

Intermediate Code Generation

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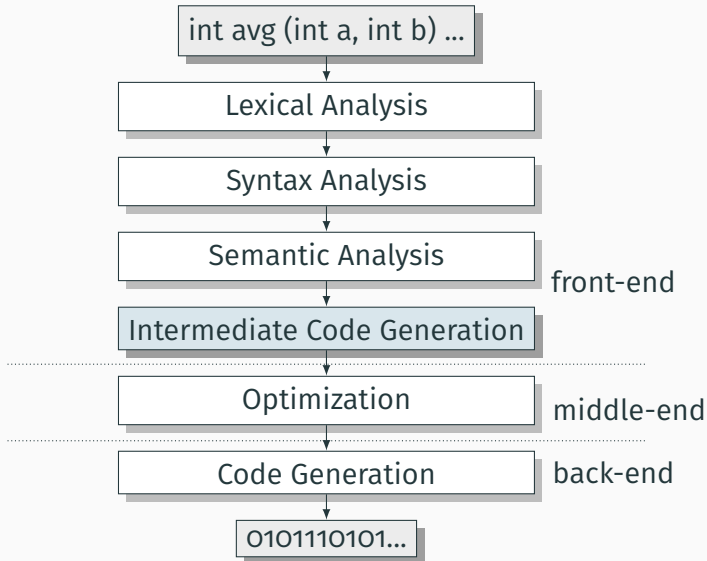
Spring 2019

Columbia University

* Course website: <https://www.cs.columbia.edu/~rgu/courses/4115/spring2019>

** These slides are borrowed from Prof. Edwards.

Intermediate Code Generation



Intermediate Representation (IR):

- An abstract machine language
- Not specific to any particular machine
- Independent of source language

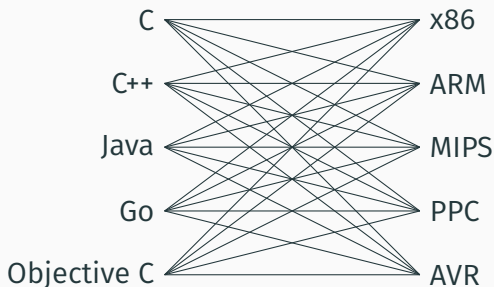
IR code generation is not necessary:

- Semantic analysis phase can generate assembly code directly.
- Hinders portability and modularity.

Intermediate Representation

Suppose we wish to build compilers for n source languages and m target machines.

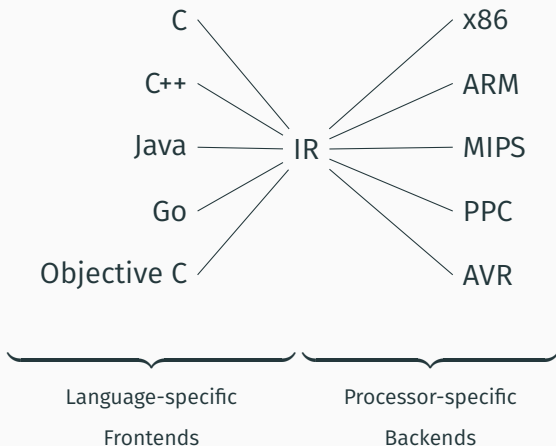
Case 1: no IR. Need $n \times m$ compilers.



Intermediate Representation

Suppose we wish to build compilers for n source languages and m target machines.

Case 2: IR present. Need just n front-ends and m back ends.



- Must be convenient for semantic analysis phase to produce.
- Must be convenient to translate into real assembly code for all desired target machines.

