Implementing a Compiler

Kenjiro Taura

2024/06/23

Contents

The MinC ("Minimum C") language 2
Overview of Inside a Compiler 5
Lexer and parser : source code $\rightarrow$ AST 11
Intermediate Representation (IR) 39
Code generation 42

The MinC (“Minimum C”) language

MinC ("Minimum C") spec overview

- all expressions have type `long` (64 bit integer)
  - no other integers, floating point numbers, pointers, or structs
  - everything is long $\Rightarrow$ *type checks are unnecessary*
- no global variables or `typedef`
  - $\Rightarrow$ a program = list of *function definitions*
- supported complex statements are `if`, `while`, and compound statement (`{ ... }`) only

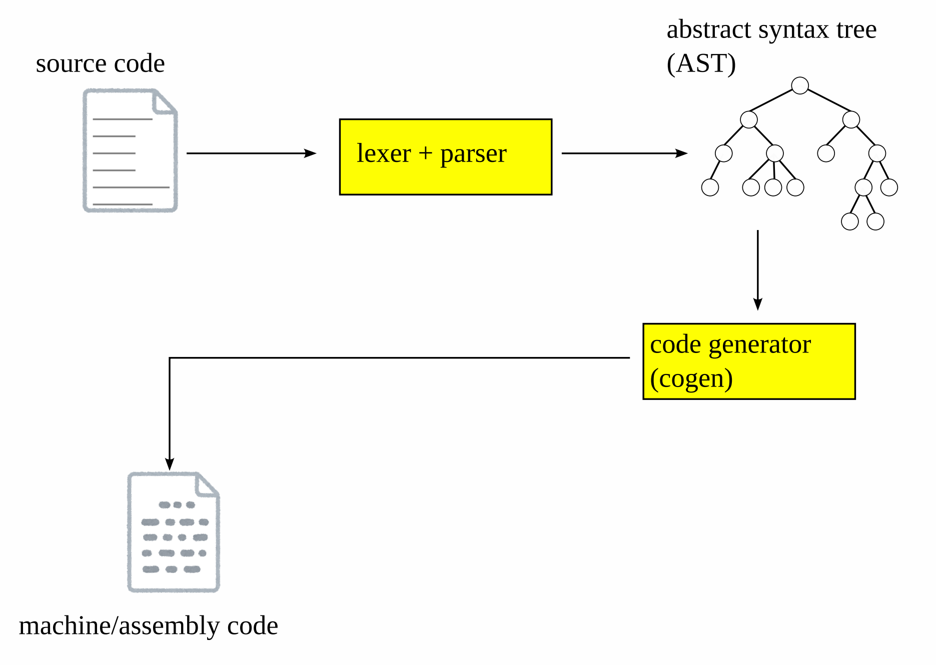
MinC (“Minimum C”) spec overview

- function calls follow the C convention ⇒ MinC code can call or be called by functions compiled by other compilers (e.g., gcc)

Overview of Inside a Compiler

Data structures

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



Data structures

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

Typical compilation steps

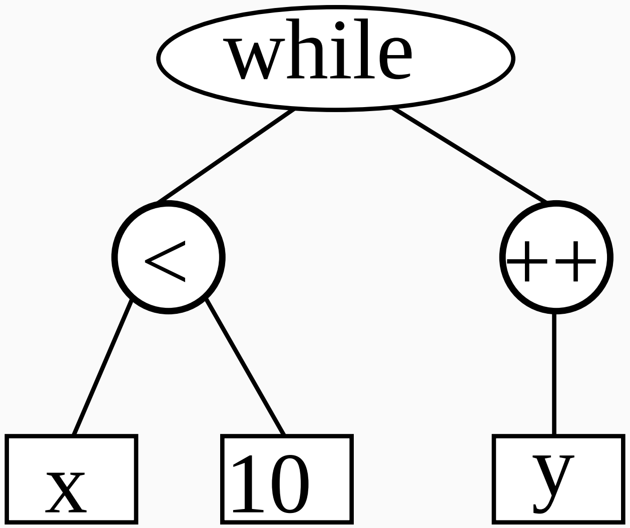
1. **lexing and parsing:** source code (string) $\to$ AST
2. IR generation: AST $\to$ IR $(*)$
3. optimization: IR $\to$ IR $(*)$
4. **code generation:** IR $\to$ assembly

$(*)$: optional

Abstract Syntax Tree (AST)

- a data structure that naturally represents a program

- expression,
- statement,
- function definition,
- the whole program,
- ...



