Implementing a Compiler

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Contents

The MinC (“Minimum C”) language

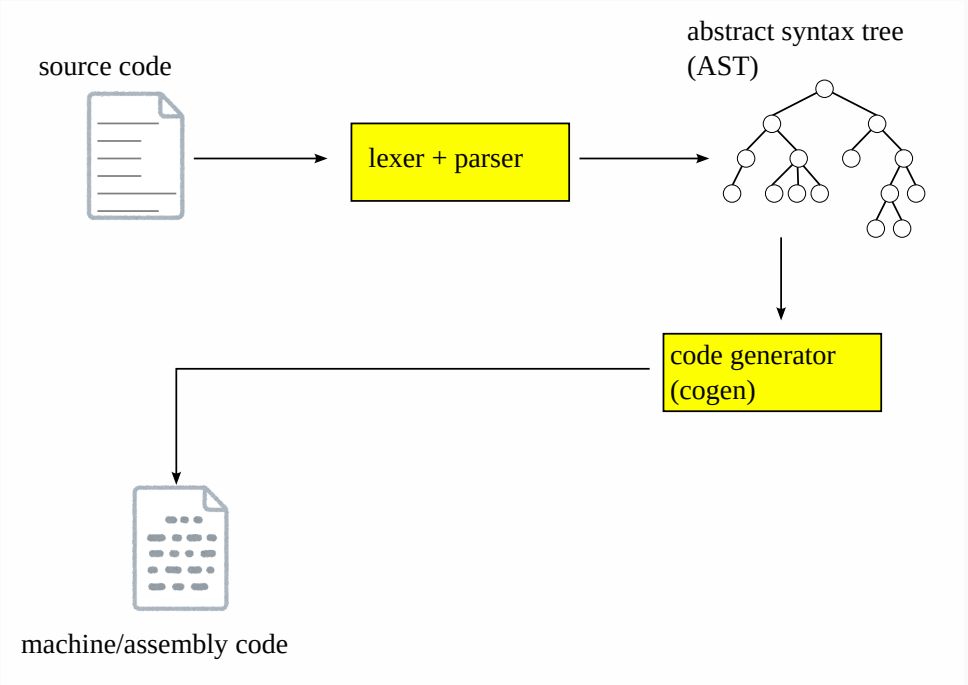
MinC (“Minimum C”) spec overview

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

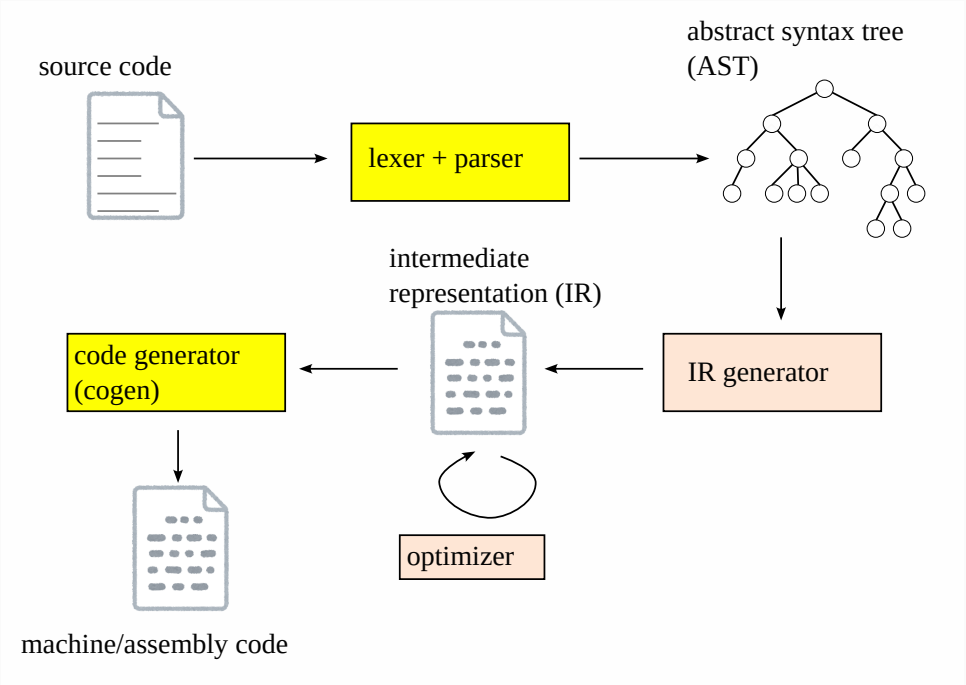
Data structures

- **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

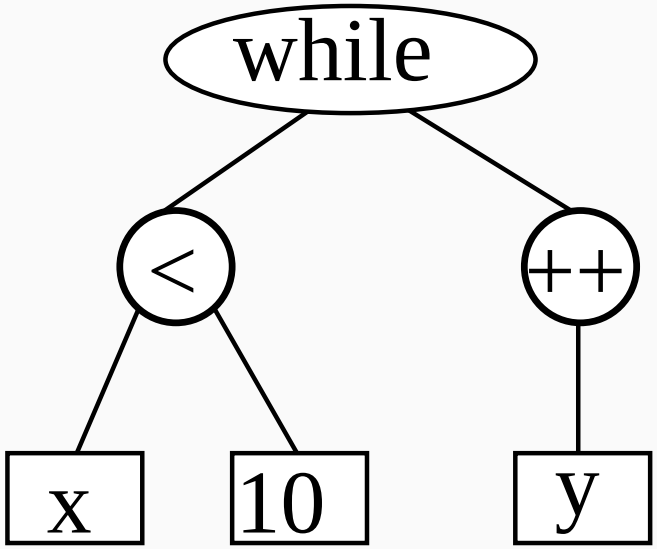
1. **lexing and parsing:** source code (string) $\rightarrow$ AST
2. IR generation: AST $\rightarrow$ IR ($*$)
3. optimization: IR $\rightarrow$ IR ($*$)
4. **code generation:** IR $\rightarrow$ assembly

($*$) : 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 → XML converter
- `{go,jl,ml,rs}/minc/`
  - `minc_ast.??` … abstract syntax tree (AST) definition
  - `minc_parse.??` … XML → AST
  - **`minc_cogen.??`** … AST → 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 $\rightarrow$ AST

Lexer and parser

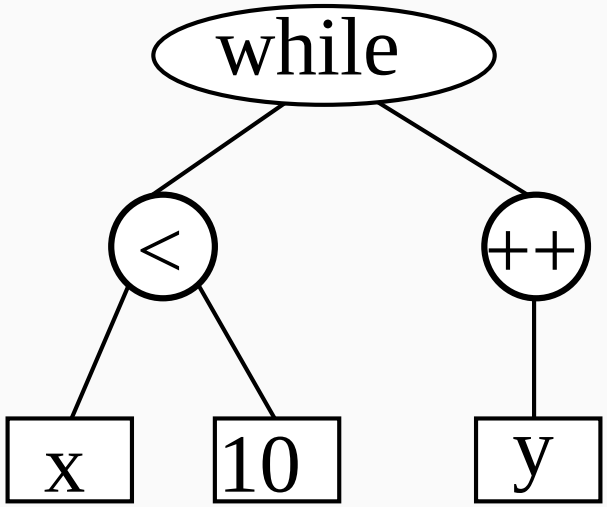
- **lexer:** string → sequence of ***tokens*** (≈ words)
  - also called ***lexical analyzer***, or ***tokenizer***
  - `while (x < 10) y++;` ⇒

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:

ε	(empty string)
c	(a character)
$E\ E$	(concatenation)
$E \mid E$	(alternation)
$E*$	(zero or more repetition)
(E)	(paren)

where E is a regular expression

- $|$, $*$, $($ and $)$ are literals

Regular expression

- expressions for convenience

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

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

alpha	=	A | B | … Z | a | b | … z	A, B, …, Z, a, b, …, z
alpha_	=	alpha | _	A, B, …, Z, a, b, …, z, _

Regular expression examples

id = alpha_ (alpha_ | digit)* a, abc, a0_b1

Regular expression semantics (just for formality …)

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

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

- note: “+” represents string concatenation

Context Free Grammar (CFG)

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

$$L \rightarrow R_0 \; R_1 \; ...$$

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

funcall	→	id (comma_exprs)	f(x, 2 * y, 1)
comma_exprs	→		
comma_exprs	→	expr	
comma_exprs	→	expr comma_expr_star	
comma_expr_star	→		
comma_expr_star	→	, expr comma_expr_star	

