Programming Language (10)
Making a compiler

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Contents

Contents

From high-level programming languages to machine code

- there are *no structured control flows* (for, while, if, etc.); everything must be done by (conditional) jump instructions ($\approx$ "goto" statement)
- an instruction can perform *only a single operation*, so nested expressions (e.g., `a * x + b * y + c * z`) must be broken down into a series of instructions
- a register $\approx$ a variable, but
  - you have *only a fixed number of them*, so some values may have to be spilled on memory (esp. at function calls)
  - function parameters and return values are on predetermined registers (*calling convention* or *Application Binary Interface*)

Code generation by hand — introspecting "human compiler"

- ex: how to convert the following (which finds $\sqrt{c}$ by the Newton method) into machine language

```
1  double sq(double c, long n) {
2    double x = c;
3    for (long i = 0; i < n; i++) {
4      x = x / 2 + c / (x + x);
5    }
6    return x;
7  }
```

Step 1 — make all controls “goto”s

```
1  double sq(double c, long n) {
2    double x = c;
3    for (long i = 0; i < n; i++) {
4      x = x / 2 + c / (x + x);
5    }
6    return x;
7  }
```

⇒

```
1  double sq(double c, long n) {
2    double x = c;
3    long i = 0;
4    if (i >= n) goto Lend;
5  Lstart:
6    x = x / 2 + c / (2 * x);
7    i++;
8    if (i < n) goto Lstart;
9  Lend:
10   return x;
11 }
```

Step 2 — flatten all nested expressions to "C = A op B"

```
1  double sq(double c, long n) {
2    double x = c;
3    long i = 0;
4    if (i >= n) goto Lend;
5  Lstart:
6    x = x / 2 + c / (2 * x);
7    i++;
8    if (i < n) goto Lstart;
9  Lend:
10   return x;
11 }
```

⇒

```
1  double sq3(double c, long n) {
2    double x = c;
3    long i = 0;
4    if (!(i < n)) goto Lend;
5  Lstart:
6    double t0 = 2;
7    double t1 = x / t0;
8    double t2 = t0 * x;
9    double t3 = c / t2;
10   x = t1 + t3;
11   i = i + 1;
12   if (i < n) goto Lstart;
13 Lend:
14   return x;
15 }
```

Step 3 —assign "machine variables" (registers or memory) to variables

- note: cannot write floating point constants in instructions

```
1  /* c : xmm0, n : rdi */
2  double sq3(double c, long n) {
3    double x = c;        /* x : xmm1 */
4    long i = 0;          /* i : rsi */
5    if (!(i < n)) goto Lend;
6   Lstart:
7    double t0 = 2;       /* t0 : xmm2 */
8    double t1 = x / t0; /* t1 : xmm3 */
9    double t2 = t0 * x; /* t2 : xmm4 */
10   double t3 = c / t2; /* t3 : xmm5 */
11   x = t1 + t3;
12   i = i + 1;
13   if (i < n) goto Lstart;
14  Lend:
15   return x;
16 }
```

Step 4 — convert them to machine instructions

```
1  /* c : xmm0, n : rdi */
2  double sq3(double c, long n) {
3   # double x = c;        /*x:xmm1*/
4   movasd %xmm0,%xmm1
5   # long i = 0;          /*i:rsi*/
6   movq $0,%rsi
7  .Lstart:
8   # if (!(i < n)) goto Lend;
9   cmpq %rdi,%rsi  # n - i
10  jle .Lend
11  # double t0 = 2;       /*t0:xmm2*/
12  movasd .L2(%rip),%xmm2
13  # double t1 = x / t0; /*t1:xmm3*/
14  movasd %xmm1,%xmm3
15  divq %xmm2,%xmm3
16  # double t2 = t0 * x; /*t2:xmm4*/
17  movasd %xmm0,%xmm4
18  mulsd xmm2,%xmm4
```

```
1   # double t3 = c/t2; /*t3:xmm5*/
2   movasd %xmm0,%xmm5
3   divsd %xmm4,%xmm5
4   # x = t1 + t3;
5   movasd %xmm3,%xmm1
6   addsd %xmm5,%xmm1
7   # i = i + 1;
8   addq $1,%rsi
9   # if (i < n) goto Lstart;
10  cmpq %rdi,%rsi  # n - i
11  jl .Lstart
12 .Lend:
13  # return x;
14  movq %xmm1,%xmm0
15  ret
16 }
```

Things are more complex in general . . .

- we've liberally assigned registers to intermediate results, but . . .

```
1  double x = c;        /* x : xmm1 */
2  Lstart:
3  if (!(i < n)) goto Lend;
4  double t0 = 2;       /* t0 : xmm2 */
5  double t1 = x / t0; /* t1 : xmm3 */
6  double t2 = t0 * x; /* t2 : xmm4 */
7  double t3 = c / t2; /* t3 : xmm5 */
```

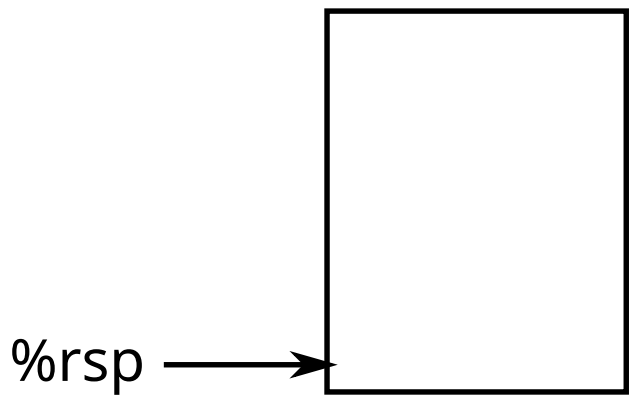
- registers are finite (may run out)
- some registers are destroyed (i.e., values on them are lost) across a function call
- some instructions demand operands to be on specific registers (e.g., dividend of integer division must be on `rax` and `rdx` ≡ `rax` and `rdx` are destroyed across an integer division)
- → you must use memory ("stack" region) as well

Register usage conventions (ABI)

- the first six integer/pointers arguments : `rdi`, `rsi`, `rdx`, `rcx`, `r8`, `r9`
- floating point number arguments : `xmm0`, `xmm1`, ...
- an integer/pointer return value : `rax`
- a floating point number return value : `xmm0`
- `rsp` : points the end of the stack upon function entry, which holds the return address
- *callee-save* registers: `rbx`, `rbp`, `r12`, `r13`, `r14`, `r15`, `rsp` (preserved across function calls → a function must save them before using (setting a value to) them)
- other registers are *caller-save* (a function must assume they are destroyed across function calls)
- see "general-purpose" registers in `https://wiki.cdot.senecacollege.ca/wiki/X86_64_Register_and_Instruction_Quick_Start`