- also called **parse tree**

Components of the baseline code

- `parser/`
  - `minc_grammar.y` … grammar definition
  - `minc_to_xml.py` … MinC $\rightarrow$ XML converter
- `{go,jl,ml,rs}/minc/`
  - `minc_ast.??` … abstract syntax tree (AST) definition
  - `minc_parse.??` … XML $\rightarrow$ AST
  - **`minc_cogen.??`** … AST $\rightarrow$ assembly
  - `main.??` or `minc.??` … main driver

Your work

- files other than `minc_cogen.??` are given and need not be modified (unless you do something extra)
- `minc_cogen.??` is almost empty and your primary job is to complete it

Lexer and parser : source code → AST

Lexer and parser

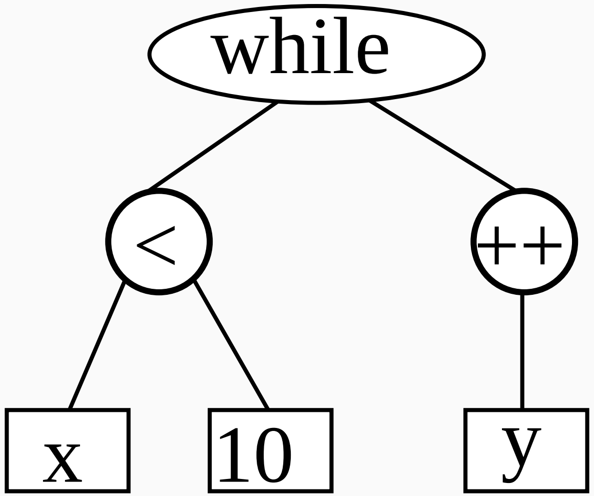
- **lexer:** string $\rightarrow$ sequence of ***tokens*** ($\approx$ words)
  - also called ***lexical analyzer***, or ***tokenizer***
  - `while (x < 10) y++;` $\Rightarrow$

while	(	x	<	10	)	y	++	;
`WHILE`	`LP`	`ID`	`CMP`	`INT`	`RP`	`ID`	`PLSPLS`	`SEMICOLON`

Lexer and parser

- **parser:** sequence of tokens → AST

while	(	x	<	10	)	y	++	;	
`WHILE`	`LP`	`ID`	`CMP`	`INT`	`RP`	`ID`	`PLSPLS`	`SEMICOLON`	⇒



Specifying a grammar

- a grammar for *tokens*
  - specifies which character sequence constitutes a valid token
  - typically uses ***Regular Expressions (RE)***
- a grammar for *the entire inputs*
  - specifies which token sequence constitutes a valid input
  - typically uses (a subset of) ***Context Free Grammar (CFG)***
- note: there is an approach that uses a single grammar for both

Regular expression

- a regular expression is any expression that can be formed by:

$$
\begin{array}{ll}
\varepsilon & \text{(empty string)} \\
c & \text{(a character)} \\
E\ E & \text{(concatenation)} \\
E \mid E & \text{(alternation)} \\
E* & \text{(zero or more repetition)} \\
(E) & \text{(paren)}
\end{array}
$$

where E is a regular expression

- |, *, (and) are literals

Regular expression

- expressions for convenience

$$
\begin{aligned}
E+ &\equiv E\ E* \quad \text{(one or more repetition)} \\
E? &\equiv \varepsilon \mid E \quad \text{(optional)}
\end{aligned}
$$

Regular expression examples

- to build complex expressions, use symbols to represent regular expressions used in other regular expressions. e.g.,

nz	=	1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9	1, 2, …, 9
digit	=	0 | nz	0, 1, 2, …, 9
non_neg	=	0 | nz digit*	0, 12, 34
int	=	-? non_neg	0, −0, 12, −34
fraction	=	int (. digit*)?	−12.34
float	=	fraction (e int)	−12.34e-5

Regular expression examples

$$
\begin{array}{lcll}
\text{alpha} & = & A \mid B \mid \ldots\ Z \mid a \mid b \mid \ldots\ z & \text{A, B, …, Z, a, b, …, z} \\
\text{alpha\_} & = & \text{alpha} \mid \_ & \text{A, B, …, Z, a, b, …, z, \_} \\
\text{id} & = & \text{alpha\_}\ (\ \text{alpha\_} \mid \text{digit}\ )^{*} & \text{a, abc, a0\_b1}
\end{array}
$$

Regular expression semantics (just for formality ...)