An example : statements

stmt → ;
stmt → continue ;
stmt → break ;
stmt → return ;
stmt → { decl* stmt* }
stmt → if (expr) stmt (else stmt)?
stmt → while (expr) stmt
stmt → expr ;

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)

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

CFG semantics (for formality)

$\rightarrow$ id (id , id + int comma_expr_star)

$\rightarrow$ id (id , id + int)

$\therefore$ 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*”

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

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 ($[\![A]\!] = \{\varepsilon, ab, aabb, aaabbb, ...\} = \{a^n b^n \mid n \geq 0\}$)

- the proof is interesting but omitted

If RE $\subset$ CFG, why use both (not just CFG)?

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

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

- 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

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

- 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, …)
- 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`

Code generation

Code generation (minc_cogen) — basic structure

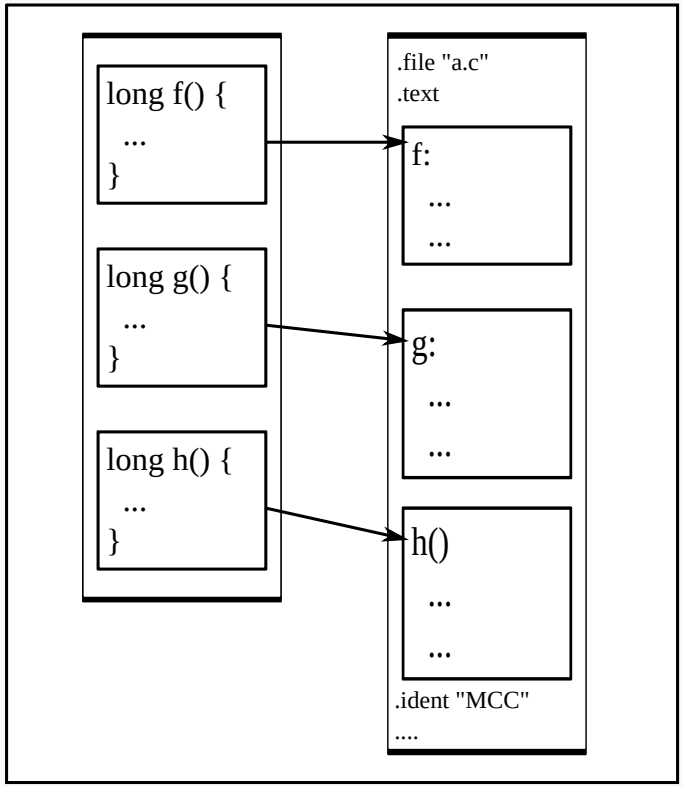
- takes an AST and returns machine code (a list of instructions)
- generate machine code for an AST $\approx$ generate machine code of its components and properly arrange them
- program $\rightarrow$ function definition $\rightarrow$ statement $\rightarrow$ expression

