Experiment in Compiler Construction

Code Generation (1)

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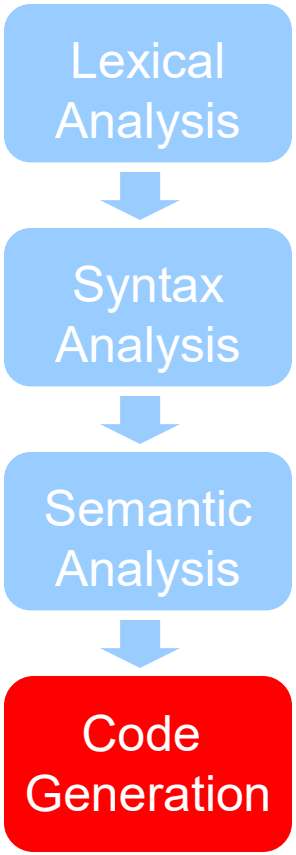
Overview

- Code generation overview
- Stack calculator
  - Stack calculator's memory
  - Instruction set
- Additional changes in symbol table
  - Variables
  - Parameters
  - Program, functions, and procedures

What is code generation?

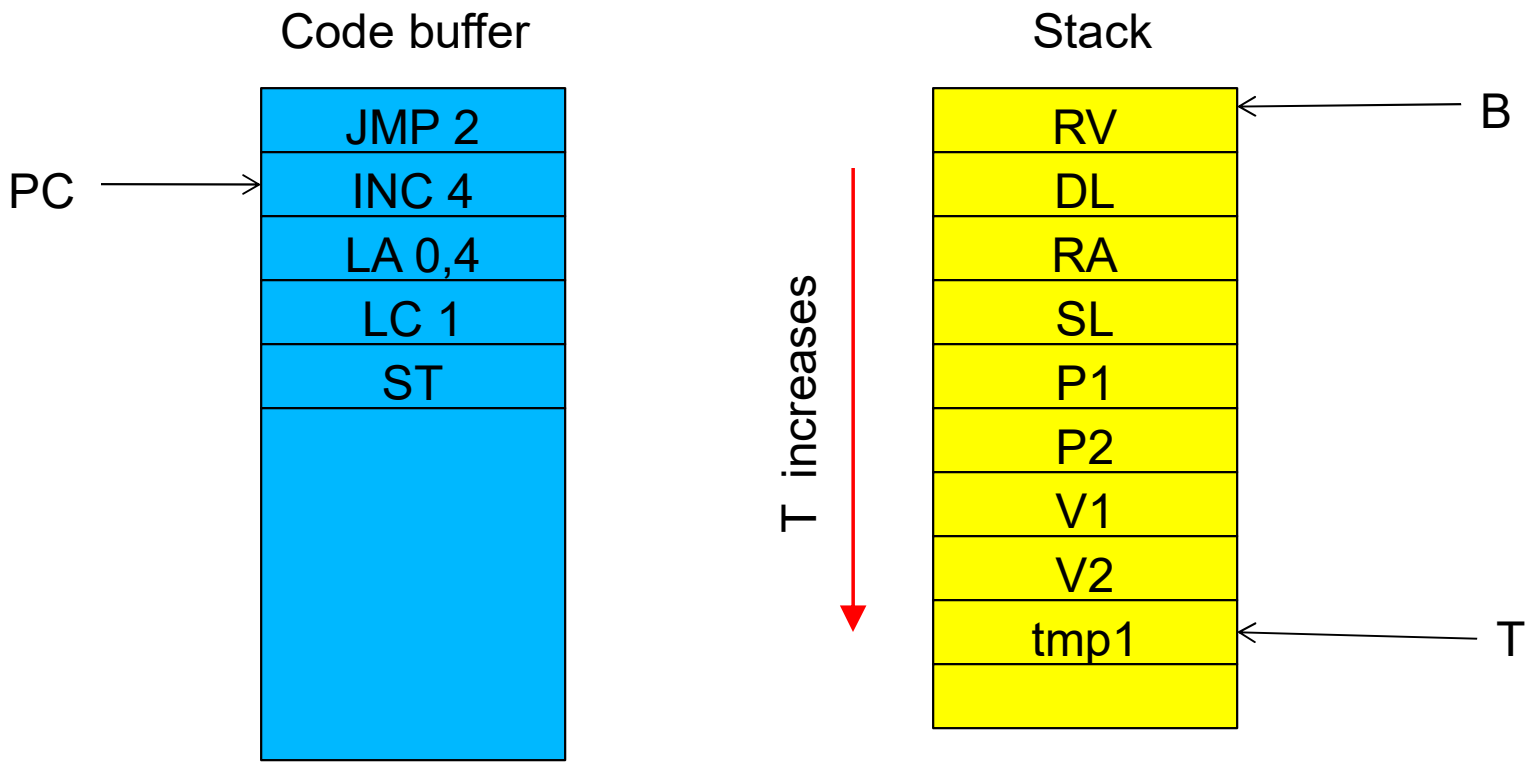


- Code generation is the phase that generates a sequence of target machine instructions corresponding to the source program's grammar.
- Program's grammar is checked and built by the syntax analyzer (parser)
- Target machine instructions are specified in execution model of target machine

