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,e1,e2)`

  ```
  instructions to compute e1 into r1 ;
  instructions to compute e2 into r2 ;
  r3 <- r1 op r2
  ```

  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, lt, lf)` *is immediately followed by* `LABEL(lf)` .

- *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_t`,` 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:

  1. the first statement is a `LABEL`
  2. the last statement is a `JUMP` or `CJUMP`
  3. there are no other `LABEL`s, `JUMP`s, or `CJUMP`s 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):*

  a) any `CJUMP` followed by its **false** label: *do nothing* ;

  b) any `CJUMP` followed by its **true** label: switch its **true** and **false** label, and **negate** the condition;

  c) remove `JUMP(l)` if it is followed by its target `l` ;

  d) any `CJUMP(cond, lt, lf)` followed by **neither** label: invent a new false label l_n , rewrite it into :

```
CJUMP(cond, lt, ln)
LABEL ln
JUMP(NAME lf)
```

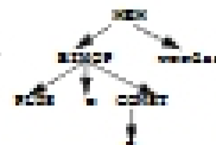
- *We are now ready to do instruction selection : generate assembly code for your favourite target machine.*

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 trees 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.*