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

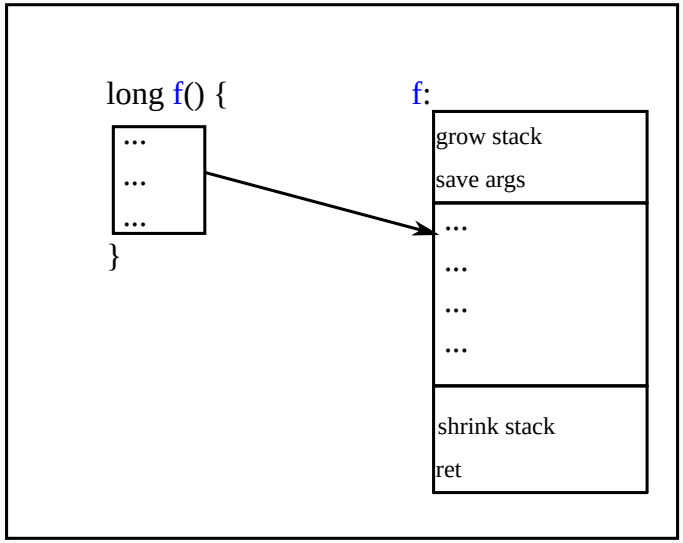


Pseudo code:

```
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.)

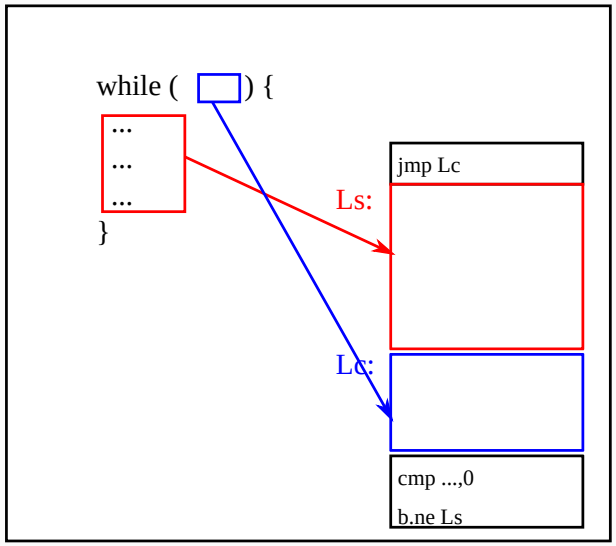


Pseudo code:

```
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)

- ≈ jump to the condition expression; body; the condition expression; compare and conditional branch

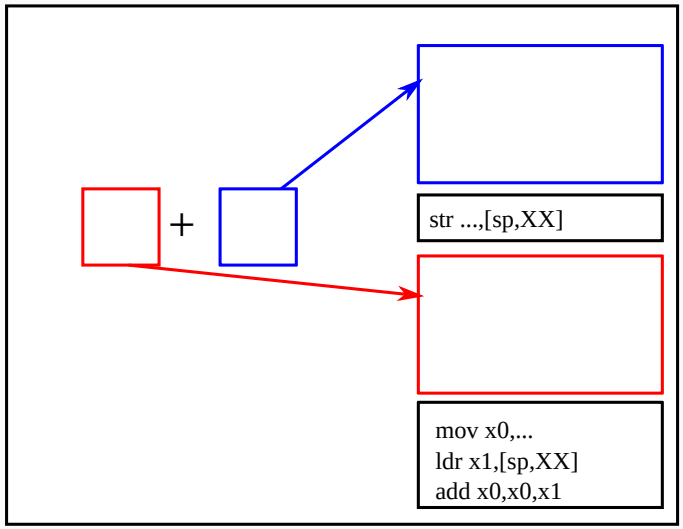



```
ast_to_asm_while_stmt (StmtWhile(cond, body)) ... =
   cond_op,cond_insns = ast_to_asm_expr cond ... ;
   body_insns = ast_to_asm_stmt body ... ;
     ...
   [ jmp Lc; Ls ]
 + body_insns
 + [ Lc ]
 + cond_insns
 + [ cmp cond_op,0; jne Ls ]
```

- (`ast_to_asm_expr` *expr* …) returns a pair: (instructions to evaluate *expr*, the location of the result)

Compiling an expression (arithmetic)

- ≈ instructions to evaluate the arguments; the arithmetic instruction



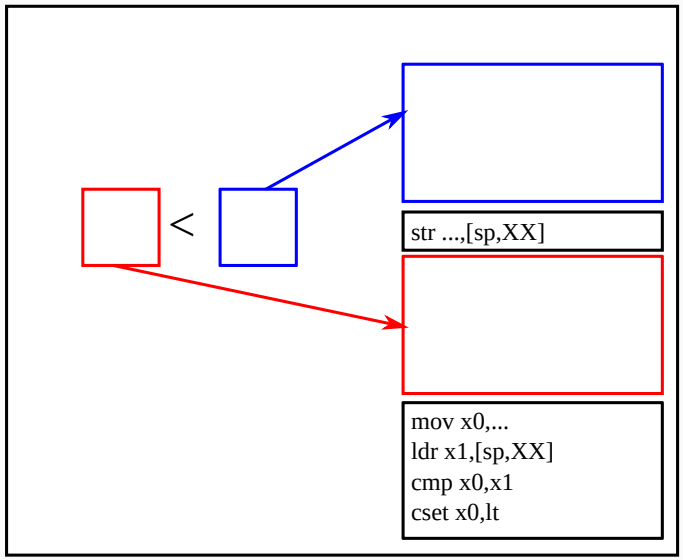

```
ast_to_asm_add_expr ExprOp("+", [e0; e1]) ... =
  insns1,op1 = ast_to_asm_expr e1 ... ;
  insns0,op0 = ast_to_asm_expr e0 ... ;
  m = (* a slot on the stack for e1 *);
  (  insns1
   + [ str op1,m ]
   + insns0
   + [ mov x0,op0;
       ldr x1,m;
       add x0,x0,x1 ],
   x0)
```