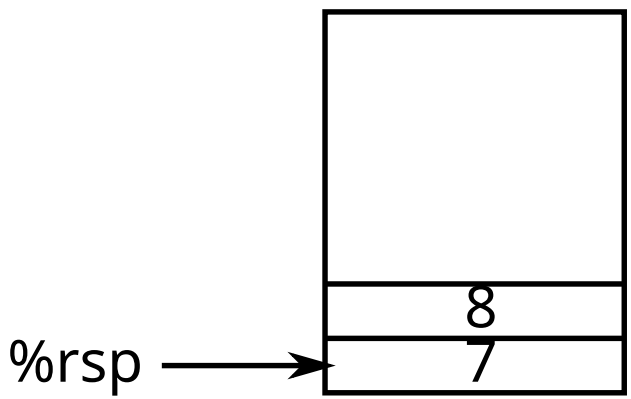
ABI (How function call works)

- `long f() { ... g(1,2,3,4,5,6,7,8); ... }`
- during `f`



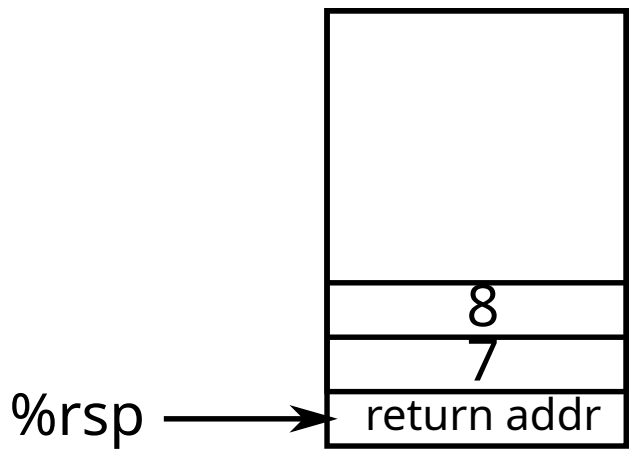
ABI (How function call works)

- `long f() { ... g(1,2,3,4,5,6,7,8); ... }`
- right before "`call g`" `rdi=1, rsi=2, rdx=3, rcx=4, r8=5, r9=6`



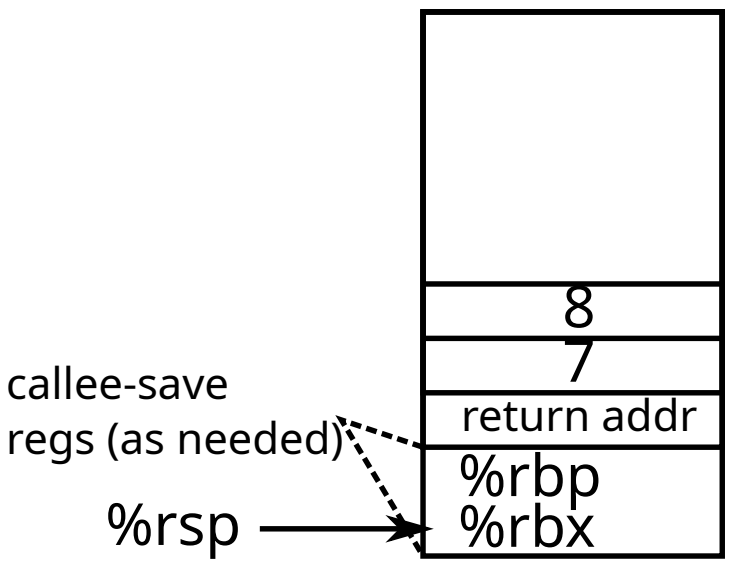
ABI (How function call works)

- `long f() { ... g(1,2,3,4,5,6,7,8); ... }`
- right after "`call g`" (when g started)



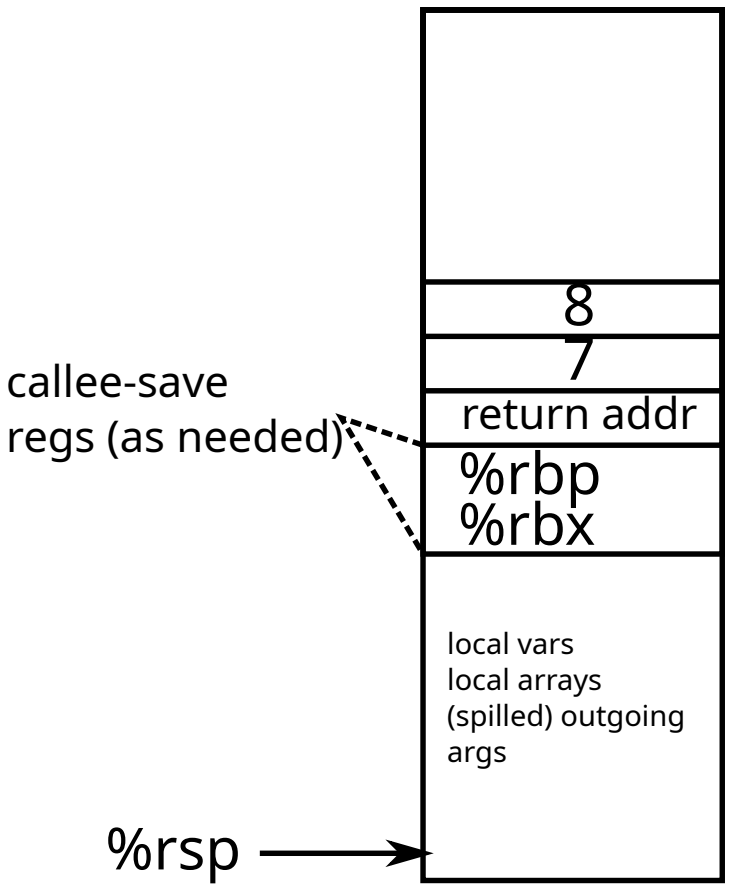
ABI (How function call works)

- `long f() { ... g(1,2,3,4,5,6,7,8); ... }`
- save callee-save registers g uses



ABI (How function call works)