- a regular expression E represents *a set of strings*, written $[\![E]\!]$

$$
\begin{aligned}
[\![\varepsilon]\!] &= \{\ \text{“”}\ \} \\
[\![c]\!] &= \{\ c\ \} \\
[\![E_0\ E_1]\!] &= \{\ e_0 + e_1 \mid e_0 \in [\![E_0]\!], e_1 \in [\![E_1]\!]\ \} \\
[\![E_0 \mid E_1]\!] &= [\![E_0]\!] \cup [\![E_1]\!] \\
[\![E*]\!] &= \{\ \text{“”}\ \} \cup \{e_0 + e_1 \mid e_0 \in [\![E]\!], e_1 \in [\![E*]\!]\ \} \\
[\![(E)]\!] &= [\![E]\!]
\end{aligned}
$$

- note: “+” represents string concatenation

Context Free Grammar (CFG)

- specified by a collection of ***production rules***
- a production rule looks like

$$L \to R_0 \; R_1 \; \ldots$$

where

- L : a symbol (***non-terminal***)
- R_i is either
  - a symbol defined by a production rule(s), or
  - a token name (a ***terminal*** symbol)

An example : expressions

expr	$\rightarrow$	int	12, 345, …
expr	$\rightarrow$	id	f, x, i, is_prime, …
expr	$\rightarrow$	unop expr	-x, exp, !a_greater_than_b
expr	$\rightarrow$	expr binop expr	x + y, a * x + b * y + 1, a & b, …
expr	$\rightarrow$	(expr)	3 * (a + 1)
expr	$\rightarrow$	funcall	

- blue symbols (int, id, unop, binop, (,)) are terminals (tokens)
- above rules overlook the fact that some operators (i.e., + and -) can be used as a unary operator and a binary operator

An example : function call

$$
\begin{aligned}
\text{funcall} &\rightarrow \text{id (comma\_exprs)} \\
\text{comma\_exprs} &\rightarrow \\
\text{comma\_exprs} &\rightarrow \text{expr} \\
\text{comma\_exprs} &\rightarrow \text{expr comma\_expr\_star} \\
\text{comma\_expr\_star} &\rightarrow \\
\text{comma\_expr\_star} &\rightarrow \text{, expr comma\_expr\_star}
\end{aligned}
$$

f(x, 2 * y, 1)

An example : statements

$$
\begin{aligned}
\text{stmt} &\rightarrow\ ; \\
\text{stmt} &\rightarrow\ \text{continue}\ ; \\
\text{stmt} &\rightarrow\ \text{break}\ ; \\
\text{stmt} &\rightarrow\ \text{return}\ ; \\
\text{stmt} &\rightarrow\ \{\ \text{decl}^*\ \text{stmt}^*\ \} \\
\text{stmt} &\rightarrow\ \text{if}\ (\ \text{expr}\ )\ \text{stmt}\ (\ \text{else}\ \text{stmt}\ )? \\
\text{stmt} &\rightarrow\ \text{while}\ (\ \text{expr}\ )\ \text{stmt} \\
\text{stmt} &\rightarrow\ \text{expr}\ ;
\end{aligned}
$$

Notes

- as you have seen,
  - the same symbol L can appear multiple times in the lefthand side (i.e., *alternation*)
  - R_i can be L or any symbol defined earlier or later (i.e., definitions can be *recursive*)

A few shorthands

- we often use shorthands (|, ?, *, +) that have similar meanings with those for RE
- they can be mechanically eliminated
- the above example using the shorthands:

$$
\begin{array}{lcl}
\text{expr} & \rightarrow & \text{int} \mid \text{id} \mid \text{unop expr} \mid \text{expr binop expr} \mid \text{funcall} \\
\text{funcall} & \rightarrow & \text{id (comma\_exprs)} \\
\text{comma\_exprs} & \rightarrow & \mid \text{expr (, expr)*}
\end{array}
$$

CFG semantics (for formality)

- each symbol L represents a set of token sequences ($[\![L]\!]$)
- $[\![L]\!]$ is the set of token sequences that can result by, starting from L, repeatedly replacing a non-terminal symbol to the righthand side of its production rule, until it becomes a sequence of tokens (terminals)

$$
\begin{array}{rcl}
\text{expr} & \rightarrow & \text{funcall} \\
 & \rightarrow & \text{id (comma\_exprs)} \\
 & \rightarrow & \text{id (expr comma\_expr\_star)} \\
 & \rightarrow & \text{id (id comma\_expr\_star)}
\end{array}
$$

CFG semantics (for formality)

$$
\begin{aligned}
&\rightarrow\ \text{id (id , expr comma\_expr\_star)}\\
&\rightarrow\ \text{id (id , expr + expr comma\_expr\_star)}\\
&\rightarrow\ \text{id (id , id + expr comma\_expr\_star)}\\
&\rightarrow\ \text{id (id , id + int comma\_expr\_star)}\\
&\rightarrow\ \text{id (id , id + int)}
\end{aligned}
$$

$$\therefore \text{id (id , id + int) (e.g., f(x, y + 1))} \in [\![\text{expr}]\!]$$

An alternative semantics

- $[\![.]\!]$ is the minimal set of token sequences satisfying:

1. $[\![\, t \,]\!] = \{\, t \,\}$ (t : terminal)
2. $L \to R_0 \ldots R_{n-1}$ implies

$$r_0 \in [\![R_0]\!], \ldots, r_{n-1} \in [\![R_{n-1}]\!]$$
$$\Rightarrow r_0 + \ldots + r_{n-1} \in [\![L]\!]$$

- "+" represents concatenation of token sequences

CFG is more expressive than RE

- as you might have noticed, RE is a special case of CFG
- all the constructs of RE can be straightforwardly expressed with CFG
- e.g., a CFG equivalent to RE "int = 0 | nz digit*"

$$
\begin{aligned}
\text{int} &\to 0 & \text{digit} &\to 0 \\
\text{int} &\to \text{nz digits} & \text{digit} &\to \text{nz} \\
\text{digits} &\to & \text{nz} &\to 1 \mid \ldots \mid 9 \\
\text{digits} &\to \text{digit digits}
\end{aligned}
$$

In general …

- below, $C(e, L)$ is a function that converts regular expression e to an equivalent CFG s.t., $[\![L]\!] = [\![e]\!]$

$$
\begin{aligned}
C(\varepsilon, L) &= \{L \rightarrow\} \\
C(c, L) &= \{L \rightarrow c\} \\
C(E_0\ E_1, L) &= \{L \rightarrow R_0\ R_1\} \cup C(E_0, R_0) \cup C(E_1, R_1) \\
C(E_0 | E_1, L) &= \{L \rightarrow R_0, L \rightarrow R_1\} \cup C(E_0, R_0) \cup C(E_1, R_1) \\
C(E^*, L) &= \{L \rightarrow \mid R\ L\} \cup C(E, R) \\
C((E))] &= C(E, L)
\end{aligned}
$$

- R, R_0 and R_1 are unique symbols that do not appear elsewhere

A CFG that cannot be expressed by RE

- intuitively, RE *can repeat (E^*) but cannot recurse*
- e.g., both "$A \to \mid a\ A$" and "$A \to \mid A\ a$" *can* be expressed by an RE (both are equivalent to a^*), but

$$A \to \mid a\ A\ b$$

cannot ($[\![A]\!] = \{\varepsilon, ab, aabb, aaabbb, \ldots\} = \{a^n b^n \mid n \geq 0\}$)

- the proof is interesting but omitted

If RE ⊂ CFG, why use both (not just CFG)?

- parsing *general* CFG is expensive ($O(\text{length}^3)$)
- the primary reason is handling *alternatives* requires *backtrack*

$$A \to B_0\ B_1\ \ldots \mid C_0\ C_1\ \ldots \mid D_0\ D_1\ \ldots$$

- practical parsers take either of the following two approaches
  1. allow only alternatives that can be determined with a *limited lookahead* (LL(1), LALR(1), etc.)
  2. allow backtrack with programmer-supplied ***cut points* (*Parsing Expression Grammar; PEG*)**

CFG with a limited lookahead (LL(1), LALR(1), etc.)

- recall the syntax of statement

$$
\begin{aligned}
\text{stmt} \quad \rightarrow \quad & ; \mid \text{continue} ; \mid \text{break} ; \mid \text{return} ; \mid \{ \text{ decl* stmt* } \} \\
& \mid \text{if (expr)} \mid \text{while (expr) stmt stmt (else stmt)?} \\
& \mid \text{expr} ;
\end{aligned}
$$

- upon parsing a statement, which branch we should take can be determined just by its *first* token
- *it is essential to have a separate tokenizer for this type of grammar* (looking ahead a token $\neq$ looking ahead a character)

Parsing Expression Grammar (PEG)

- PEG allows unlimited lookahead (uses backtrack)
- in an alternative, it always tries branches in the written order (the order *does* matter!)
  - 1st branch,
  - if failed, 2nd branch,
  - if failed, 3rd branch, …
- the programmer may insert a ***cut point***
  - if a parser succeeds thus far, it tries no other branches

Lexer/parser generators

- based on the grammar, either:
  - write them by hand, or
  - use a **lexer/parser generators**
- **lexer generator** generates a lexer from the definition of *tokens* (variables, numbers, …)
- **parser generator** generates a parser from the definition of higher-level constructs (expressions, statements, …)

Lexer/parser generators

- some grammar frameworks (PEG) specify them in a single framework

Lexer/parser generators

- many programming languages have lexer/parser generators:
  - lex/yacc (flex/bison): C/C++
  - ANTLR: C, C++, Java, Python, JavaScript, Go, …
  - ocamllex/menhir: OCaml
  - tatsu: Python
  - etc.

