let func_name = CStr::from_ptr(LLVMGetValueName(func));
    if func_name != "_start" {
        LLVMSetLinkage(func, LLVMLinkage::LLVMPrivateLinkage);
    }

    func = LLVMGetNextFunction(func);
}
```

References & advertising

LLVM

- llvm.org

`llvm-sys`

- Rust $\rightarrow$ LLVM C library bindings
- crates.io:llvm-sys

Reference `merthc`

- bitbucket.org/tari/merthc

Me

- @PMarheine
- @tari

Incidental foxes

- きつねさんでもわかるＬＬＶＭ

Ferris the Rustacean

- Karen Rustad Tölva (public domain)

Ask me questions now.