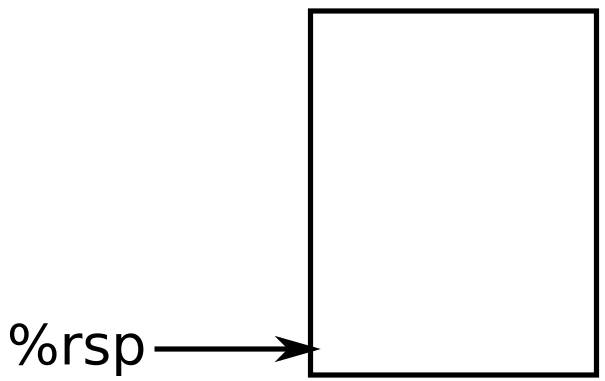
- `long f() { ... g(1,2,3,4,5,6,7,8); ... }`
- extend stack as needed to execute g



A simplest general strategy for code generation

- in general,
  - there may be too many intermediate results to hold on registers
  - values used after a function call must be saved on memory (or callee-save registers)

  $\Rightarrow$ *"always"* using memory (stack) is the simplest strategy
- a register is used only "temporarily" to apply an instruction



A code generation based on the simple strategy

```
1  double integ(long n) {
2    double x = 0;
3    double dx = 1 / (double)n;
4    double s = 0;
5    for (long i = 0; i < n; i++) {
6      s += f(x);
7      x += dx;
8    }
9    return s * dx;
10 }
```

converting to "goto"s and "C = A op B"s

```
1  double integ(long n) {
2    double x = 0;
3    double t0 = 1;
4    double t1 = (double)n;
5    double dx = t0 / t1;
6    double s = 0;
7    long i = 0;
8    if (!(i < n)) goto Lend;
9   Lstart:
10   double t2 = f(x);
11   s += t2;
12   x += dx;
13   i += 1;
14   if (i < n) goto Lstart;
15   Lend:
16   double t3 = s * dx;
17   return t3;
18 }
```

allocate memory slot for intermediate values

```
1  double integ(long n) {      /*  n :  0(%rsp) */
2    double x = 0;             /*  x :  8(%rsp) */
3    double t0 = 1;            /* t0 : 16(%rsp) */
4    double t1 = (double)n;    /* t1 : 24(%rsp) */
5    double dx = t0 / t1;      /* dx : 32(%rsp) */
6    double s = 0;             /*  s : 40(%rsp) */
7    long i = 0;               /*  i : 48(%rsp) */
8    if (!(i < n)) goto Lend;
9   Lstart:
10   double t2 = f(x);         /* t2 : 56(%rsp) */
11   s += t2;
12   x += dx;
13   i += 1;
14   if (i < n) goto Lstart;
15   Lend:
16   double t3 = s * dx;       /* t3 : 64(%rsp) */
17   return t3;
18 }
```

機械語 / Machine code

```
1  double integ(long n) {
2    subq $72,%rsp
3    /* n : 0(%rsp) */
4    movq %rdi,0(%rsp)
5    # double x = 0;
6    /* x : 8(%rsp)*/
7    movsd .L0(%rip),%xmm0
8    movsd %xmm0,8(%rsp)
9    # double t0 = 1;
10   /* t0 : 16(%rsp)*/
11   movsd .L1(%rip), %xmm0
12   movsd %xmm0,16(%rsp)
13   # double t1 = (double)n;
14   /* t1 : 24(%rsp)*/
15   cvtsi2sdq 0(%rsp),%xmm0
16   movsd %xmm0,24(%rsp)
17   # double dx = t0 / t1;
18   /* dx : 32(%rsp) */
19   movsd 16(%rsp),%xmm0
20   divsd 24(%rsp),%xmm0
21   movsd %xmm0,32(%rsp)
22   # double s = 0;
23   /* s : 40(%rsp) */
```

```
1    movsd .L0(%rip),%xmm0
2    movsd %xmm0,40(%rsp)
3    # long i = 0;
4    /* i : 48(%rsp) */
5    movq $0,48(%rsp)
6    # if (!(i < n)) goto Lend;
7    movq 0(%rsp),%rdi
8    cmpq 48(%rsp),%rdi # n - i
9    jle .Lend
10 .Lstart:
11   # double t2 = f(x);
12   /* t2 : 56(%rsp) */
13   movq 8(%rsp),%rdi
14   call f
15   movq %rax,56(%rsp)
16   # s += t2;
17   movq 40(%rsp),%xmm0
18   addsd 56(%rsp),%xmm0
19   movq %xmm0,40(%rsp)
20   # x += dx;
21   movsd 8(%rsp),%xmm0
22   addsd 32(%rsp),%xmm0
23   movsd %xmm0,8(%rsp)
```

機械語 / Machine code

```
1    # i += 1;
2    movq 48(%rsp),%rdi
3    addq $1,%rdi
4    movq %rdi,48(%rsp)
5    # if (i < n) goto Lstart;
6    movq 0(%rsp),%rdi
7    cmpq 48(%rsp),%rdi # n - i
8    jg .Lstart
9  .Lend:
10   movsd 40(%rsp),%xmm0
11   addsd 32(%rsp),%xmm0
12   addsd %xmm0,64(%rsp)
13   # return t3;
14   addsd 64(%rsp),%xmm0
15   ret
16 }
```