In this exercise …

- we use tatsu, a parser generator tool based on PEG, to generate a Python program that converts C source into XML,
- which is then read by the respective XML library you have used before for your language
- see grammar syntax in tatsu
  - thanks to PEG, no need for separate definitions of tokens
- the MinC grammar in tatsu is given in `minc_grammar.y`

Intermediate Representation (IR)

Intermediate Representation (IR)

- a common representation of programs used by a compiler
- roughly $\approx$ an assembly with unlimited variables
- purposes

1. achieve portability
   - hopefully independent from the source language (C, C++, Rust, Go, Julia, etc.)
   - hopefully independent from the target language (x86, ARM, PowerPC, etc.)
2. formulate optimizations as IR $\rightarrow$ IR transformations

Intermediate Representation (IR)

- **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

Code generation (minc_cogen) — basic structure

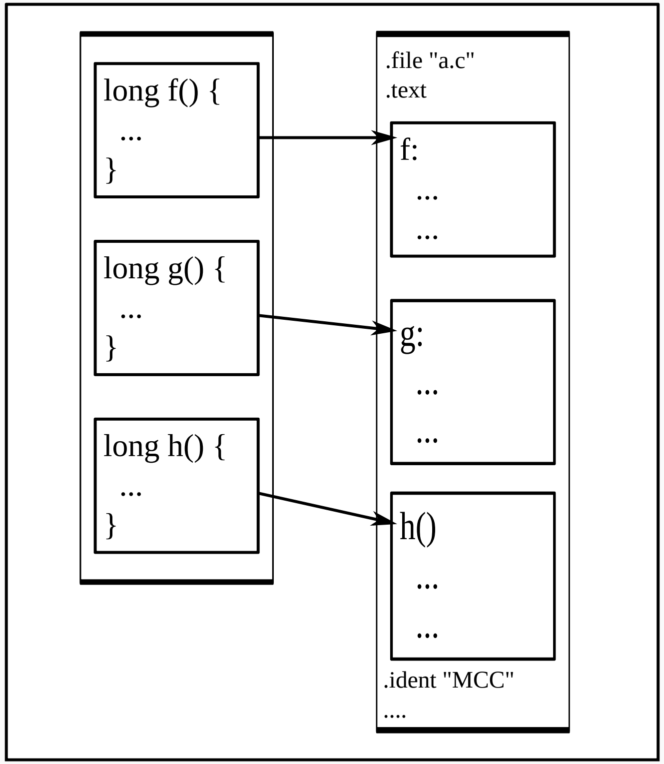
- takes an AST and returns machine code (a list of instructions)
- generate machine code for an AST $\approx$ generate machine code of its components and properly arrange them
- program $\to$ function definition $\to$ statement $\to$ expression

Code generation (minc_cogen) — basic structure

- code generator has lots of:
  - case analysis based on the type of the tree; use:
    - pattern matching (match à la OCaml and Rust), 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

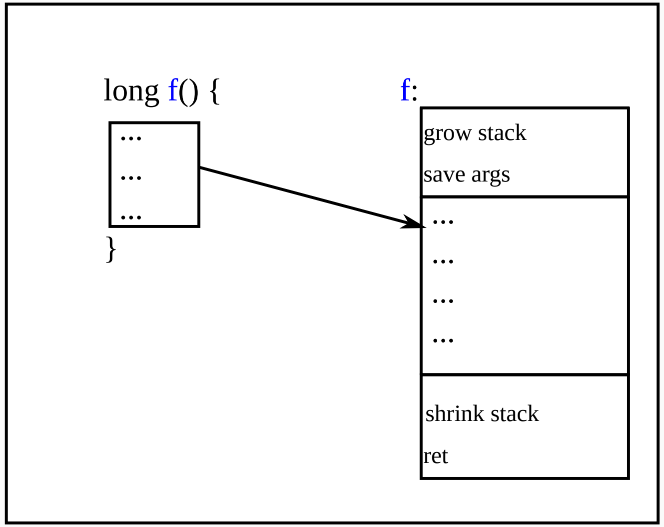


Pseudo code:

```
ast_to_asm_program (Program([d0, d1, ...])) ... =
    ...
    header
  + (ast_to_asm_def d0 ...)
  + (ast_to_asm_def d1 ...)
  + ...
  + trailer
```

Compiling a function definition

- ≈ prologue (grow the stack, etc.) + code for the body (statement) + epilogue (shrink the stack, `ret`, etc.)