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)

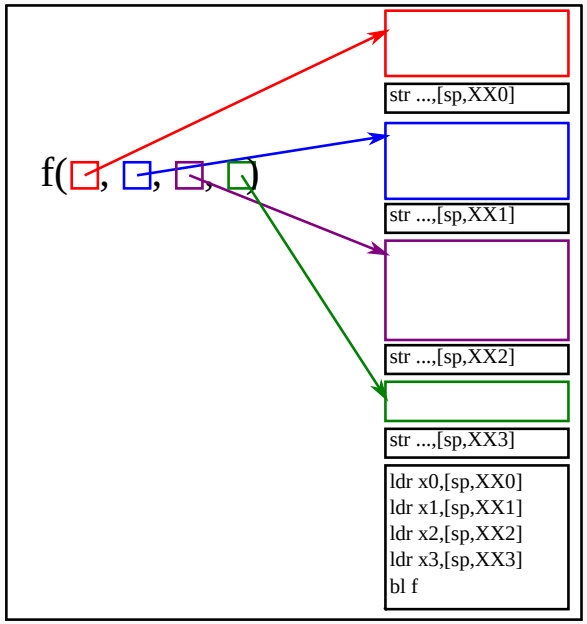
- ≈ compile the arguments; compare; conditional set




```
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 for e1 *);
    ...
  (insns1
   + [ str op1,m1 ]
   + insns0
   + [ mov x0,op0;
       ldr x1,m1;
       cmp x0,x1;
       cset x0,lt ],
   x0)
```

Compiling an expression (function call)

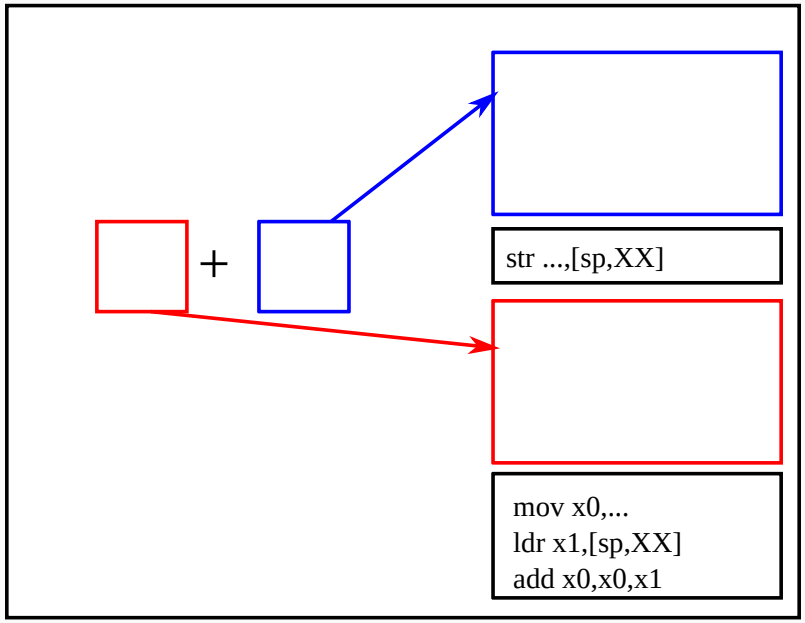
- ≈ instructions for all arguments; put them to positions specified by ABI; a `bl` instruction




```
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)
```