Intermediate Representations/Formats

Stack-Based IR: Java Bytecode

```
int gcd(int a, int b) {  
    while (a != b) {  
        if (a > b)  
            a -= b;  
        else  
            b -= a;  
    }  
    return a;  
}
```

Method int gcd(int, int)

0 goto 19

3 iload_1 // Push a

4 iload_2 // Push b

5 if_icmple 15 // if a <= b goto 15

8 iload_1 // Push a

9 iload_2 // Push b

10 isub // a - b

11 istore_1 // Store new a

12 goto 19

15 iload_2 // Push b

16 iload_1 // Push a

17 isub // b - a

18 istore_2 // Store new b

19 iload_1 // Push a

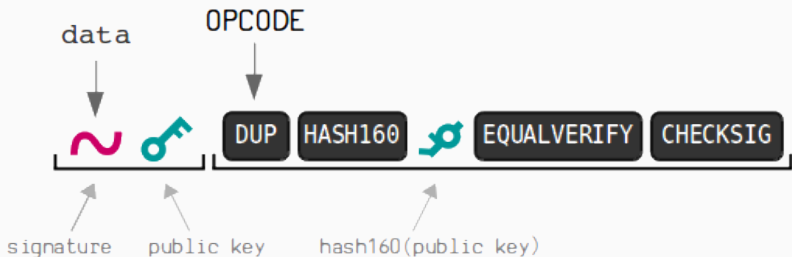
20 iload_2 // Push b

21 if_icmpne 3 // if a != b goto 3

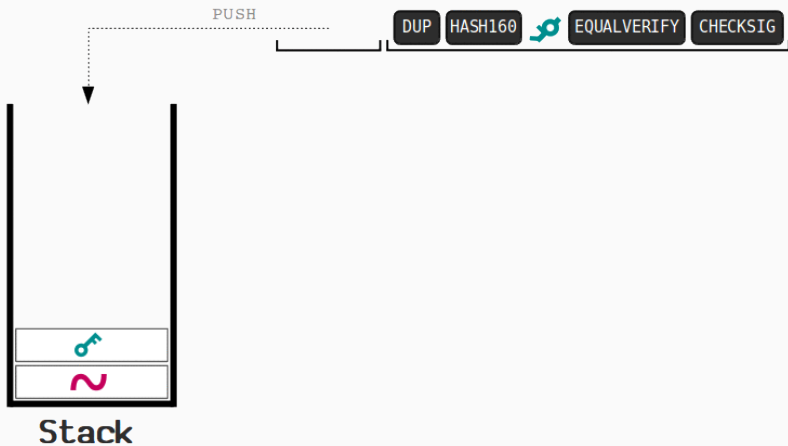
24 iload_1 // Push a

25 ireturn // Return a

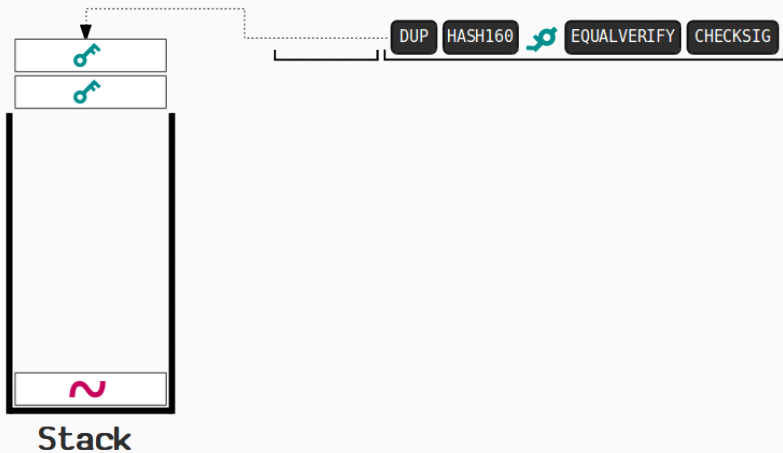
Stack-Based IR: Bitcoin Script



Stack-Based IR: Bitcoin Script



Stack-Based IR: Bitcoin Script



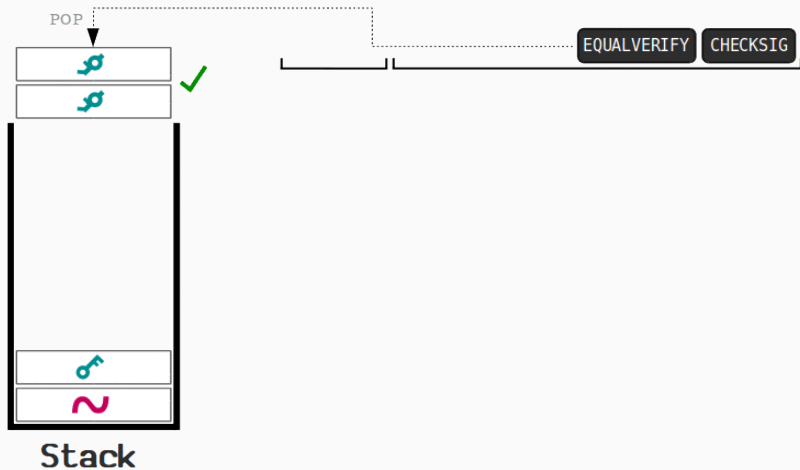
Stack-Based IR: Bitcoin Script



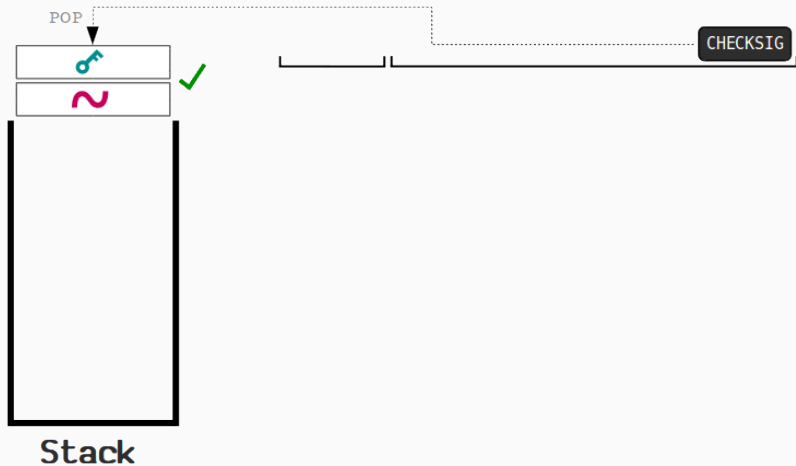
Stack-Based IR: Bitcoin Script



Stack-Based IR: Bitcoin Script



Stack-Based IR: Bitcoin Script



Stack-Based IRs