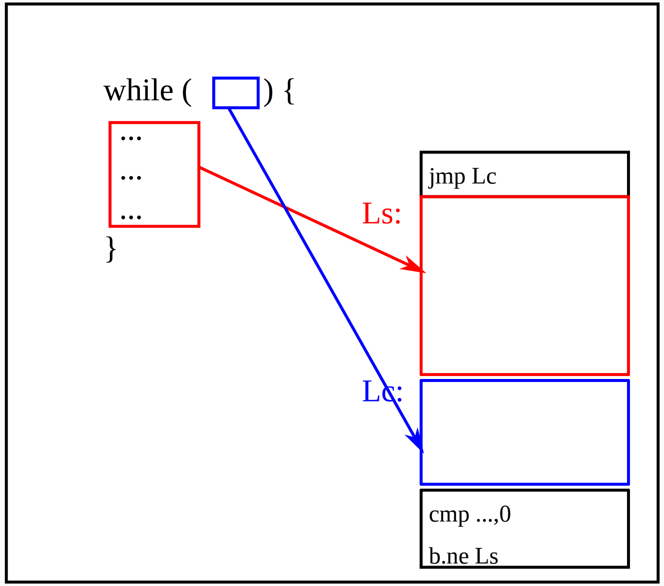


Pseudo code:

```
ast_to_asm_def (DefFun(f, params, ret_type, body)) =
    (gen_prologue f ...)
  + (ast_to_asm_stmt body ...)
  + (gen_epilogue f ...)
```

Compiling a statement (while statement)

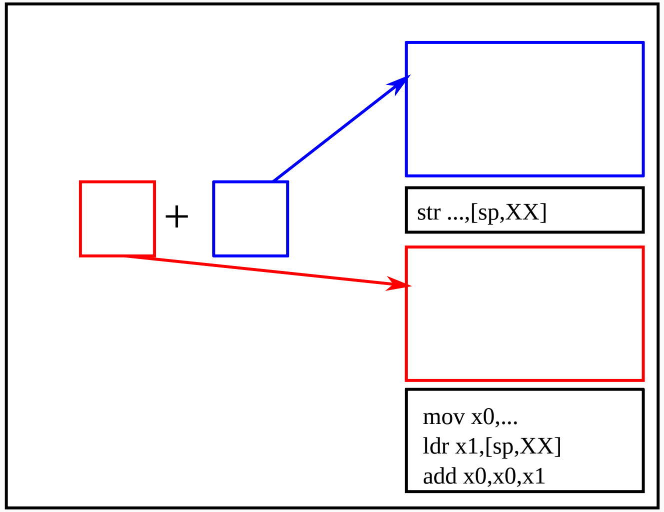
- ≈ place code for the body, condition expression, compare, and a conditional branch




```
ast_to_asm_while_stmt (StmtWhile(cond, body)) ... =
   cond_op,cond_insns = ast_to_asm_expr cond ... ;
   body_insns = ast_to_asm_stmt body ... ;
     ...
   [ jmp Lc; Ls ]
 + body_insns
 + [ Lc ]
 + cond_insns
 + [ cmp cond_op,0; jne Ls ]
```

Compiling an expression (arithmetic)

- ≈ code for the arguments; the arithmetic instruction



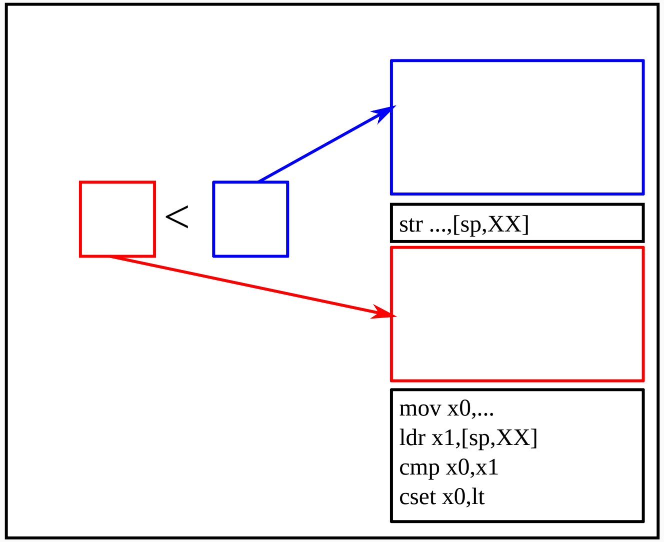

```
ast_to_asm_add_expr ExprOp("+", [e0; e1]) ... =
  insns1,op1 = ast_to_asm_expr e1 ... ;
  insns0,op0 = ast_to_asm_expr e0 ... ;
  m = (* a slot on the stack *);
  (insns1
   + [ str op1,m ]
   + insns0
   + [ mov x0,op0;
       ldr x1,m;
       add x0,x0,x1 ],
   x0)
```

Compiling an expression (comparison)

- $A < B$ is an expression that evaluates to:
  - 1 if $A < B$
  - 0 if $A >= B$
- this can be done by cmp + conditional set (cset)