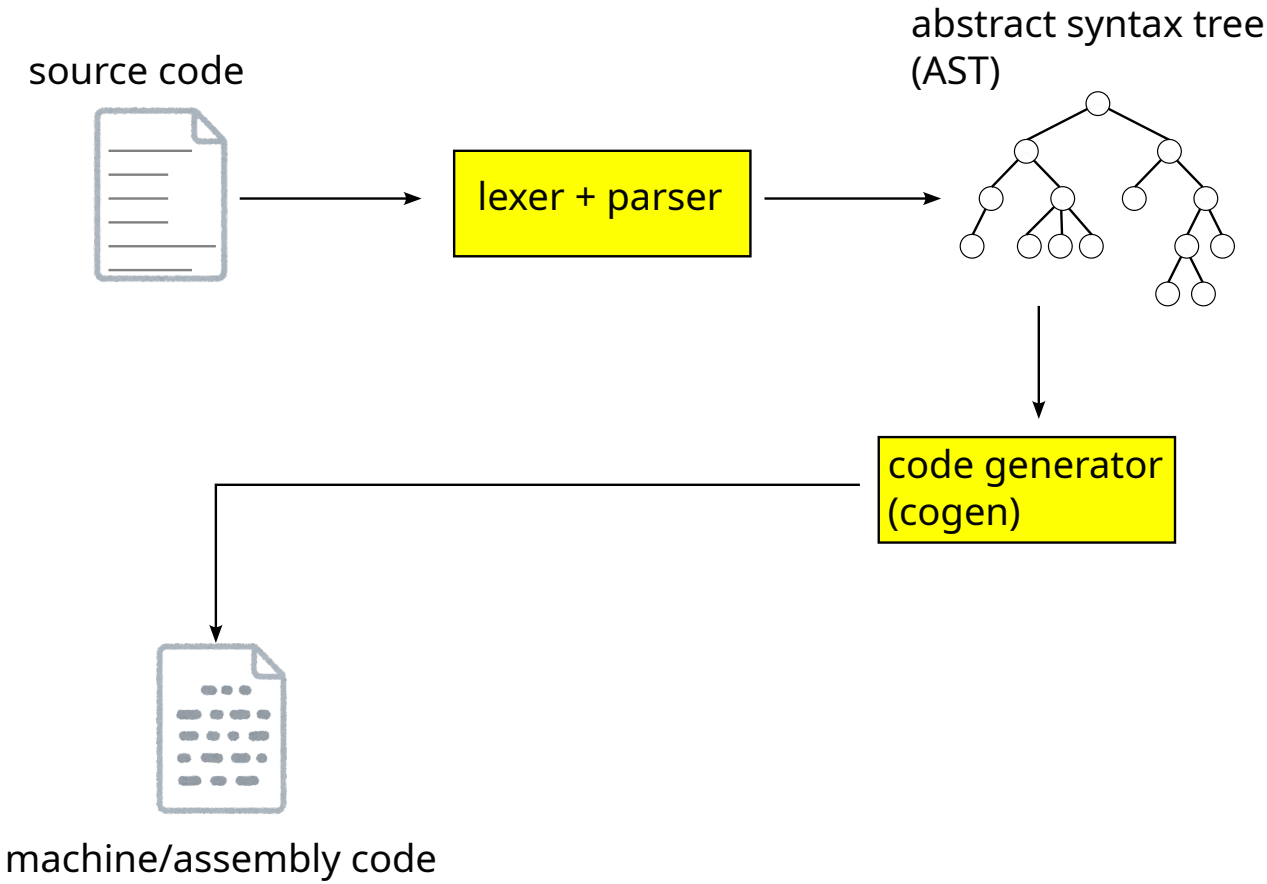
Contents

MinC ("Minimum C") spec overview

- this will be your final report if you choose option A
- all expressions have type `long (8 byte integers)`
  - no `typedef`s
  - no `int`s, floating point numbers, or pointers
  - everything is long, so type checks are unnecessary
- no global variables ⇒
  - a program = list of function definitions
- function calls with C conventions, so you can call or be called by C functions compiled by ordinary compilers (e.g., gcc)
- supported complex statements are `if`, `while` and compound statement ({ ... }) only

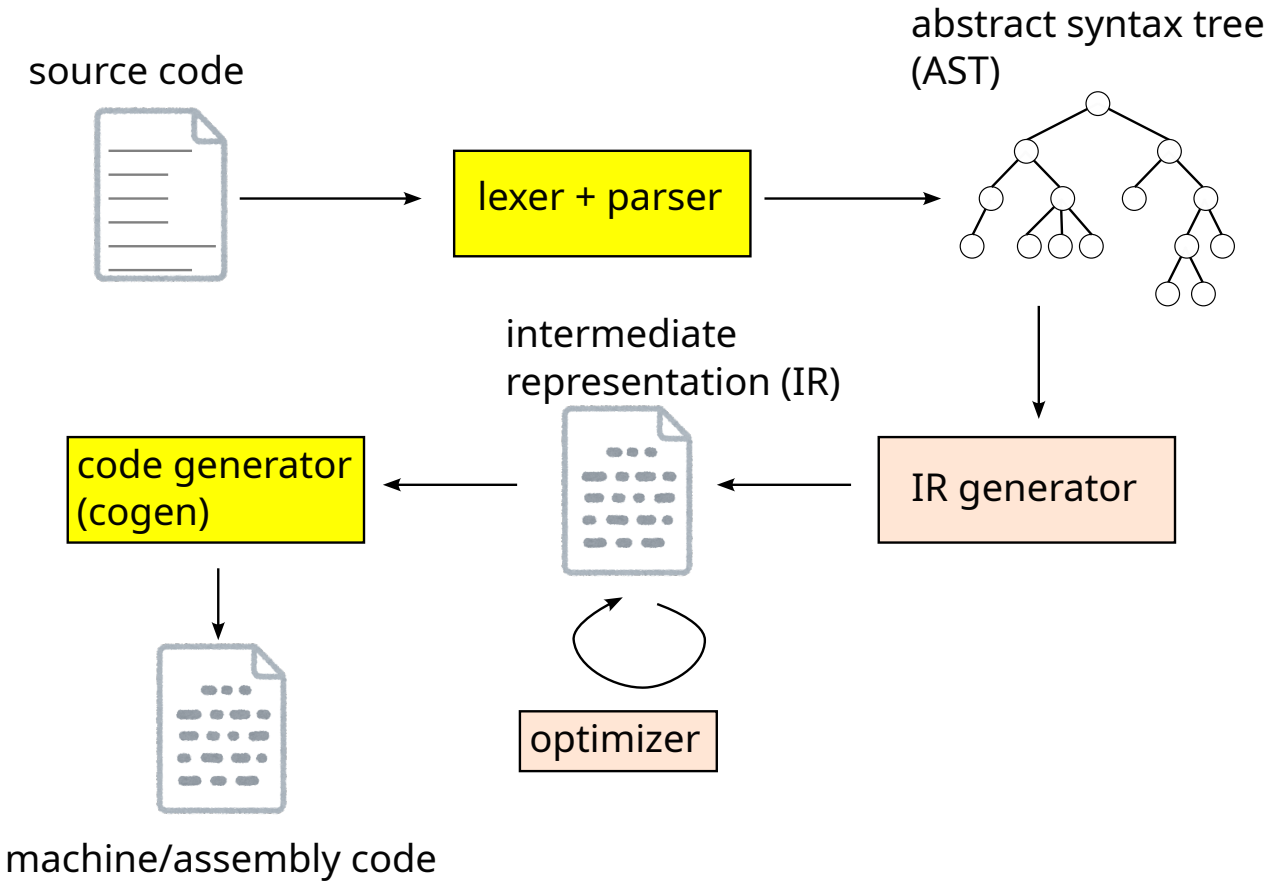
Structure of compilers

- Abstract Syntax Tree (AST) : data structure representing the program



Structure of compilers

- Abstract Syntax Tree (AST) : data structure representing the program
- Intermediate Representatin (IR) : common representation portable across multiple source/target languages