Advantages:

- Trivial translation of expressions
- Trivial interpreters
- No problems with exhausting registers
- Often compact

Disadvantages:

- Semantic gap between stack operations and modern register machines
- Hard to see what communicates with what
- Difficult representation for optimization

Register-Based IR: Mach SUIF

```
int gcd(int a, int b)
{
    while (a != b) {
        if (a > b)
            a -= b;
        else
            b -= a;
    }
    return a;
}
```

```
gcd:
gcd._gcdTmp0:
    sne $vr1.s32 <- gcd.a,gcd.b
    seq $vr0.s32 <- $vr1.s32,0
    btrue $vr0.s32,gcd._gcdTmp1 // if !(a != b) goto Tmp1

    sl $vr3.s32 <- gcd.b,gcd.a
    seq $vr2.s32 <- $vr3.s32,0
    btrue $vr2.s32,gcd._gcdTmp4 // if !(a < b) goto Tmp4

    mrk 2, 4 // Line number 4
    sub $vr4.s32 <- gcd.a,gcd.b
    mov gcd._gcdTmp2 <- $vr4.s32
    mov gcd.a <- gcd._gcdTmp2 // a = a - b
    jmp gcd._gcdTmp5
gcd._gcdTmp4:
    mrk 2, 6
    sub $vr5.s32 <- gcd.b,gcd.a
    mov gcd._gcdTmp3 <- $vr5.s32
    mov gcd.b <- gcd._gcdTmp3 // b = b - a
gcd._gcdTmp5:
    jmp gcd._gcdTmp0

gcd._gcdTmp1:
    mrk 2, 8
    ret gcd.a // Return a
```

