Admin

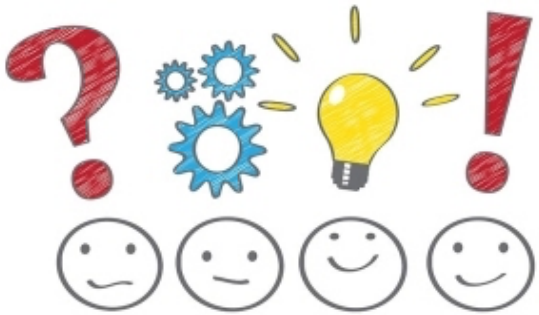
Weekly cycle: lectures → lab → assign

Lab release after Monday lecture

Pre-lab to prepare

Assign release after Wed lab

YEAH session Thursday 10:30am in Gates B02



Check in

Week 1: RISC-V assembly

Week 2: C control/pointers

Today: From Assembly to C

(and back again)

C language as "high-level" assembly

What does a compiler do?

Makefiles

RISC-V in a nutshell

RISC-V Instruction-Set

Erik Engheim <erik.engheim@ma.com>

Arithmetic Operation

Mnemonic	Instruction	Type	Description
ADD rd, rs1, rs2	Add	R	rd ← rs1 + rs2
SUB rd, rs1, rs2	Subtract	R	rd ← rs1 - rs2
ADDI rd, rs1, imm12	Add immediate	I	rd ← rs1 + imm12
SLT rd, rs1, rs2	Set less than	R	rd ← rs1 < rs2 ? 1 : 0
SLTI rd, rs1, imm12	Set less than immediate	I	rd ← rs1 < imm12 ? 1 : 0
SLTU rd, rs1, rs2	Set less than unsigned	R	rd ← rs1 < rs2 ? 1 : 0
SLTIU rd, rs1, imm12	Set less than immediate unsigned	I	rd ← rs1 < imm12 ? 1 : 0
LUI rd, imm20	Load upper immediate	U	rd ← imm20 << 12
AUIP rd, imm20	Add upper immediate to PC	U	rd ← PC + imm20 << 12

Logical Operations

Mnemonic	Instruction	Type	Description
AND rd, rs1, rs2	AND	R	rd ← rs1 & rs2
OR rd, rs1, rs2	OR	R	rd ← rs1 | rs2
XOR rd, rs1, rs2	XOR	R	rd ← rs1 ^ rs2
ANDI rd, rs1, imm12	AND immediate	I	rd ← rs1 & imm12
ORI rd, rs1, imm12	OR immediate	I	rd ← rs1 | imm12
XORI rd, rs1, imm12	XOR immediate	I	rd ← rs1 ^ imm12
SLL rd, rs1, rs2	Shift left logical	R	rd ← rs1 << rs2
SRL rd, rs1, rs2	Shift right logical	R	rd ← rs1 >> rs2
SRA rd, rs1, rs2	Shift right arithmetic	R	rd ← rs1 >> rs2
SLLI rd, rs1, shamt	Shift left logical immediate	I	rd ← rs1 << shamt
SRLI rd, rs1, shamt	Shift right logical imm.	I	rd ← rs1 >> shamt
SRAI rd, rs1, shamt	Shift right arithmetic immediate	I	rd ← rs1 >> shamt

Load / Store Operations

Mnemonic	Instruction	Type	Description
LD rd, imm12(rs1)	Load doubleword	I	rd ← mem[rs1 + imm12]
LW rd, imm12(rs1)	Load word	I	rd ← mem[rs1 + imm12]
LH rd, imm12(rs1)	Load halfword	I	rd ← mem[rs1 + imm12]
LB rd, imm12(rs1)	Load byte	I	rd ← mem[rs1 + imm12]
LWU rd, imm12(rs1)	Load word unsigned	I	rd ← mem[rs1 + imm12]
LHU rd, imm12(rs1)	Load halfword unsigned	I	rd ← mem[rs1 + imm12]
LBU rd, imm12(rs1)	Load byte unsigned	I	rd ← mem[rs1 + imm12]
SD rs2, imm12(rs1)	Store doubleword	S	rs2 → mem[rs1 + imm12]
SW rs2, imm12(rs1)	Store word	S	rs2(31:0) → mem[rs1 + imm12]
SH rs2, imm12(rs1)	Store halfword	S	rs2(15:0) → mem[rs1 + imm12]
SB rs2, imm12(rs1)	Store byte	S	rs2(7:0) → mem[rs1 + imm12]

