

Back-End Code Generation

- Given a list of *itree fragments*, how to generate the corresponding *assembly code* ?

```
datatype frag
= PROC of {name : Tree.label,      function name
           body : Tree.stm,        function body itree
           frame : Frame.frame}    static frame layout
| DATA of string
```

- Main challenges:** certain aspects of *itree statements and expressions* do not correspond *exactly* with machine languages:

of temp. registers on real machines are limited

real machine's conditional-JUMP statement takes only one label

high-level constructs **ESEQ** and **CALL** ---- side-effects

Itree Stmts and Exprs

- itree statements* **stm** and *itree expressions* **exp**

```
datatype stm = SEQ of stm * stm
              | LABEL of label
              | JUMP of exp
              | CJUMP of test * label * label
              | MOVE of exp * exp
              | EXP of exp

and exp = BINOP of binop * exp * exp
         | CVTOP of cvtop * exp * size * size
         | MEM of exp * size
         | TEMP of temp
         | NAME of label
         | CONST of int
         | CONSTF of real
         | ESEQ of stm * exp
         | CALL of exp * exp list
```

Side-Effects

- Side-effects* means updating the contents of a memory cell or a temporary register. What are itree expressions that might cause side effects ?

ESEQ and **CALL** nodes

- ESEQ(s,e)** where **s** is a list of statements that may contain **MOVE** statement

The natural way to generate assembly code for **BINOP**(**op**, t_1 , t_2)

instructions to compute t_1 into r_i ;

instructions to compute t_2 into r_j ;

$r_k \leftarrow r_i \text{ OP } r_j$

But it won't work for this:

BINOP(PLUS, TEMP a, **ESEQ**(**MOVE**(TEMP a, u), v))

- CALL(e, el)** by default puts the result in the *return-result register*.

BINOP(PLUS, **CALL**(...), **CALL**(...))

Summary: IR -> Machine Code

- Step #1** : Transform the *itree* code into a list of *canonical trees*

a. eliminate **SEQ** and **ESEQ** nodes

b. the arguments of a **CALL** node should never be other **CALL** nodes

---- the parent of each **CALL** node should either be

EXP(...) or **MOVE**(TEMP t , ...)

- Step #2** : Perform various *code optimizations* on canonical trees

- Step #3** : Rearrange the *canonical trees* (into *traces*) so that every

CJUMP(**cond**, l_t , l_f) is immediately followed by **LABEL**(l_f).

- Step #4** : **Instruction Selection** ---- generate the pseudo-assembly code from the *canonical trees* in the step #3.

- Step #5** : Perform *register allocations* on pseudo-assembly code

Canonical Trees

- A **canonical tree** is a simple **itree** statement in the following form (it is really a restricted-kind of **itree statement**):

```
datatype stm = LABEL of label
             | JUMP of exp
             | CJUMP of test * label * label
             | MOVE of exp * exp
             | EXP of exp

and exp = BINOP of binop * exp * exp
         | CVTOP of cvtop * exp * size * size
         | MEM of exp * size
         | TEMP of temp
         | NAME of label
         | CONST of int
         | CONSTF of real
         | CALL of exp * exp list
```

Restrictions:

- no **SEQ** statements, no **ESEQ** expressions.
- each **CALL** node doesn't contain other **CALL** nodes as subtrees

Canonicalizer

- The body of each **PROC** fragment is **translated** into an **ordered list of canonical trees**

stms: Tree.stm list

- Step 1**: transformation on **CALL** nodes.

```
CALL( ... ) =====>
  ESEQ(MOVE(TEMP t, CALL( ... ), TEMP t)
```

- Step 2**: elimination of **ESEQ** nodes. (see Appel pp 174-179)

lift them higher and higher until they become **SEQ** nodes ...

Rearranging itree statements

- Goal**: rearrange the list of **canonical trees** so that every **CJUMP**(*cond*, *l_f*, *l_f*) is immediately followed by its false branch **LABEL**(*l_f*).
- Step #1**: take a list of canonical trees and form them into **basic blocks**

A **basic block** is a sequence of statements that is always entered at the beginning and exited at the end:

- the first statement is a **LABEL**
- the last statement is a **JUMP** or **CJUMP**
- there are no other **LABELS**, **JUMPS**, or **CJUMPS** in between

basic blocks are often used to analyze a program's **control flow**

- Step #2**: re-order the list of **basic blocks** into **traces**

Canonical Trees => Basic Blocks

- Input**: a sequence of statements (i.e., canonical trees --- the body of a function);
- Output**: a set of basic blocks

- Algorithm**:

if a new **LABEL** is found, end the current block and start a new block;

if a **JUMP** or **CJUMP** is found, end the current block;

if it results a block not ending with a **JUMP** or **CJUMP**, then a **JUMP** to the next block's label is appended to the block;

if it results a block without a **LABEL** at the beginning, invent a new **LABEL** and stuck it there;

invent a new label *done* for the beginning of the **epilogue**;

put **JUMP**(**NAME** *done*) at the end of the last basic block.