Register-Based IRs

Most common type of IR

Advantages:

- Better representation for register machines
- Dataflow is usually clear

Disadvantages:

- Slightly harder to synthesize from code
- Less compact
- More complicated to interpret

Three-Address Code & Static Single Assignment

Most register-based IRs use **three-address code**:

Arithmetic instructions have (up to) three operands: two sources and one destination.

SSA Form: each variable in an IR is assigned exactly once

C code:

```
int gcd(int a, int b)
{
    while (a != b)
        if (a < b)
            b -= a;
        else
            a -= b;
    return a;
}
```

Three-Address:

```
WHILE: t = sne a, b
      bz DONE, t
      t = slt a, b
      bz ELSE, t
      b = sub b, a
      jmp LOOP
ELSE:  a = sub a, b
LOOP: jmp WHILE
DONE: ret a
```

SSA:

```
WHILE: t1 = sne a1, b1
      bz DONE, t1
      t2 = slt a1, b1
      bz ELSE, t2
      b1 = sub b1, a1
      jmp LOOP
ELSE:  a1 = sub a1, b1
LOOP:  jmp WHILE
DONE:  ret a1
```

Three-Address Code

What is an “Address” in Three-Address Code?

- **Name:** (from the source program) e.g., x, y, z
- **Constant:** (with explicit primitive type) e.g., 1, 2, 'a'
- **Compiler-generated temporary:** (“register”) e.g., t1, t2, t3

Instructions of Three-Address Code

- $x = \text{op } y, z$: where op is a binary operation
- $x = \text{op } y$: where op is a unary operation
- $x = y$: copy operation
- $\text{jmp } L$: unconditional jump to label L
- $\text{bz } L, x$: jump to L if x is zero
- $\text{bnz } L, x$: jump to L if x is not zero
- $\text{param } x, \text{call } L, y, \text{return } z$: function calls

Three-Address Code (TAC) Generation

Goal: take statements (AST) and produce a sequence of TAC.

Example:

`a := b + c * d;`

TAC:

`t1 = mul c, d`

`t2 = add b, t1`

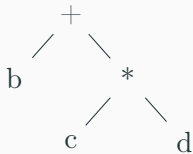
`a = t1`

Translate **expressions** and **statements**

Translating Expressions

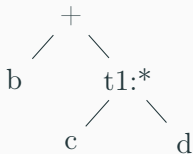
Example

b + c * d



Example

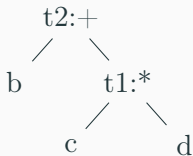
`b + c * d`



`t1 = mul c, d`

Example

`b + c * d`



`t1 = mul c, d`
`t2 = add b, t1`

Algorithm: Syntax-Directed Translation (SDT)

For each expression E , we'll synthesize two attributes:

- $E.addr$: the name of the variable (often a temporary variable)
- $E.code$: the IR instructions generated from E

SDT: each semantic rule corresponds to actions computing two attributes with the following auxiliary functions:

- Call **NewTemp** to create a new temporary variable
- Call **Gen**: to print a new three-address instruction
$$\text{Gen}(t, "=", op, x, ",", y) \Rightarrow "t = op\ x, y"$$

Syntax-Directed Translation (SDT)

CFG rule: $E_0 \rightarrow \mathbf{id}$

Actions:

$E_0.\text{addr} := \mathbf{id}$

$E_0.\text{code} := ""$ empty string

We do not consider scopes here.