Stack calculator

- Stack calculator is a computing system
  - Using stack to store intermediate results during computation process.
  - Simple organization
  - Simple instruction set
- Stack calculator consists of 2 memory areas
  - Code buffer: containing execution code corresponding to source program
  - Stack: storing intermediate results

Stack calculator



Stack calculator

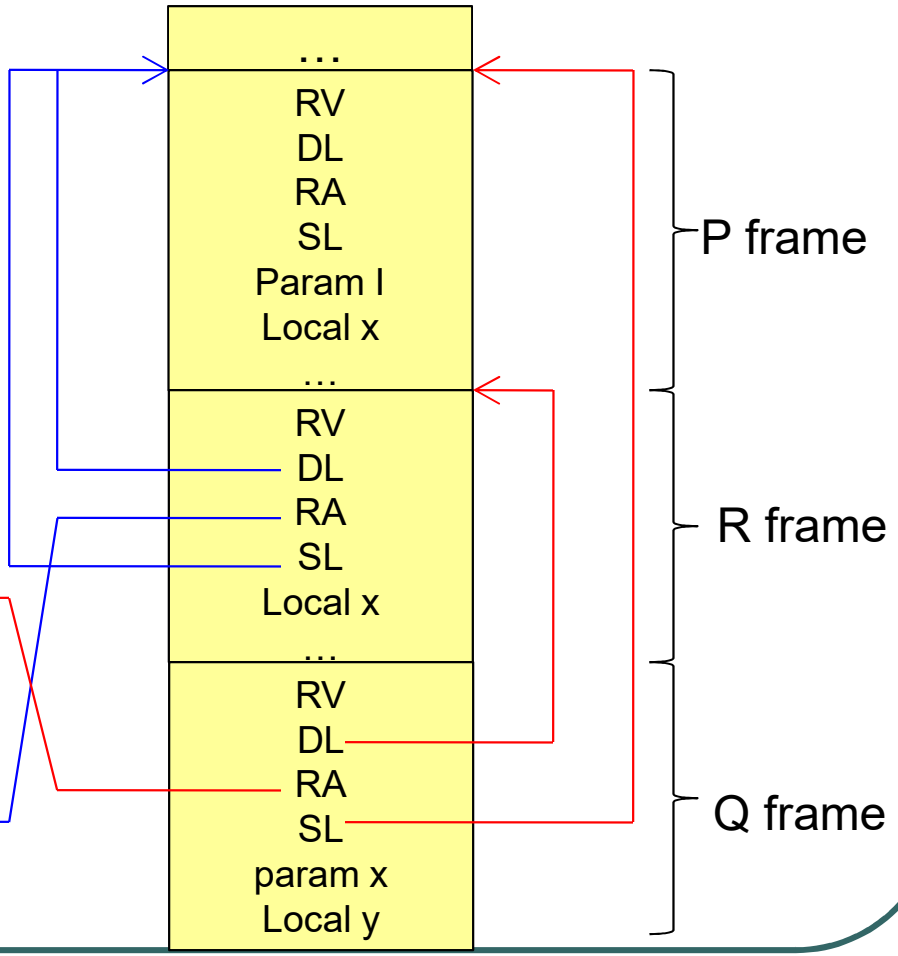
- Registers
  - PC (program counter): pointing to currently being executed instruction on Code buffer
  - B (base): pointing to the base address of data area of active block on Stack. Local varialbes are accessed via B
  - T (top): pointing to Stack's top element

