Compiler Construction 2012/2013: Intermediate Representation

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Outline

1. Contexts
2. Canonical Trees

From Parse Trees to Intermediate Representation

- Parser generates ASTs according to the underlying CFG
- AST high-level and generic
- Translation to IR already incorporates some design decisions and code improvements

Expressions Appear in Different Contexts

Compare the translation for `x > 3` in

- `y = x > 3;`
- `if (x > 3) s1 else s2`

In C-like languages, what about `x = 3` in

- `x = 3;`
- `if (x = 3) s1 else s2`

Contexts

Key ideas

An expression may be used in different ways...

- to further compute with it value: no problem
- as a statement: `x = 3`
- as a condition: create branch instruction with test against 0

A statement may be used as...

- in MiniJava only as statement!

ExCtx(exp)	context where a value is required
NxCtx(stm)	context where no value is required
CxCtx	context with condition (abstract)
	RelCxCtx(op,left,right) relational operations
IfThenElseCtx	context of if-then-else construct

Contexts

A general framework for conversion operations in contexts.
They enable to use a form in the context of another :

- **unEx** converts to IR expression that evaluates inner tree and returns its value
- **unNx** converts to IR statement that evaluates inner tree but returns no value
- **unCx(t,f)** converts to IR statement that evaluates inner tree and branches to true destination **t** if non-zero, to false destination **f**, otherwise

Translating MiniJava Expressions

Simple variables For now, we declare them as temporaries

ExCtx(TEMP t)

Arithmetic operations Choose the right binary operation!

a op b $\rightarrow$ ExCtx(BINOP (op,a.unEx(),b.unEx()))

Unary operations are translated with a trick:

- negation of integers $\rightarrow$ subtraction from zero
- ones complement $\rightarrow$ XOR with all ones

Translating MiniJava Expressions

Array elements Arrays are allocated on the heap.

$$e[i] \rightarrow \text{ExCtx(MEM (ADD(e.unEx(), MUL(i.unEx(), CONST w))))}$$

Here, w is the target machine's word size.
In MiniJava, all values are word-sized.
Array bounds check: Check that array index *i* is between 0 and `e.size`. To this end, the array representation stores the size in the word preceding the base.

Object fields Objects are allocated on the heap.

$$e.f \rightarrow \text{ExCtx(MEM (ADD(e.unEx(), CONST o)))}$$

where o is the byte offset of field f in the object.
Null pointer check: Check that object expression is non-null.

Translating MiniJava Expressions

Array allocation - on the heap

- Call external memory allocation function with size $+1$.
- Store size of array in the first word.
- Initialize all elements with default values.
- Return address of first element as base of array.

Object allocation - on the heap

- In constructor, call external memory allocation function with needed size.
- Store pointer to the corresponding vtable (virtual method table).
- Initialize all fields with default values.
- Return address of first field as base of object.

Translating MiniJava Expressions

Method call

In OO language, `this` is an implicit variable. The pointer of the calling object will be added as parameter to each function!

- Fetch the class descriptor at offset 0 from object *c*.
- Fetch the method-instance pointer *p* from offset f.
- Call *p*.

e0.m (e1, . . . , en) $\longrightarrow$

```
ExCtx(CALL(MEM( +(MEM(-(e0.unEx(), CONST(w)),
                  *(m.index ,CONST(w))),
          e0.unEx(),e1.unEx(),...,en.unEx()))
```

Null pointer check: Check that object expression is non-null. For static methods, the function label/address can be done at compile time.

Translating MiniJava Control Structures

Code is structured into basic blocks:

- a maximal sequence of instructions without branches (straight-line code)
- a label starts a new basic block

For implementing control structures:

- Link up the basic blocks!
- Implementation requires bookkeeping (labels!).