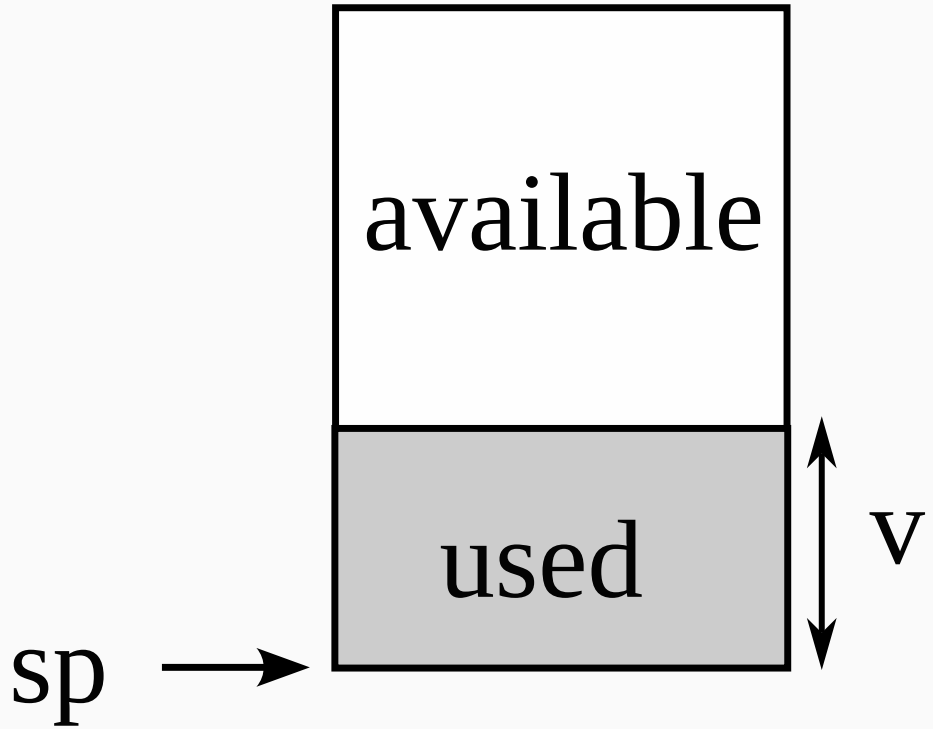
A few left-out details

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



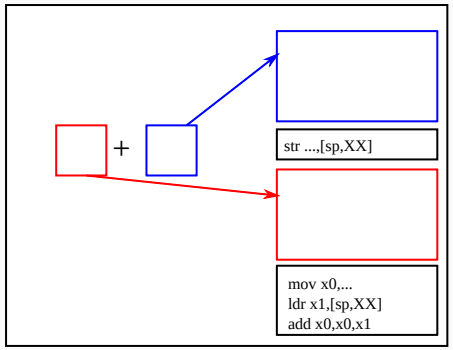
Determining where to save subexpressions

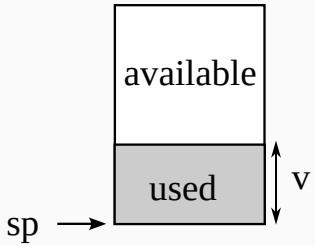
- `ast_to_asm_expr E` receives a value (`v`) pointing to the lowest end of free space in the current stack frame
- `ast_to_asm_expr E` v `...` generates instructions that evaluate `E` using (destroying) only addresses at or above SP+v



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

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

we obviously need to store `a, b, c` somewhere, but where?

- the problem is almost identical to saving values of subexpressions
- $\rightarrow$ `ast_to_asm_stmt` also takes v pointing to the free space
- (`ast_to_asm_stmt` S v ...) generates instructions to execute S, using only addresses at or above SP $+ v$
- $\Rightarrow$
  - $a \mapsto (\text{SP} + v)$
  - $b \mapsto (\text{SP} + v + 8)$
  - $c \mapsto (\text{SP} + v + 16)$

Environment: records where variables are held

- variable locations must be known when generating code for expressions referencing them
  - 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`
  - generating code for variables look up the environment
  - a compound statement (`{ ... }`) adds new mappings to the environment

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 (*association list*)
- `v = env_lookup x env`
  - returns the location paired with `x` in environment `env`
- `env' = env_add x v env`
  - returns a new environment `env'` which has a new mapping $x \mapsto v$ in addition to `env`
- `(env', v') = env_extend decls v env`
  - can be easily built on `env_add` (left for you)

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
- **note:** in the exercise you could design your IR, but it is not necessary (it is possible to directly go from AST $\rightarrow$ asm)

Optimizations performed on IR level (a brief)

- **constant folding and propagation** — compute values at compile time where possible
- **hoisting** — lift instructions in a loop outside of it
- **function call inlining** — replace a call to a function with its body
- **register allocation** — assign registers to variables to reduce memory access