Compiling an expression (comparison)

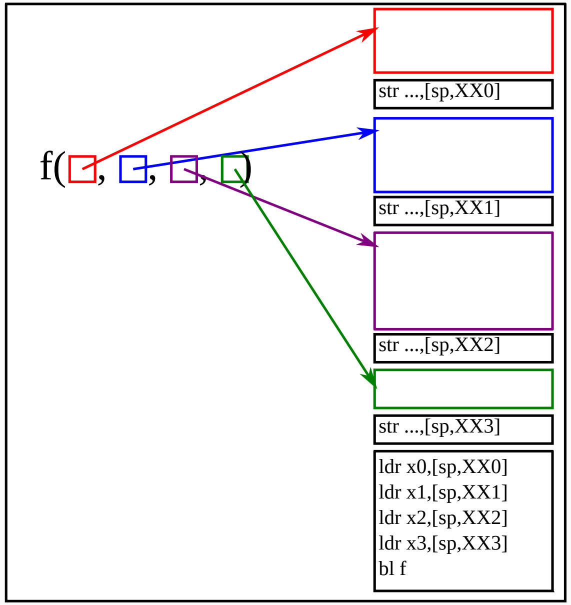
- ≈ compile the arguments; compare; conditional set




```
ast_to_asm_cmp_expr (ExprOp("<", [e0; e1])) ... =
  insns1,op1 = ast_to_asm_expr e1 ... ;
  insns0,op0 = ast_to_asm_expr e0 ... ;
  m1 = (* a slot on the stack *);
    ...
  (insns1
   + [ str op1,m1 ]
   + insns0
   + [ mov x0,op0;
       ldr x1,m1;
       cmp x0,x1;
       cset x0,lt ],
   x0)
```

Compiling an expression (function call)

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

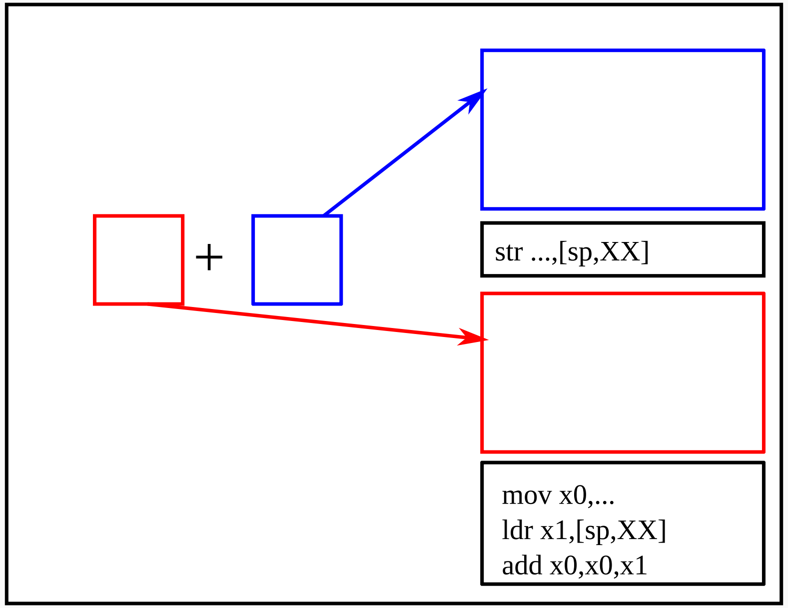



```
ast_to_asm_call_expr (ExprCall(f, [e0;e1;...])) ... =
  [(i0,op0);(i1,op1);..],[m0;m1;...]
    = ast_to_asm_exprs [e0;e1;...] ...;
  (   (i0 + [str op0,m0])
   + (i1 + [str op1,m1])
   + ...
   + [ldr x0,m0;
      ldr x1,m1;
      ...;
      bl f],
   x0)
```