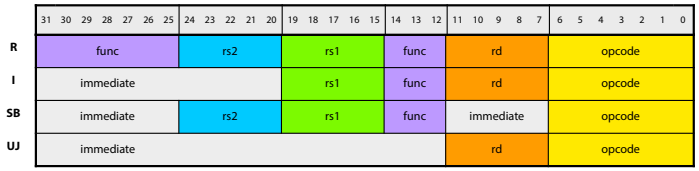
Branching

Mnemonic	Instruction	Type	Description
BEQ rs1, rs2, imm12	Branch equal	SB	if rs1 = rs2 pc ← pc + imm12
BNE rs1, rs2, imm12	Branch not equal	SB	if rs1 ≠ rs2 pc ← pc + imm12
BGE rs1, rs2, imm12	Branch greater than or equal	SB	if rs1 ≥ rs2 pc ← pc + imm12
BGEU rs1, rs2, imm12	Branch greater than or equal unsigned	SB	if rs1 >= rs2 pc ← pc + imm12
BLT rs1, rs2, imm12	Branch less than	SB	if rs1 < rs2 pc ← pc + imm12
BLTU rs1, rs2, imm12	Branch less than unsigned	SB	if rs1 < rs2 pc ← pc + imm12 << 1
JAL rd, imm20	Jump and link	UJ	rd ← pc + 4 pc ← pc + imm20
JALR rd, imm12(rs1)	Jump and link register	I	rd ← pc + 4 pc ← rs1 + imm12

Pseudo Instructions

Mnemonic	Instruction	Base instruction(s)
LI rd, imm12	Load immediate (near)	ADDI rd, zero, imm12
LI rd, imm	Load immediate (far)	LUI rd, imm[31:12] ADDI rd, rd, imm[11:0]
LA rd, sym	Load address (far)	AUIPC rd, sym[31:12] ADDI rd, rd, sym[11:0]
MV rd, rs	Copy register	ADDI rd, rs, 0
NOT rd, rs	One's complement	XORI rd, rs, -1
NEG rd, rs	Two's complement	SUB rd, zero, rs
BGT rs1, rs2, offset	Branch if rs1 > rs2	BLT rs2, rs1, offset
BLE rs1, rs2, offset	Branch if rs1 ≤ rs2	BGE rs2, rs1, offset
BGTU rs1, rs2, offset	Branch if rs1 > rs2 (unsigned)	BLTU rs2, rs1, offset
BLEU rs1, rs2, offset	Branch if rs1 ≤ rs2 (unsigned)	BGEU rs2, rs1, offset
BEQZ rs1, offset	Branch if rs1 = 0	BEQ rs1, zero, offset
BNEZ rs1, offset	Branch if rs1 ≠ 0	BNE rs1, zero, offset
BGEZ rs1, offset	Branch if rs1 ≥ 0	BGE rs1, zero, offset
BLEZ rs1, offset	Branch if rs1 ≤ 0	BGE zero, rs1, offset
BGTZ rs1, offset	Branch if rs1 > 0	BLT zero, rs1, offset
J offset	Unconditional jump	JAL zero, offset
CALL offset12	Call subroutine (near)	JALR ra, ra, offset12
CALL offset	Call subroutine (far)	AUIPC ra, offset[31:12] JALR ra, ra, offset[11:0]
RET	Return from subroutine	JALR zero, 0(ra)
NOP	No operation	ADDI zero, zero, 0

32-bit instruction format



Register File

r0	r1	r2	r3
r4	r5	r6	r7
r8	r9	r10	r11
r12	r13	r14	r15
r16	r17	r18	r19
r20	r21	r22	r23
r24	r25	r26	r27
r28	r29	r30	r31

Register Aliases

zero	ra	sp	gp
tp	t0	t1	t2
s0/fp	s1	a0	a1
a2	a3	a4	a5
a6	a7	s2	s3
s4	s5	s6	s7
s8	s9	s10	s11
t3	t4	t5	t6

ra - return address
sp - stack pointer
gp - global pointer
tp - thread pointer

t0 - t6 - Temporary registers
s0 - s11 - Saved by callee
a0 - 17 - Function arguments
a0 - a1 - Return value(s)

ISA design is an art form!