Example: $E_0 = \text{ID}(\text{"a"})$

$E_0.\text{addr} := \text{"a"}$

$E_0.\text{code} := ""$ empty string

Syntax-Directed Translation (SDT)

CFG rule: $E_0 \rightarrow E_1 + E_2$

Actions:

$E_0.addr := \text{NewTemp}()$

$E_0.code := E_1.code \parallel E_2.code \parallel$

$\text{Gen}(E_0.addr, "=", "add", E_1.addr, ",", E_2.addr)$

Example: $a + b$

$E_0 = \text{PLUS}(E_1, E_2) \quad E_1 = \text{ID}("a") \quad E_2 = \text{ID}("b")$

$E_1.addr := "a" \quad E_1.code := ""$

$E_2.addr := "b" \quad E_2.code := ""$

$E_0.addr := "t1"$

$E_0.code := "t1 = add a, b"$

Syntax-Directed Translation (SDT)

Example: $b + c * d$

$$E_0 = \text{PLUS}(E_1, E_2) \quad E_1 = \text{ID}(\text{"b"})$$
$$E_2 = \text{MUL}(\text{ID}(\text{"c"}), \text{ID}(\text{"d"}))$$
$$E_0.\text{code} := E_1.\text{code} \parallel E_2.\text{code} \parallel$$
$$\text{Gen}(E_0.\text{addr}, "=", \text{"add"}, E_1.\text{addr}, ",", E_2.\text{addr})$$

Syntax-Directed Translation (SDT)

Example: $b + c * d$

$$E_0 = \text{PLUS}(E_1, E_2) \quad E_1 = \text{ID}(\text{"b"})$$
$$E_2 = \text{MUL}(\text{ID}(\text{"c"}), \text{ID}(\text{"d"}))$$
$$E_0.\text{code} := E_1.\text{code} \parallel E_2.\text{code} \parallel$$
$$\text{Gen}(E_0.\text{addr}, "=", \text{"add"}, E_1.\text{addr}, ",", E_2.\text{addr})$$

Syntax-Directed Translation (SDT)

Example: $b + c * d$

$E_0 = \text{PLUS}(E_1, E_2) \quad E_1 = \text{ID}(\text{"b"})$

$E_2 = \text{MUL}(\text{ID}(\text{"c"}), \text{ID}(\text{"d"}))$

$E_0.\text{code} := "" \parallel E_2.\text{code} \parallel$

$\text{Gen}(E_0.\text{addr}, "=", \text{"add"}, E_1.\text{addr}, ",", E_2.\text{addr})$

$E_1.\text{addr} = \text{"b"}$

Syntax-Directed Translation (SDT)

Example: $b + c * d$

$E_0 = \text{PLUS}(E_1, E_2) \quad E_1 = \text{ID}(\text{"b"})$

$E_2 = \text{MUL}(\text{ID}(\text{"c"}), \text{ID}(\text{"d"}))$

$E_0.\text{code} := \text{""} \parallel \text{"t1 = mul c, d"} \parallel$

$\text{Gen}(E_0.\text{addr}, \text{"="}, \text{"add"}, E_1.\text{addr}, \text{","}, E_2.\text{addr})$

$E_1.\text{addr} = \text{"b"} \quad E_2.\text{addr} = \text{"t1"}$

Syntax-Directed Translation (SDT)

Example: $b + c * d$

$E_0 = \text{PLUS}(E_1, E_2) \quad E_1 = \text{ID}(\text{"b"})$

$E_2 = \text{MUL}(\text{ID}(\text{"c"}), \text{ID}(\text{"d"}))$

$E_0.\text{code} := \text{""} \parallel \text{"t1 = mul c, d"} \parallel$

$\text{Gen}(\text{NewTemp}(), \text{"="}, \text{"add"}, E_1.\text{addr}, \text{","}, E_2.\text{addr})$

$E_1.\text{addr} = \text{"b"} \quad E_2.\text{addr} = \text{"t1"}$

Syntax-Directed Translation (SDT)