A few left-out details

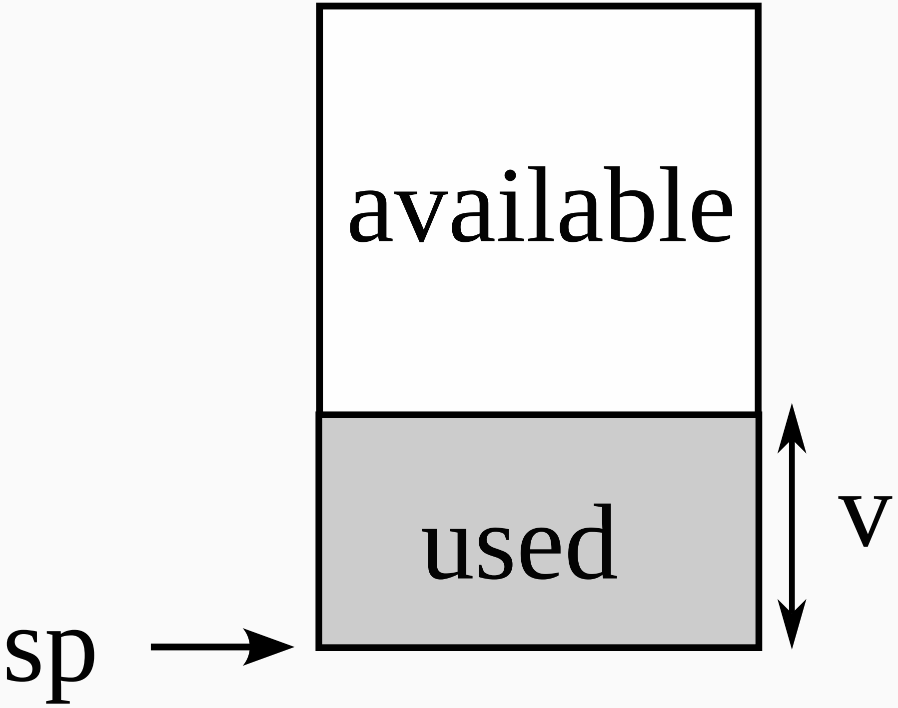
- how to determine locations to save values of *subexpressions* and *variables*
- that is, how to determine XX below:

A few left-out details



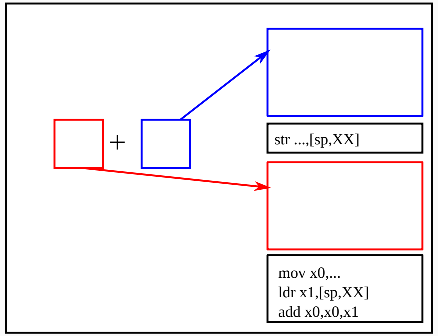
Determining where to save subexpressions

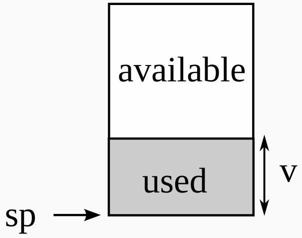
- `ast_to_asm_expr E` receives a value (`v`) pointing to the lowest end of free space in the current stack frame
- `ast_to_asm_expr E` v `...` generates instructions that evaluate `E` using (destroying) only addresses at or above SP+v



Determining where to save subexpressions

- when evaluating $A + B$,
  1. evaluate B, using SP+v and higher; save the result at SP+v
  2. evaluate A, using $v + 8$ and higher addresses






```
ast_to_asm_add_expr ExprOp("+",[e0;e1]) v ... =
  insns1,op1 = ast_to_asm_expr e1  v    ... ;
  insns0,op0 = ast_to_asm_expr e0 (v+8) ... ;
  (   insns1
   + [ str op1,[sp,v] ]
   + insns0
   + [ mov x0,op0;
       ldr x1,[sp,v];
       add x0,x0,x1],
   x0)
```

Locations to hold variables

- example:

```
if (...) {
  long a, b, c;
  ...
}
```

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

Locations to hold variables

- `ast_to_asm_stmt S v ...` generates instructions to execute S; they use (destroy) only addresses at or above SP+v
- $\rightarrow$ hold a, b, and c at:
  - a $\mapsto$ SP+v,
  - b $\mapsto$ SP+v+8
  - c $\mapsto$ SP+v+16

Environment: records where variables are held

- when a variable occurs in an expression, we need to get the location that holds the variable
  - e.g., to compile `x + 1`, we need to know where `x` is stored
- $\rightarrow$ make a data structure that holds a mapping variable $\mapsto$ location ***(environment)*** and pass it to `ast_to_asm_stmt` and `ast_to_asm_expr`
- when new variables are declared at the beginning of a compound statement (`{ ... }`), add new mappings to it

ast_to_asm_expr receives an environment

```
ast_to_asm_expr (ExprId(x)) env v =
  m = env_lookup x env;
  ([ ldr x0,m ], x0)
```

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

ast_to_asm_stmt receives an environment too

```
ast_to_asm_stmt (StmtCompound(decls, stmts)) env v =
  env', v' = env_extend decls env v;
  ast_to_asm_stmts stmts env' v' ...
```

- `env_extend decls env v`:
  - assigns locations (v, v+8, v+16, …) to variables declared in decls
  - registers them in env
  - returns the new environment env' and the new free space v'

Implementing environment

- an environment is a list of (*variable name*, *location*) pairs
- `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`
- `(env', v') = env_extend decls loc env`
  - can be easily built on `env_add` (left for you)