Stack calculator

- Activation record / Stack frame
  - Is the memory area allocated to every function, procedure and the main program when it is activated (becoming active block)
    - Storing parameters' values
    - Storing local variables's values
    - Other information
      - Return value – RV
      - Dynamic link – DL
      - Return address – RA
      - Static link – SL
  - A function/procedure may have several Stack frames on Stack

Stack calculator

```
Procedure P(I : integer);
  Var a : integer;
  Function Q;
    Var x : char;
    Begin
      …
      return
    End;
  Procedure R(X: integer);
    Var y : char;
    Begin
      …
      y = Call Q;
      …
    End;
  Begin
    …
    Call R(1);
    …
  End;
…
```



Stack calculator

- RV (return value): stores return value of a function
- DL (dynamic link): is the base address of caller's Stack frame. DL is used to recover caller's context when the callee ends.
- RA (return address): address of caller's instruction that would be executed when callee ends.
- SL (static link): base address of outer's Stack frame. SL is useful when we track non-local variables.

Stack calculator

- Instruction set

LA	Load Address	t:=t+1; s[t]:=base(p)+q;
LV	Load Value	t:=t+1; s[t]:=s[base(p)+q];
LC	Load Constant	t:=t+1; s[t]:=q;
LI	Load Indirect	s[t]:=s[s[t]];
INT	Increment T	t:=t+q;
DCT	Decrement T	t:=t-q;

Stack calculator

- Instruction set

J	Jump	pc:=q;
FJ	False Jump	if s[t]=0 then pc:=q; t:=t-1;
HL	Halt	Halt
ST	Store	s[s[t-1]]:=s[t]; t:=t-2;
CALL	Call	s[t+2]:=b; s[t+3]:=pc; s[t+4]:=base(p); b:=t+1; pc:=q;
EP	Exit Procedure	t:=b-1; pc:=s[b+2]; b:=s[b+1];
EF	Exit Function	t:=b; pc:=s[b+2]; b:=s[b+1];

Stack calculator

- Instruction set

RC	Read Character	read one character into s[s[t]]; t:=t-1;
RI	Read Integer	read integer to s[s[t]]; t:=t-1;
WRC	Write Character	write one character from s[t]; t:=t-1;
WRI	Write Integer	write integer from s[t]; t:=t-1;
WLN	New Line	CR & LF

Stack calculator

- Instruction set

AD	Add	t:=t-1; s[t]:=s[t]+s[t+1];
SB	Subtract	t:=t-1; s[t]:=s[t]-s[t+1];
ML	Multiply	t:=t-1; s[t]:=s[t]*s[t+1];
DV	Divide	t:=t-1; s[t]:=s[t]/s[t+1];
NEG	Negative	s[t]:=-s[t];
CV	Copy Top of Stack	s[t+1]:=s[t]; t:=t+1;