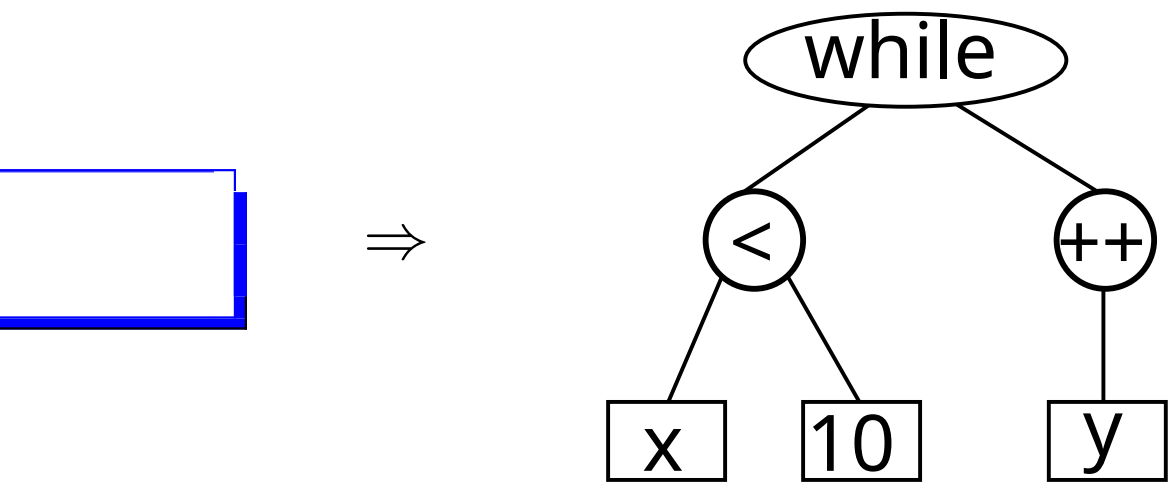
Structure of the program

- `parser/`
  - `minc_grammar.y` — grammar definition
  - `minc_to_xml.py` — minC → XML converter
- `{ml,jl,go,rs}/minc/`
  - `minc_ast.??` — abstract syntax tree (AST) definition
  - `minc_parse.??` — XML → AST
  - `minc_cogen.??` — AST → assembly
  - `main.??` or `minc.??` — main driver
- the exact location depends on the language
- your work will be mostly done in `minc_cogen.??`
- other parts are given

Abstract Syntax Tree (AST)

- a data structure that naturally represents a program
  - the whole program,
  - function definition,
  - statement,
  - expression,
  - ...
- also called *parse tree*
- see `minc_ast.??`

```
1 while (x < 10)
2   y++;
```

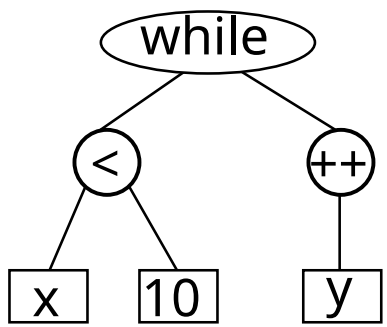


Lexer and parser

- lexer (lexical analyzer, tokenizer) : string → sequence of "tokens" (words)

  "`while (x < 10) y++;`"
  ⇒ `while` `(` `x` `<` `10` `)` `y` `++` `;`
- parser : sequence of tokens ⇒ AST

`while` `(` `x` `<` `10` `)` `y` `++` `;` ⇒



Implementing lexer and parser

- first write a *grammar*, typically in the Backus-Naur form (BNF)
- e.g., (part of C grammar)
  - *statement* = *while-statement* | *if-statement* | ...
  - *while-statement* = `'while' '('` *expr* `')'` *statement*
  - *expr* = *number* | *expr* `'+'` *expr* | ...
  - *number* = *digit*+ | *digit*+ `.` *digit** | ...
  - *digit* = [0-9]
  - ...
- based on the grammar, either
  - write them by hand, or
  - use a *lexser/parser generators*

Lexer/parser generators

- *lexer generator* generates a lexer from a syntax of *tokens* (variables, numbers, ...)
- *parser generator* generates a parser from a syntax of higher-level constructs (expressions, statements, ...)
- some grammar frameworks (PEG) specify them in a single framework

Lexer/parser generators

- many programming languages have lexer/parser generators for them
  - lex/yacc (flex/bison) : C/C++
  - ANTLR : C, C++, Java, Python, JavaScript, Go, ...
  - ocamllex/menhir : OCaml
  - tatsu : Python
  - etc.
- this exercise uses tatsu, to generate a Python program that converts C source into XML
  - the grammar is in `minc_grammar.y`
- each language reads the XML by the respective XML library you have used before

Intermediate Representation (IR)

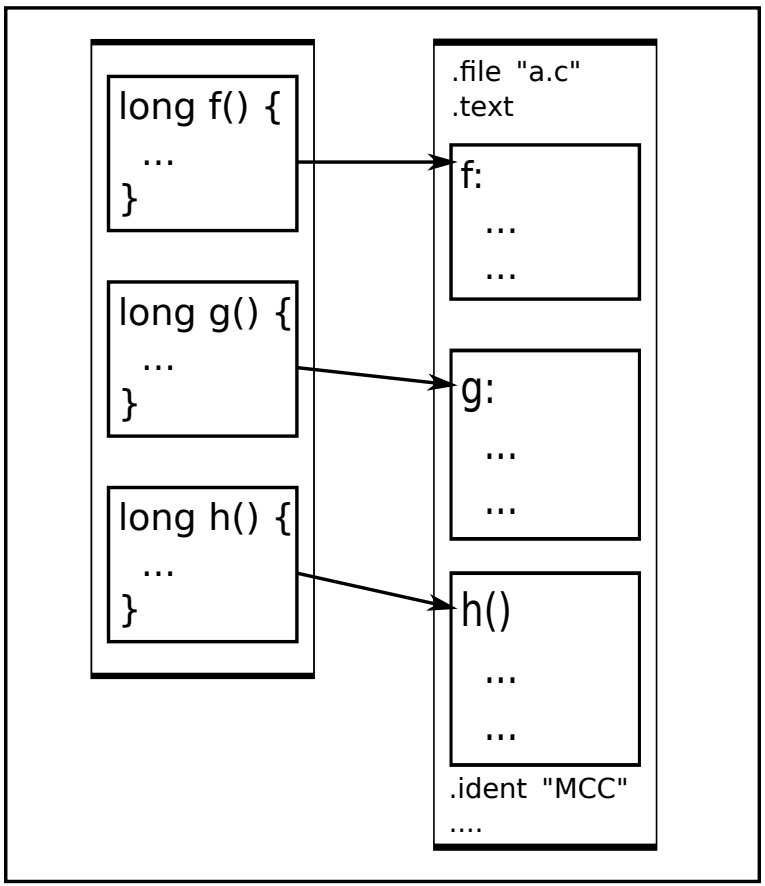
- a common representation of programs internally used by a compiler
  - hopefully independent from the source language (C, C++, Rust, Go, Julia, etc.)
  - hopefully independent from the target language (x86, ARM, PowerPC, etc.)
- it generally looks like "an assembly with infinite registers (variables)"
- a compiler performs optimizations as IR $\rightarrow$ IR transformations
- *note:* in the exercise you could design your IR, but it is not necessary (it is possible to directly go from AST $\rightarrow$ asm)