Example: $b + c * d$

$E_0 = \text{PLUS}(E_1, E_2) \quad E_1 = \text{ID}(\text{"b"})$

$E_2 = \text{MUL}(\text{ID}(\text{"c"}), \text{ID}(\text{"d"}))$

$E_0.\text{code} := \text{""} \parallel \text{"t1 = mul c, d"} \parallel$

$\text{Gen}(\text{"t2"}, \text{"="}, \text{"add"}, E_1.\text{addr}, \text{","}, E_2.\text{addr})$

$E_1.\text{addr} = \text{"b"} \quad E_2.\text{addr} = \text{"t1"}$

Syntax-Directed Translation (SDT)

Example: $b + c * d$

$$E_0 = \text{PLUS}(E_1, E_2) \quad E_1 = \text{ID}("b")$$
$$E_2 = \text{MUL}(\text{ID}("c"), \text{ID}("d"))$$
$$E_0.\text{code} := "" \parallel "t1 = \text{mul } c, d" \parallel$$
$$\text{Gen}("t2", "=", "add", "b", ",", "t1")$$

Syntax-Directed Translation (SDT)

Example: $b + c * d$

$$E_0 = \text{PLUS}(E_1, E_2) \quad E_1 = \text{ID}(\text{"b"})$$
$$E_2 = \text{MUL}(\text{ID}(\text{"c"}), \text{ID}(\text{"d"}))$$
$$E_0.\text{code} := \text{""} \parallel \text{"t1 = mul c, d"} \parallel \\ \text{"t2 = add b, t1"}$$

Translating Statements

Assignment

CFG rule: $S \rightarrow \mathbf{id} := E$

Actions:

$S.\text{code} := E.\text{code} \parallel \text{Gen}(\mathbf{id}, "=", E.\text{addr})$

Example: $a := b + c$

$S = \text{ASG}(\text{ID}("a"), E) \quad E = \text{PLUS}(\text{ID}("b"), \text{ID}("c"))$

$E.\text{code} := "t1 = \text{add } b, c" \quad E.\text{addr} := "t1"$

$S.\text{code} := "t1 = \text{add } b, c" \parallel "a = t1"$

IF Statement

AST: $\text{IF}(E, S)$

Generated IR:

$E.\text{code}$

bz Label_End , $E.\text{addr}$

$S.\text{code}$

Label_End :

Example: $\text{if } (a > b) \{ a -= b \}$

$t1 = \text{slt } a, b$

bz Label_End , $t1$

$a = \text{sub } a, b$

Label_End :

IF-ELSE Statement

AST: IFELSE(E, S_1, S_2)

Generated IR:

```
 $E$ .code  
bz Label_Else,  $E$ .addr  
 $S_1$ .code  
jmp Label_End  
Label_Else:  
 $S_2$ .code  
Label_End:
```

IF-ELSE Statement

Example: `if (a > b) { a -= b } { b -= a }`

```
t1 = slt a, b
```

```
bz Label_Else, t1
```

```
a = sub a, b
```

```
jmp Label_End
```

```
Label_Else:
```

```
b = sub b, a
```

```
Label_End:
```

Loop

AST: WHILE(E , S)

Generated IR:

Label_While:

$E.code$

bz Label_End, $E.addr$

$S.code$

jmp Label_While

Label_End:

Function Calls

$f(E_1, \dots, E_n)$

Generated IR:

$E_n.code$

$E_{n-1}.code$

...

$E_1.code$

param $E_n.addr$

...

param $E_1.addr$

call f, n

Function Calls

$f(E_1, \dots, E_n)$

Generated IR:

E_n .code

E_{n-1} .code

...

E_1 .code

param E_n .addr how to pass parameters?

...

param E_1 .addr

call f, n

And One More Thing...

`int x;` where is this x stored? what is x.addr?

`int main () {`

`x = 4;`

`int y;` where is this y stored? what is y.addr?