Basic Blocks => Traces

- **Control Flow Graph (CFG):** basic blocks as the nodes, pairs (a, b) as the edges if block a ends with a **CJUMP** or **JUMP** statement to block b .
- Basic blocks can be arranged in **any order**, but we want:
 - each **CJUMP** is followed by its **false** label
 - each **JUMP** should be followed by its **target** label whenever possible
- A **trace** is a **path** in the **CFG** --- it characterizes some fragment of a real program execution.
- **Algorithm** for gathering traces: just do the **depth-first traversal** of the CFG --- (can also take advantage of **branch prediction** information)

Traces => List of Statements

- Flatten the **traces** back to an ordered list of statements (canonical trees):
 - any **CJUMP** followed by its **false** label: *do nothing* ;
 - any **CJUMP** followed by its **true** label: switch its **true** and **false** label, and **negate** the condition;
 - remove **JUMP** (l) if it is followed by its target l ;
 - any **CJUMP** ($cond, l_t, l_f$) followed by **neither** label: invent a new false label l_n , rewrite it into :

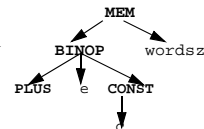

```
CJUMP(cond, l_t, l_n)
LABEL l_n
JUMP(NAME l_f)
```
- We are now ready to do **instruction selection** : generate assembly code for your favourite target machine.

Instruction Selection

- **Input** : an ordered list of canonical trees;
- **Output**: the pseudo-assembly code (without register assignments)
- **Algorithm**: translating each **canonical tree** into an assembly code sequence, and then **concatenate** all sequences together.
- **Main Problem**: how to map the canonical tree to the assembly code ?
- Each **machine instruction** can be expressed as a **tree pattern** --- a fragment of the canonical tree :

Load the value at addr $e + c$ in the memory !

Each machine instruction may correspond to several layer of **tree** expressions



Instruction Selection via Tiling

- Express each machine instruction as a **tree pattern**.
- Given a **canonical tree**, the instruction selection is just to **tile** the tree using various tree patterns (for all possible machine instructions) ----- cover the **canonical tree** using nonoverlapping **tiles**.
- **Optimum Tiling** : ---- one whose tiles sum to the lowest possible value (suppose we give each machine instruction a cost)
- **Optimal Tiling** : ---- one where no two adjacent tiles can be combined into a single tile of lower cost
- Even **optimum** tiling is also **optimal**, but no vice versa.
- **Algorithm**: **maximum munch** finds the **optimal** tiling;
dynamic programming finds the **optimum** tiling.

Maximal Munch

- Algorithm --- **Maximal Munch**:

Start at the root of a canonical tree, find the **largest tile** that fits; the **largest tile** is the one with the most nodes (if tie, break arbitrarily)

Cover the **root** node and perhaps several other nodes near the root with this tile, leaving several subtrees; the instruction corresponding to the **tile** is generated.

Repeat the same algorithm for each subtree.

- Maximal Munch** generates the instructions in **reverse** order.
- Implementation**: see Appel pp 190-191, 204-205.

Dynamic Programming

- the **dynamic programming** algorithm is used to find the **optimum tiling**

Main Idea: assign a cost to every node in the tree (via bottom-up)

the algorithm works bottom-up: at each node, we calculate the cost of the best instruction sequence that can tile the subtree rooted at that node.

- after the cost of the root node (thus the entire tree) is found, we do the **instruction emission**:

Emission(node n): for each leaves l_i of the tile selected at node n , perform **Emission**(l_i). Then emit the instruction matched at node n .

Code-Generator Generator

- Same as **Lex** and **Yacc**, the **instruction selection** phase can also be **automatically** built, using a **code-generator generator**.
- The **input specification** is a set of grammar rules used to specify the **tree pattern** for each machine instruction:

each grammar rule is associated with a **cost** and an **action**;
cost is for finding optimum tiling; **action** is for instruction emission.

Example:

\bar{d} ->	MEM (+ (\bar{a} , CONST))	...
\bar{d} ->	MEM (+ (CONST , \bar{a}))	...
\bar{d} ->	MEM (CONST)	...
\bar{d} ->	MEM (\bar{a})	...

\bar{a} : expressions for "addressing" \bar{d} : expressions for "data"

- The code-generator generator computes the minimum-cost match at each node for each nonterminal of the grammar using **dynamic programming** (Appel pp 191-193)

Instruction Selection for Tiger

- we will implement the **maximal munch** for instruction selection in the Tiger compiler (using ML pattern matching)
- main problem**: how to deal with registers ?
- solution**: the register allocation will occur after instruction selection, the instruction selection phase will generate instructions with simple **register templates**.

first, generate the **assembly tree** --- the assembly language without register assignments;

second, do the **register allocation**

third, emit the procedure entry exit sequence

Assembly Trees

- the assembly language without register assignments in ML datatype:

```

structure Assem : sig
  type reg = string
  type temp = Temp.temp
  type label = Temp.label

  datatype instr
    = OPER of {assem: string, dst: temp list,
               src: temp list, jump: label list option}
      | LABEL of {assem: string, lab: label}
      | MOVE of {assem: string, dst: temp, src: temp}

  val format: (temp -> string) -> instr -> string
end

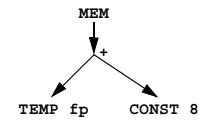
```

The **format** function will fill in the register information in the future.

Tiger Assembly Trees (cont'd)

- A **OPER** node `OPER{assem, dst, src, jump}` holds an assembly-language instruction `assem`. The source registers are `src`, the target registers are `dst`; `jump` would be `NONE` if it is not a branch instruction.

a canonical tree exp



the assembly tree

a **OPER** node:

LOAD 'd0 <- M['s0+8]

TEMP fp

after register allocations

real assembly code:

LOAD r1 <- M[r27+8]

- An **MOVE** node `MOVE{assem, dst, srcs}` holds an assembly-language **move** instruction `assem` that moves from `src` to `dst`.

If later in register allocation, `src` and `dst` are assigned the same register, then this instruction will be deleted.