Code generation (`minc_cogen`) — basic structure

- takes an AST and returns machine code (a list of instructions)
- generate machine code for an AST $\approx$ generate machine code of its components and properly arrange them
- the program (`program`) $\rightarrow$ function definition (`definition`) $\rightarrow$ statement (`stmt`) $\rightarrow$ expression (`expr`)
- code generator has lots of
  - case analysis based on the type of the tree; use
    - pattern matching (OCaml match and Rust match) or
    - polymorphism (OCaml objects, Julia function, Go interface, Rust trait)
  - recursive calls to child trees

Compiling an entire file

- ≈ concatenate compilation of individual function definitions

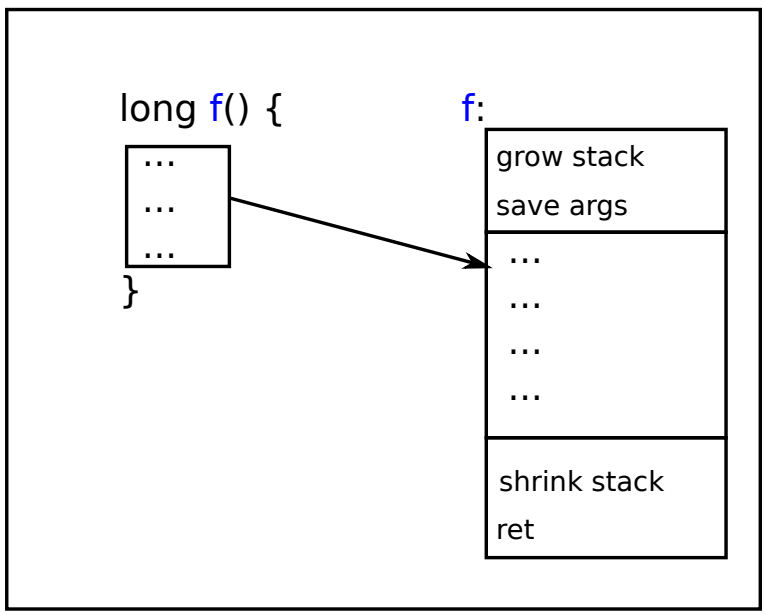


In OCaml, it will look like . . .

```
1  let ast_to_insns_program defs ... =
2    List.concat (List.map (fun def ->
                    ast_to_insns_def def ...) defs)
```

Compiling a function definition

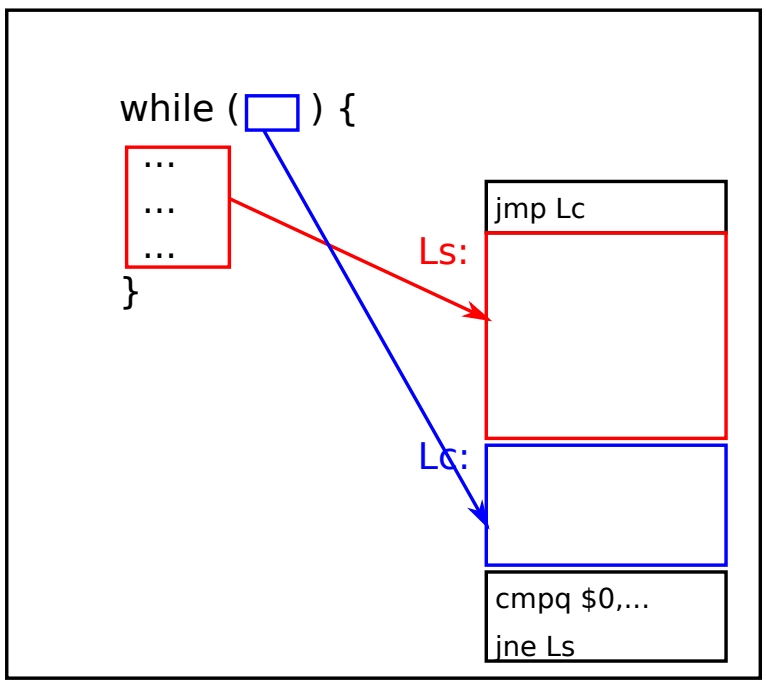
- ≈ compile the body (statement); put prologue (grow the stack, etc.) and epilogue (shrink the stack, ret, etc.)




```
1  let ast_to_insns_def def ... =
2    match def with
3      DefFun(f, params, ret_type, body) ->
4        (gen_prologue def)
5        @ (ast_to_insns_stmt body ...)
6        @ (gen_epilogue def)
```

Compiling a statement (e.g., `while` statement)

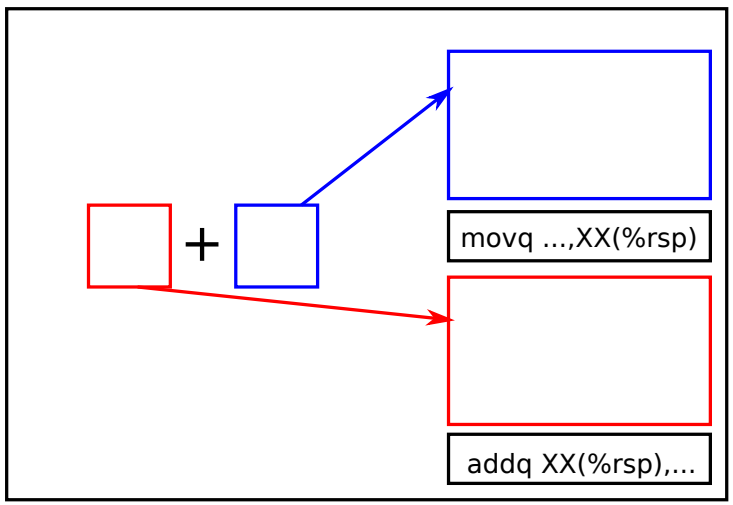
- ≈ place compilation of the condition expression and the body as follows. add a conditional to determine if the loop continues




```
1  let rec ast_to_insns_stmt stmt ...  =
2    match stmt with
3      ...
4    | StmtWhile(cond, body) ->
5      let cond_op,cond_insns =
           ast_to_insns_expr cond ... in
6      let body_insns = ast_to_insns_stmt body
           ... in
7      let ... in
8      [ jmp Lc;
9        Ls ]
10     @ body_insns
11     [ Lc ]
12     @ cond_insns @
13     [ cmpq $0,cond_op;
14       jne Ls ]
```