Stack calculator

- Instruction set

op	p	q

EQ	Equal	t:=t-1; if s[t] = s[t+1] then s[t]:=1 else s[t]:=0;
NE	Not Equal	t:=t-1; if s[t] != s[t+1] then s[t]:=1 else s[t]:=0;
GT	Greater Than	t:=t-1; if s[t] > s[t+1] then s[t]:=1 else s[t]:=0;
LT	Less Than	t:=t-1; if s[t] < s[t+1] then s[t]:=1 else s[t]:=0;
GE	Greater or Equal	t:=t-1; if s[t] >= s[t+1] then s[t]:=1 else s[t]:=0;
LE	Less or Equal	t:=t-1; if s[t] <= s[t+1] then s[t]:=1 else s[t]:=0;

Changes in symbol table

- Variable's new attributes
  - localOffset: variable's location on local frame.
  - scope
- Parameter's new attributes
  - localOffset: parameter's location on local frame.
  - scope
- Program/function/procedure's new attributes
  - codeAddress: address of first instruction on Code buffer
  - frameSize: size of corresponding Stack frame
  - paramCount: number of parameters

Changes in symbol table

- Variable's new attributes
  - Scope
  - localOffset: location in local frame (its distance to local frame's base)

```
struct VariableAttributes_ {
  Type *type;
  struct Scope_ *scope;
  int localOffset;
};
```

Changes in symbol table

- Parameter's new attributes
  - Scope
  - localOffset

```
struct ParameterAttributes_ {
  enum ParamKind kind;
  Type* type;
  struct Scope_ *scope;
  int localOffset;
};
```

Changes in symbol table

- Scope's new attribute
  - frameSize

```
struct Scope_ {
  ObjectNode *objList;
  Object *owner;
  struct Scope_ *outer;
  int frameSize;
};
```

Changes in symbol table

- Function's new attributes
  - codeAddress
  - paramCount

```
struct FunctionAttributes_ {
  struct ObjectNode_ *paramList;
  Type* returnType;
  struct Scope_ *scope;

  int paramCount;
  CodeAddress codeAddress;
};
```

Changes in symbol table

- Procedure's new attributes
  - codeAddress
  - paramCount

```
struct ProcedureAttributes_ {
  struct ObjectNode_ *paramList;
  struct Scope_* scope;

  int paramCount;
  CodeAddress codeAddress;
};
```

Changes in symbol table

- Program's new attribute
  - codeAddress

```
struct ProgramAttributes_ {
  struct Scope_ *scope;
  CodeAddress codeAddress;
};
```

Assignments

- Implement following function in *symtab.c*

```
int sizeOfType(Type* type);
void declareObject(Object* obj);
```

- Note: for simplicity, each integer/char occupies one word (4 bytes) in Stack
- Order of words in a local frame is as following:
  - 0: RV
  - 1: DL
  - 2: RA
  - 3: SL
  - 4 $\rightarrow$ (4+k): for k parameters
  - (4+k+1) $\rightarrow$ (4+k+n): for local variables

Experiment in Compiler Construction

Code generation (2)

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Overview

- kplrun utility
- Overview of instructions.*, codegen.*
- Generate code for (no subprogram/array)
  - ASSIGN (substitute) statement
  - IF statement
  - WHILE statement
  - FOR statement
  - CONDITION
  - EXPRESSION

kplrun

- Interpreter for Stack calculator. Syntax:

```
$ kplrun <source> [-s=stack-size] [-c=code-size] [-debug] [-dump]
```

- Options:
  - –s: define Stack size
  - –c: define maximum size of source program
  - –dump: output generatated instruction code to standard output
  - –debug: debugging mode

kplrun

- Options in debugging mode
  - a: corresponding absolute address of a Stack location (level, offset)
  - v: value stored in a Stack location (level, offset)
  - t: value stored in Stack's top
  - c: exit debugging mode