As much about what is **omitted** as what is **included**

Reduce/simplify: Eliminate redundancies, registers all general-purpose, memory access only through load/store, single addressing mode

Abstraction: Isolate architecture from implementation, no delay slots branch/load, no condition codes

Regularity: all instructions 4-bytes (2-byte compressed extension), same placement of bits in encoding for ease of decode, common data paths

Modular, **extensible:** tiny base ISA, optional additions design to be orthogonal, room for growth

Data-informed design: learn from past, decisions backed by "receipts"

Why assembly?

What you see is what you get

No surprises

Precise control, timing

Unfettered access to hardware

***But**... tedious, hard to read, hardware-specific, difficult to port*

Why C?

More concise

Easier to read

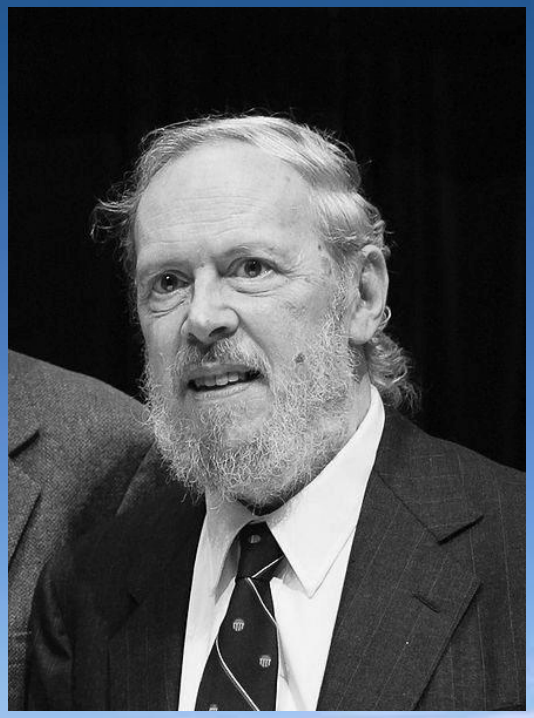
Names for variables and data types

Type-checking

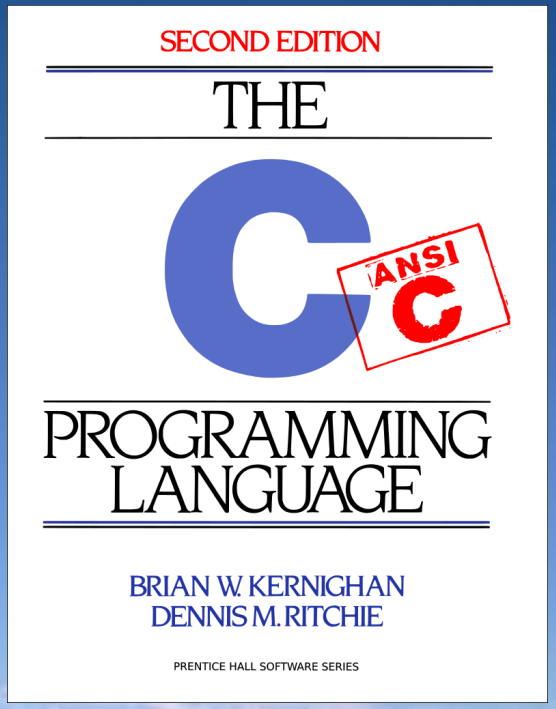
Portable, architecture-neutral

Higher-level abstractions (functions, user-defined types)

*Real question is not whether to use assembly, but **when**...*



Dennis Ritchie



C is language of choice for systems

Ken Thompson built UNIX using C

This is not coincidence!