`...`

`}`

Basic Blocks

A **Basic Block** is a sequence of IR instructions with two properties:

1. The first instruction is the only entry point
(no other branches in; can only start at the beginning)
2. Only the last instruction may affect control
(no other branches out)

∴ If any instruction in a basic block runs, they all do

Typically “arithmetic and memory instructions, then branch”

```
ENTER:  t2 = add t1, 1  
        t3 = slt t2, 10  
        bz  NEXT, t3
```


Basic Blocks and Control-Flow Graphs

```
WHILE:  t1 = sne a1, b1  ◀  
        bz DONE, t1  
        t2 = slt a1, b1  ◀  
        bz ELSE, t2  
        b1 = sub b1, a1  ◀  
        jmp LOOP  
ELSE:   a1 = sub a1, b1  ◀  
LOOP:   jmp WHILE       ◀  
DONE:   ret a1          ◀
```

- Leaders: branch targets & after conditional branch

Basic Blocks and Control-Flow Graphs

WHILE:	<code>t1 = sne a1, b1</code>	◀
	<code>bz DONE, t1</code>	
	<hr/>	
	<code>t2 = slt a1, b1</code>	◀
	<code>bz ELSE, t2</code>	
	<hr/>	
	<code>b1 = sub b1, a1</code>	◀
	<code>jmp LOOP</code>	
	<hr/>	
ELSE:	<code>a1 = sub a1, b1</code>	◀
	<hr/>	
LOOP:	<code>jmp WHILE</code>	◀
	<hr/>	
DONE:	<code>ret a1</code>	◀

- Leaders: branch targets & after conditional branch
- Basic blocks: start at a leader; end before next

Basic Blocks and Control-Flow Graphs

WHILE: `t1 = sne a1, b1` ◀

`bz DONE, t1`

`t2 = slt a1, b1` ◀

`bz ELSE, t2`

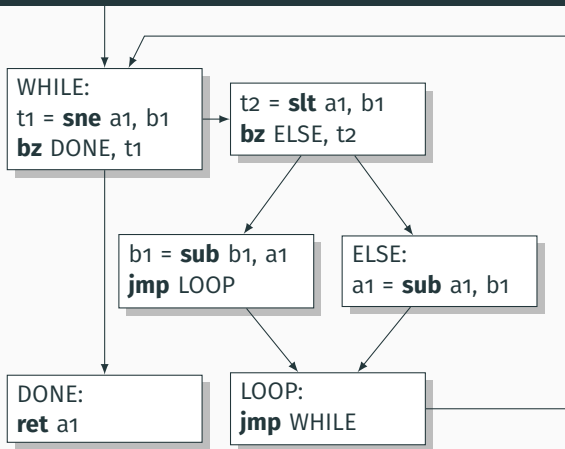
`b1 = sub b1, a1` ◀

`jmp LOOP`

ELSE: `a1 = sub a1, b1` ◀

LOOP: `jmp WHILE` ◀

DONE: `ret a1` ◀



- Leaders: branch targets & after conditional branch
- Basic blocks: start at a leader; end before next
- Basic Blocks are nodes of the Control-Flow Graph

The LLVM IR

Three-address code instructions; Static single-assignment;
Explicit control-flow graph; Local names start with %;
Types throughout; User-defined functions

```
int add(int x, int y)
{
    return x + y;
}
```

```
define i32 @add(i32 %x, i32 %y) {
entry:
    %x1 = alloca i32
    store i32 %x, i32* %x1
    %y2 = alloca i32
    store i32 %y, i32* %y2
    %x3 = load i32* %x1
    %y4 = load i32* %y2
    %tmp = add i32 %x3, %y4
    ret i32 %tmp
}
```