Instructions.c

```
enum OpCode {
  OP_LA,    // Load Address:
  OP_LV,    // Load Value:
  OP_LC,    // load Constant
  OP_LI,    // Load Indirect
  OP_INT,   // Increment t
  OP_DCT,   // Decrement t
  OP_J,     // Jump
  OP_FJ,    // False Jump
  OP_HL,    // Halt
  OP_ST,    // Store
  OP_CALL,  // Call
  OP_EP,    // Exit Procedure
  OP_EF,    // Exit Function
```

```
  OP_RC,    // Read Char
  OP_RI,    // Read Integer
  OP_WRC,   // Write Char
  OP_WRI,   // Write Int
  OP_WLN,   // WriteLN
  OP_AD,    // Add
  OP_SB,    // Substract
  OP_ML,    // Multiple
  OP_DV,    // Divide
  OP_NEG,   // Negative
  OP_CV,    // Copy Top
  OP_EQ,    // Equal
  OP_NE,    // Not Equal
  OP_GT,    // Greater
  OP_LT,    // Less
  OP_GE,    // Greater or Equal
  OP_LE,    // Less or Equal

  OP_BP     // Break point.
};
```

Instructions.c

```
struct Instruction_ {
  enum OpCode op;
  WORD p;
  WORD q;
};


struct CodeBlock_ {
  Instruction* code;
  int codeSize;
  int maxSize;
};
```

```
CodeBlock* createCodeBlock(int maxSize);
void freeCodeBlock(CodeBlock* codeBlock);
void printInstruction(Instruction* instruction);
void printCodeBlock(CodeBlock* codeBlock);

void loadCode(CodeBlock* codeBlock, FILE* f);
void saveCode(CodeBlock* codeBlock, FILE* f);

int emitLA(CodeBlock* codeBlock, WORD p, WORD q);
int emitLV(CodeBlock* codeBlock, WORD p, WORD q);
int emitLC(CodeBlock* codeBlock, WORD q);
….
int emitLT(CodeBlock* codeBlock);
int emitGE(CodeBlock* codeBlock);
int emitLE(CodeBlock* codeBlock);

int emitBP(CodeBlock* codeBlock);
```

codegen.c

```
void initCodeBuffer(void);
void printCodeBuffer(void);
void cleanCodeBuffer(void);
int serialize(char* fileName);

int genLA(int level, int offset);
int genLV(int level, int offset);
int genLC(WORD constant);
….
int genLT(void);
int emitGE(void);
int emitLE(void);
```

Generate code for ASSIGN statement

v := exp

```
<code of l-value v>  // load address of v
<code of exp>        // load value of of exp
ST
```

Generate code for IF statement

If <cond> Then statement;

```
  <code of cond>     // load value of condition
  FJ L
  <code of statement>
L:
  …
```

If <cond> Then st1 Else st2;

```
  <code of cond>     // load value of condition
  FJ L1
  <code of st1>
  J L2
L1:
  <code of st2>
L2:
  …
```

Generate code for WHILE statement

While <cond> Do statement

```
L1:
  <code of cond> // load value of condition
  FJ L2
  <code of statement>
  J L1
L2:
  …
```

Generate code for FOR statement

For v := exp1 to exp2 do statement

```
  <code of l-value v>
  CV   // copy top of stack – duplicate address of v
  <code of exp1>
  ST   // store original value of v
L1:
  CV
  LI   // get value of v
  <code of exp2>
  LE
  FJ L2
  <code of statement>
  CV;CV;LI;LC 1;AD;ST;  // increase v's value by 1
  J L1
L2:
  DCT 1
  …
```

Assignments

- Complete following function in *codegen.c*
  - `genVariableAddress(Object* var)`

    // push address of a variable to Stack's top
  - `genVariableValue(Object* var)`

    // push value of a variable to Stack's top

Note: non-local variable temporarily exclusive

Assignments

- Complete following functions in *parser.c*
  - Generate code for a varialbe l-value
  - Generate code for statements: Assign, If, While, For
  - Generate code for Condition
  - Generate code for Expression

Experiment in Compiler Construction

Code generation (3)