C features closely model the ISA: data types, arithmetic/logical operators, control flow, access to memory, ... all provided in form of portable abstractions

"BCPL, B, and C family of languages are particularly oriented towards system programming, are small and compactly described, and are amenable to translation by simple compilers. They are "close to the machine" in that the abstractions they introduce are readily grounded in the concrete data types and operations supplied by conventional computers, and they rely on library routines for input-output and other interactions with an operating system. … At the same time, their abstractions lie at a sufficiently high level that, with care, portability between machines can be achieved."
— *Dennis Ritchie*

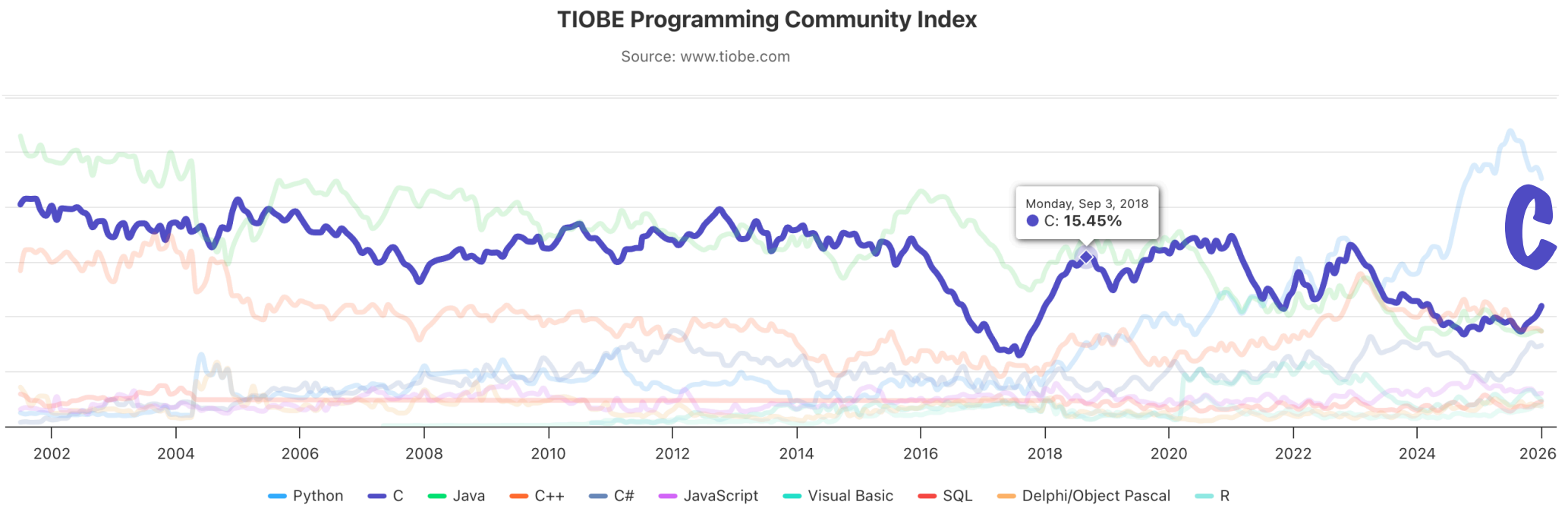
The C Programming Language

"C is quirky, flawed, and an enormous success"
— *Dennis Ritchie*

"C gives the programmer what the programmer wants; few restrictions, few complaints"
— *Herbert Schildt*

"C: A language that combines all the elegance and power of assembly language with all the readability and maintainability of assembly language"
— *Unknown*

Language popularity over time



Know your tools: assembler

The *assembler* reads assembly instructions (text) and outputs as machine-code (binary). This translation is mechanical and fully deterministic.

```
$ riscv64-unknown-elf-as blink.s -o blink.o
$ riscv64-unknown-elf-objcopy blink.o -O binary blink.bin
$ hexdump -C blink.bin
37 05 00 02 93 05 10 00  ...
```