i32: 32-bit signed integer type

alloca: Allocate space on the stack; return a pointer

store: Write a value to an address

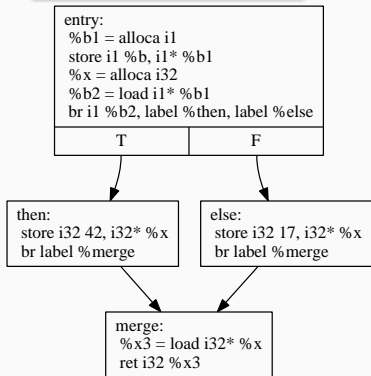
load: Read a value from an address

add: Add two values to produce a third

ret: Return a value to the caller

Basic Blocks

```
int cond(bool b) {  
    int x;  
    if (b) x = 42;  
    else   x = 17;  
    return x;  
}
```



CFG for 'cond' function

```
define i32 @cond(i1 %b) {  
entry:  
    %b1 = alloca i1  
    store i1 %b, i1* %b1  
    %x = alloca i32  
    %b2 = load i1* %b1  
    br i1 %b2, label %then, label %else
```

```
merge:        ; preds = %else, %then  
    %x3 = load i32* %x  
    ret i32 %x3
```

```
then:         ; preds = %entry  
    store i32 42, i32* %x  
    br label %merge
```

```
else:         ; preds = %entry  
    store i32 17, i32* %x  
    br label %merge  
}
```

```

int gcd(int a, int b) {
    while (a != b)
        if (a > b) a = a - b;
        else b = b - a;
    return a;
}

```

```

define i32 @gcd(i32 %a, i32 %b) {
entry:
    %a1 = alloca i32
    store i32 %a, i32* %a1
    %b2 = alloca i32
    store i32 %b, i32* %b2
    br label %while

while:                                ; preds = %merge, %entry
    %a11 = load i32* %a1
    %b12 = load i32* %b2
    %tmp13 = icmp ne i32 %a11, %b12
    br i1 %tmp13, label %while_body, label %merge14

while_body:                          ; preds = %while
    %a3 = load i32* %a1
    %b4 = load i32* %b2
    %tmp = icmp sgt i32 %a3, %b4
    br i1 %tmp, label %then, label %else

merge:                               ; preds = %else, %then
    br label %while

then:                                ; preds = %while_body
    %a5 = load i32* %a1
    %b6 = load i32* %b2
    %tmp7 = sub i32 %a5, %b6
    store i32 %tmp7, i32* %a1
    br label %merge

else:                                ; preds = %while_body
    %b8 = load i32* %b2
    %a9 = load i32* %a1
    %tmp10 = sub i32 %b8, %a9
    store i32 %tmp10, i32* %b2
    br label %merge

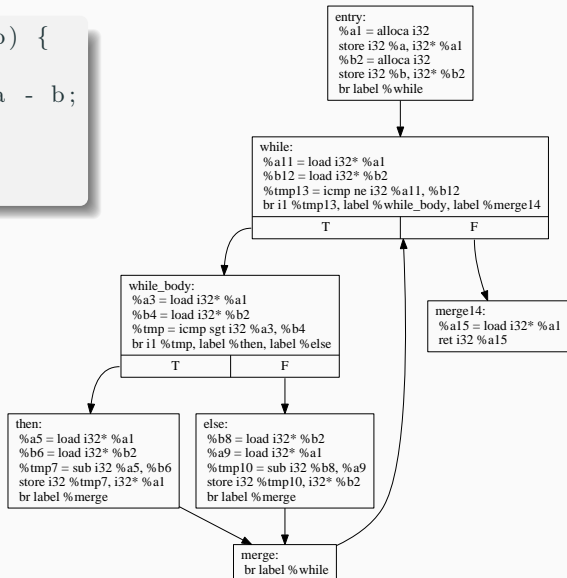
merge14:                             ; preds = %while
    %a15 = load i32* %a1
    ret i32 %a15
}

```

```

int gcd(int a, int b) {
    while (a != b)
        if (a > b) a = a - b;
        else b = b - a;
    return a;
}

```



CFG for 'gcd' function