Compiling an expression (arithmetic)

- ≈ compile the arguments; an arithmetic instruction




```
1  let rec ast_to_insns_expr expr ... =
2    match expr with
3      ...
4    | ExprOp("+", [e0; e1]) ->
5      let insns1,op1 = ast_insns_expr e1 ... in
6      let insns0,op0 = ast_insns_expr e0 ... in
7      let m = a slot on the stack in
8      ((insns1
9      @ [ movq op1,m ]
10     @ insns0
11     @ [ addq m,op0 ]), (* op0 = op0 + m *)
12     op0)
13   | ...
```

- Remark: `movq XX(%rsp),...` saves the first operand, ensuring it won't be destroyed during the evaluation of the second
- remember we are following the simplest strategy = "save all intermediate results on the stack"

Compiling an expression (comparison)

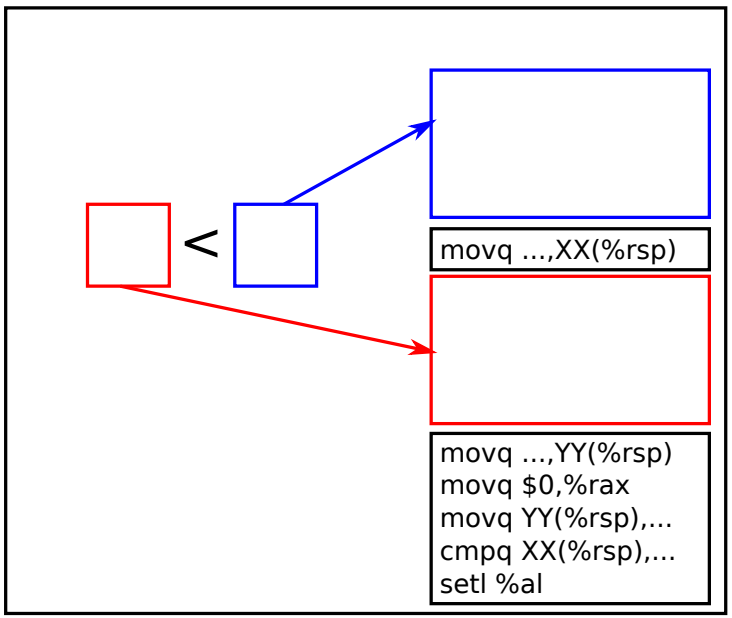
- A `<` B is an expression that evaluates to
  - 1 if $A < B$
  - 0 if $A \geq B$
- no single instruction exactly does this
- note that they can appear anywhere expression can
  - `z = x < y`, `(x < y) + z`, and `f(x < 1)` are allowed (they do not necessarily appear in condition expression of `if` or `while`)
- how to do it in assembly code?
  1. conditional branch
  2. *conditional set instruction*. e.g.,

```
1 movq $0,%rax
2 cmpq %rdi,%rsi
3 setle %al
```

will set `%al` (the lowest 8 bits of `%rax`) to 1 when `%rsi - %rdi` ≤ 0 (less-than-or-equal)

Compiling an expression (comparison)

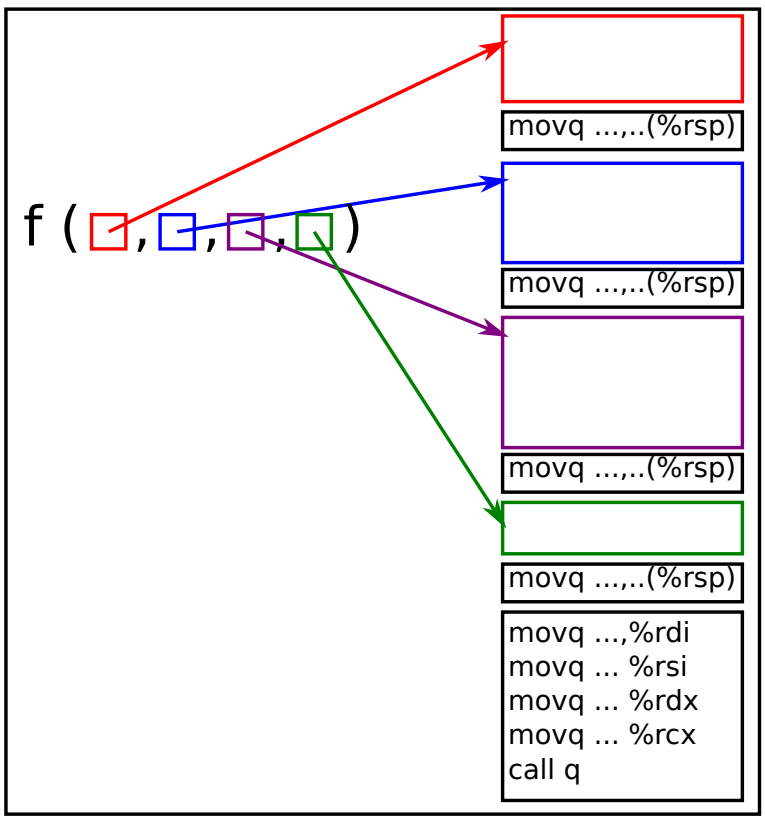
- ≈ compile the arguments; compare; conditional set




```
1  let rec ast_to_insns_expr expr ... =
2    match expr with
3      ...
4    | ExprOp("<", [e0; e1]) ->
5      let insns1,op1 = ast_to_insns_expr e1 ...
           in
6      let insns0,op0 = ast_to_insns_expr e0 ...
           in
7      let m0 = a slot on the stack in
8      let m1 = a slot on the stack in
9        ...
10     ((insns1
11       @ [ movq op1,m1 ]
12       @ insns0
13       @ [ movq op0,m0;
14           movq $0,%rax;
15           movq m0,op0;
16           cmpq m1,op0;
17           setl rax ]
18     op0)
19   | ...
```