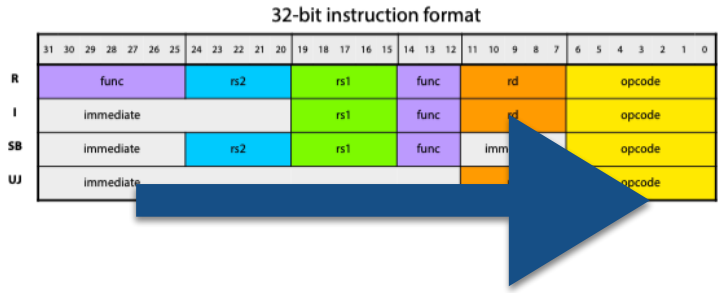
```
    lui     a0,0x2000
    addi    a1,zero,1
    sw      a1,0x30(a0)

loop:
    xori    a1,a1,1
    sw      a1,0x40(a0)

    lui     a2,0x3f00
delay:
    addi    a2,a2,-1
    bne     a2,zero,delay

    j       loop
```

blink.s




```
37 05 00 02 93 05 10 00
23 28 b5 02 93 c5 15 00
23 20 b5 04 37 06 f0 03
13 06 f6 ff e3 1e 06 fe
6f f0 df fe
```

blink.bin

Know your tools: **compiler**

The *compiler* reads C source (text) and translates to assembly instructions (assembler used to convert to binary from there)

```
int sum(int a, int b) {
    return a + b;
}
```

```
sum:
    addw    a0,a0,a1
    ret
```

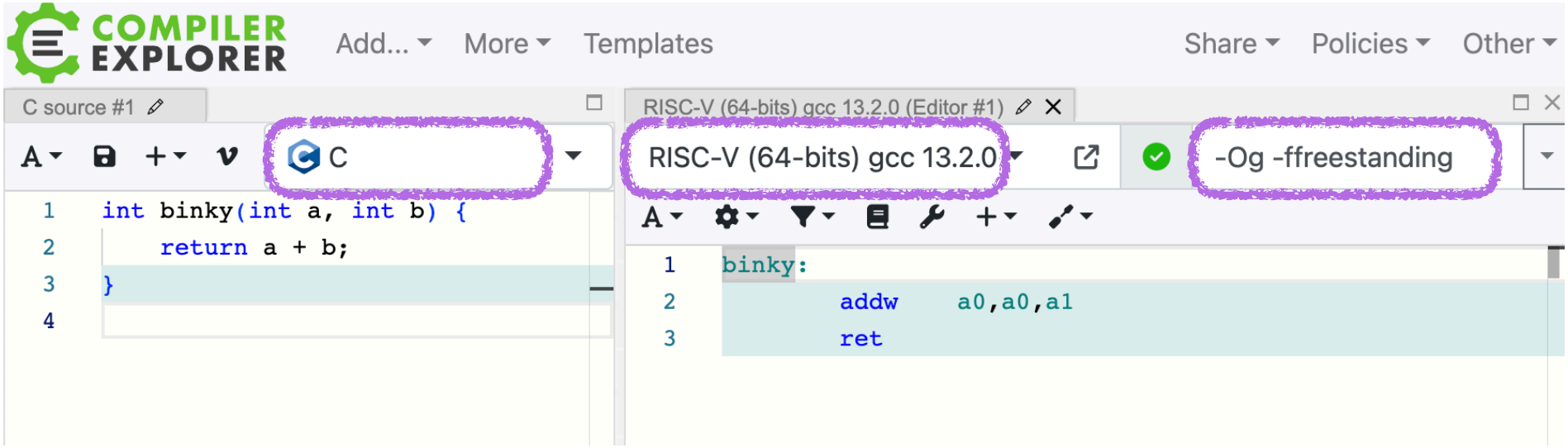
Tokenize → Parse → Semantic analysis → Code generation

This translation is complex, high artistry

Compiler Explorer

Neat interactive translation from C to assembly

Follow along as we try it now!



https://godbolt.org

Configure settings to follow along:

C

RISC-V (64 bits) gcc 13.2

-Og -ffreestanding

Major props to the C compiler

Higher-level abstractions, structured programming

- Named variables, constants
- Arithmetic/logical operators
- Control flow

Portable

- Not tied to particular ISA or architecture

Low-level enough to get to machine when needed

- Bitwise operations
- Direct access to memory
- Embedded assembly, too!