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Overview

- Generate code for variable's address/value (non-local inclusive)
- Generate code for parameter's address/value (non-local inclusive)
- Generate code for address of function's return value
- Generate code for calling function/procedure
  - Generate code for arguments
- Treatment of array

Generate code for VARIABLE's address and value

- When generate code for a variable's address/value, pay attention to its scope
  - Local variable: track in active Stack frame
  - Non-local variable: track static links and depth of tracking equals depth from current scope to variable's scope

```
computeNestedLevel(Scope* scope)
```

Generate code for PARAMETER's address

- Dosage: when `LValue` is a parameter
- As variable, pay attention to its scope
- Call by value: push to top of Stack parameter's address.
- Call by reference: push to top of Stack parameter's value

Generate code for PARAMETER's value

- Dosage: when compute value of **`Factor`**
- As variable, pay attention to its scope
- Call by value: push to Stack parameter's value
- Call by reference: push to Stack the value located at the address which is parameter's value

Generate code for address of FUNCTION's return value

- Offset = 0.
- Level = depth from current scope to function's scope

Generate code for CALLING function/procedure

- Dosage
  - Calling a function: when generate code for **`factor`**
  - Calling a procedure: when generate code for **`CallSt`** statement.
- Preparation: identify values of parameters
  - Increase value of T by 4 (omit RV, DL, RA, SL)
  - Generate code for k arguments
  - Decrease value of T by 4 + k
  - Generate code for CALL statement

Generate code for CALL(p,q) statement

```
CALL (p, q)  s[t+2]:=b;          // store dynamic link
             s[t+3]:=pc;         // store return address
             s[t+4]:=base(p);    // store static link
             b:=t+1;        // new base, new return value address
             pc:=q;              // jump to new instruction
```

CALL (p, q) to a function/procedure A require 2 parameters

p: Depth of CALL statement

= depth of A's outer

= depth from current scope to scope of A's outer

p tells A's static link

q: Address of new instruction code

Operation of stack calculator when a CALL(p, q) instruction is performed

1. `pc` changes to codeAddress (beginning address) of called sub-program`/* pc = p */`
2. Increase `pc` by 1 `/* pc ++ */`
3. First code instruction would be Jump instruction `J` to omit code instruction of local declaration in `code buffer`.
4. Next statement would be `INT` to increase `T` exactly by size of frame to omit Stack area corresponding to local parameters and variables.

Operation of stack calculator when a CALL(p, q) instruction is performed

5. Execute next instructions and Stack would changes correspondingly.
6. Ending
    1. A procedure (instruction `EP`): release active frame and set `T` to previous frame's top.
    2. Function (lệnh `EF`): release active frame, except return value at `offset 0`, set `T` to `offset 0`.

Treatment of ARRAY

- An array that is declared like

  $A : array(.n_1.)\ of\ \ldots\ of\ array(.n_k.)\ of\ integer/char$

  would occupies $n_1 * \ldots * n_k$ word in Stack frame
- Element $A(.i_1.)\ldots(.i_k.)$ is located at address

  $= A + (i_1 - 1) * n_2 * \ldots * n_k$

  $+ (i_2 - 1) * n_3 * \ldots * n_k$

  $\ldots$

  $+ (i_{k-1} - 1) * n_k$

  $+ (i_k - 1)$
- This address is accumulated when compiling indexes

Assignments

- Complete functions in ***codegen.c***

```
int computeNestedLevel(Scope* scope);
void genVariableAddress(Object* var)
void genVariableValue(Object* var)
void genParameterAddress(Object* param)
void genParameterValue(Object* param)
void genReturnValueAddress(Object* func)
void genReturnValueValue(Object* func)
void genProcedureCall(Object* proc)
void genFunctionCall(Object* func)
```

Assignments

- Make changes to ***parser.c***

```
Type* compileLValue(void);
void compileCallSt(void);
Type* compileFactor(void);
Type* compileIndexes(Type* arrayType);
```