Compiling an expression (function call)

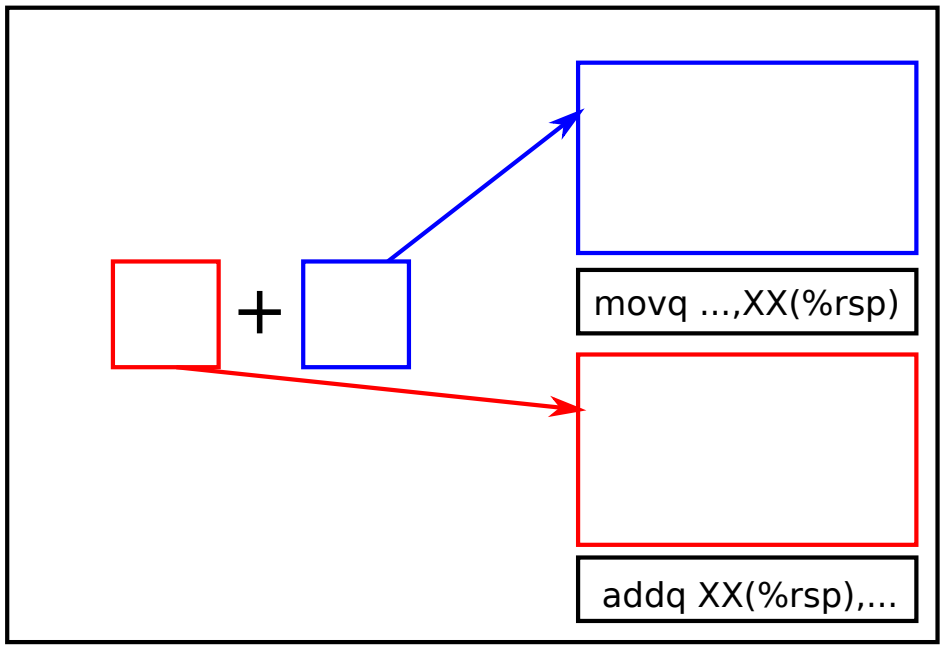
- ≈ compile all arguments; put them to positions specified by ABI; a `call` instruction




```
1  let rec ast_to_insns_expr expr ... =
2    match expr with
3      ...
4    | ExprCall(f, args) ->
5       let insns,arg_vars =
              ast_to_insns_exprs args env
              var_idx in
6       ((insns @ (make_call f arg_vars)),
              rax)
```

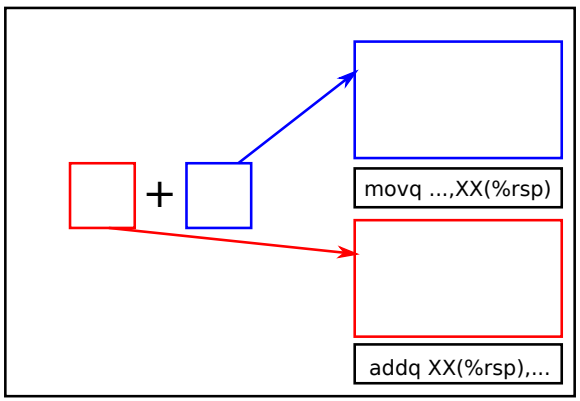
Details we have been leaving out

- how to determine locations to save values of *subexpressions* and *variables*
- that is, how to determine XX below



Determining where to save subexpressions

- `ast_to_insns_expr` receives a value (v) pointing to the lowest end of free space
  `ast_to_insns_expr` E v ... generates instructions that evaluate E using (destroying) only addresses above v`(%rsp)`
- $\rightarrow$ when evaluating $\boxed{A} + \boxed{B}$, save $\boxed{B}$ at v`(%rsp)`
- let $\boxed{A}$ use $v + 8$ and higher addresses




```
1  let rec ast_to_insns_expr expr v =
2   match expr with
3    ...
4   | ExprOp("+", e0, e1) ->
5    let insns1,op1 = ast_to_insns_expr e1 v .. in
6    let insns0,op0 = ast_to_insns_expr e0 (v + 8) .. in
7    let m = v(%rsp) in
8    ((insns1
9    @ [ movq op1,m ]
10   @ insns0
11   @ [ addq m,op0 ]), (* op0 = op0 + m *)
12   op0)
13  | ...
```

Locations to hold variables

- ex:

```
1 if (...) {
2   long a, b, c;
3   ...
4 }
```

- we need to hold `a, b, c` on the stack
- the problem is almost identical to saving values of subexpressions
- → `ast_to_insns_stmt` also takes v pointing to the beginning of the free space

  spec: `ast_to_insns_stmt` S v ... generates instructions to execute S; they use (destroy) only addresses above v`(%rsp)`
- → e.g., hold `a` $\mapsto v$`(%rsp)`, `b` $\mapsto v + 8$`(%rsp)`, `c` $\mapsto v + 16$`(%rsp)`

Environment: records where variables are held

- when a variable occurs in an expression, we need to get the location that holds the variable
  - ex: to compile `x + 1`, we need to know where `x` is held
- make a data structure that holds a mapping "variable $\mapsto$ location" *(environment)* and pass it to `ast_to_insns_stmt` and `ast_to_insns_expr`
- when new variables are declared at the beginning of a compound statement ($\{ \ldots \}$), add new mappings to it

`ast_to_insns_expr` receives an environment

```
1  let rec ast_to_insns_expr expr env v =
2    match expr with
3      ...
4    | ExprId(x) ->
5       let loc = env_lookup x env in
6       ([ movq loc,... ], ...)
7    | ...
```

- `env_lookup` x env searches environment env for x and returns its location

`ast_to_insns_stmt` receives an environment too

```
1  let rec ast_to_insns_stmt expr env v =
2    match expr with
3      ...
4    | StmtCompound(decls, stmts) ->
5       let env',v' = env_extend decls env v in
6       cogen_stmts stmts env' v' ...
7    | ...
```

- `env_extend` *decls env v*
  - assign locations $(v,\ v+8,\ v+16,\ \dots)$ to variables declared in *decls*
  - register them in *env*
  - return the new environment *env'* and the new free space *v'*

Implementing environment

- an environment is a list of (variable name, location)'s
- *loc* = `env_lookup` x *env*

  returns the location paired with x in environment *env*
- *env'* = `env_add` x *loc* *env*

  returns a new environment *env'* which has a new mapping $x \mapsto$ *loc* in addition to *env* (`(`x`,` *loc*`)::`*env*)
- an environment can be easily implemented with a list of (variable name, location)'s and is left for your exercise