Compile-time vs. runtime

Compile-time: compiler running on your laptop

- read C source text, parse/check semantically valid
- analyze code to understand structure/intent
- generate assembly instructions, assembler to binary

Runtime: program binary running on Pi

- load machine instructions to memory
- fetch/decode/execute

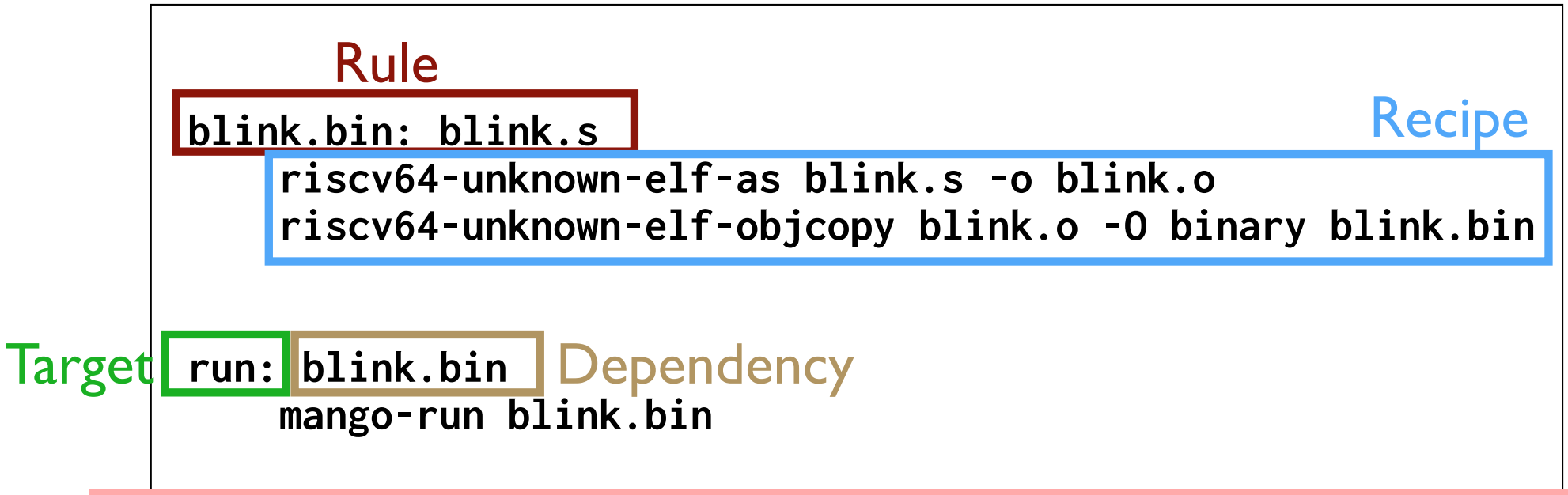
Optimizer does work at CT to streamline count of instructions to be executed at RT

Make

One-step build process using **make**

Makefile is text file that describes build steps as "recipes"

Dependencies determine which steps needed to re-build



Writing explicit recipes for every file is onerous,
Use **make** match by pattern to create general rules

Make pattern rules

```
NAME    = myprogram

ARCH    = -march=rv64im -mabi=lp64
CFLAGS  = $(ARCH) -g -Og -Wall -ffreestanding
LDFLAGS = $(ARCH) -nostdlib

all: $(NAME).bin

%.bin: %.elf
        riscv64-unknown-elf-objcopy $< -O binary $@

%.elf: %.o
        riscv64-unknown-elf-ld $(LDFLAGS) $< -o $@

%.o: %.c
        riscv64-unknown-elf-gcc $(CFLAGS) -c $< -o $@
```

Bare-metal vs. Hosted

Default build process for C assumes a **hosted** environment.

What does a hosted system have that we don't?

- standard libraries
- standard start-up sequence
- OS services

To build bare-metal, our Makefile disables these defaults
We supply our own replacements where needed

Build settings for bare-metal

Compile freestanding

```
CFLAGS = -ffreestanding
```

Link excludes standard library and start files

```
LDFLAGS = -nostdlib
```

Write our own code for all libs and start files

This puts us in an exclusive club…

```
int getRandomNumber()
{
    return 4;  // chosen by fair dice roll.
               // guaranteed to be random.
}
```