While loops

```
while(c) s
```

- evaluate *c*
- if true, jump to loop body, else jump to next statement after loop
- evaluate loop body *s*
- jump to conditional
- if true, jump back to loop body

```
NxCtx(SEQ( SEQ(
        LABEL(cond), c.unCx(body,done)),
      SEQ( SEQ(
        LABEL(body), SEQ(s.unNx(),JUMP(cond)))),
        LABEL(done)))
```

For loops

```
for(i, c, u) s
```

- evaluate initialization statement *i*
- evaluate *c*
- if true, jump to loop body, else jump to next statement after loop
- evaluate loop body *s*
- evaluate update statement *u*
- jump to condition statement

```
NxCtx(SEQ( i.unNx(),
      SEQ(SEQ(
           LABEL(cond),c.unCx(body,done)),
      SEQ(SEQ(
         LABEL(body), SEQ(s.unNx(),SEQ(u.unNx(),
           JUMP(cond)))),
         LABEL(done)))))
```

Break statement

- when translating a loop, push the done label on some stack
- `break` simply jumps to label on top of stack
- when done with translating the loop and its body, pop the label from the stack

Switch statement

`case E of` V_1`:` S_1 `...` V_n`:` S_n `end`

- evaluate the expression
- find value in case list equal to value of expression
- execute statement associated with value found
- jump to next statement after case

Key issue: finding the right case!

- sequence of conditional jumps (small case set): $O(|cases|)$
- binary search of an ordered jump table (sparse case set): $O(\log_2 |cases|)$
- hash table (dense case set): $O(1)$

Switch statement

	evaluate E into t
	if t != V_1 jump L_1
	code for S_1
	jump next
L_1:	if t != V_2 jump L_2
	code for S_2
	jump next
...	
L_{n-1}:	if t != V_n jump L_n
	code for S_n
	jump next
L_n:	code to raise run-time exception
next:	

Switch statement

```
          evaluate E into t
          jump test
L1:       code for S1
          jump next
L2:       code for S2
          jump next
. . .
Ln:       code for Sn
          jump next
test:     if t = V1 jump L1
          if t = V2 jump L2
. . .
          if t = Vn jump Ln
          code to raise run-time exception
next:
```

Multi-dimensional arrays

Array allocation

- constant bounds:
  - allocate in static area, stack, or heap
  - no run-time descriptor is needed
- dynamic arrays: bounds fixed at run-time
  - allocate in stack or heap
  - descriptor is needed
- dynamic arrays: bounds can change at run-time
  - allocate in heap
  - descriptor is needed

Multi-dimensional arrays

Array layout

- Contiguous:
  - Row major: Rightmost subscript varies most quickly

    ```
    A[1,1], A[1,2], ...
    A[2,1], A[2,2], ...
    ```

    Used in PL/1, Algol, Pascal, C, Ada, Modula, Modula-2, Modula-3
  - Column major: Leftmost subscript varies most quickly

    ```
    A[1,1], A[2,1], ...
    A[1,2], A[2,2], ...
    ```

    Used in FORTRAN
- By vectors:
  - Contiguous vector of pointers to (non-contiguous) subarrays

Multi-dimensional arrays: Row-major layout

- Array $[1..N, 1..M]$ of T corresponds to array $[1..N]$ of array $[1..M]$ of T
- For an array $[\ldots, L_j..U_j, \ldots]$, the number of elements in dimension j is: $D_j = U_j - L_j + 1$
- Position of $A[i_1, \ldots, i_n]$:

$$
\begin{array}{rl}
 & (i_n - L_n) + (i_{n-1} - L_{n-1})D_n + \cdots + (i_1 - L_1)D_nD_{n-1}\cdots D_2 \\
= & i_n + i_{n-1}D_n + \cdots + i_1 D_nD_{n-1}\cdots D_2 \\
 & -(L_n + L_{n-1}D_n + \cdots - L_1 D_nD_{n-1}\cdots D_2) \\
= & \text{variable part} \\
 & -\text{constant part}
\end{array}
$$

The vector of partial products $D_nD_{n-1}, \ldots, D_n\cdots D_2$ can be precomputed

- Address of $A[i_1, \ldots, i_n]$:

address(A) + ((variable part - constant part) * element size)

Kinds of Contexts

ExCtx(exp)	context where a value is required
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CxCtx	context with condition (abstract)
	RelCxCtx(op,left,right) relational operations
IfThenElseCtx	context of if-then-else construct

Conversion operations enable using a form in the context of another :

unEx	converts to IR expression that evaluates inner tree and returns its value
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Implementation

```
interface Ctx {
  Exp unEx();
  Stm unNx();
  Stm unCx(Label t, Label f);
}
```

```
class ExCtx implements Ctx {
  Exp exp;
  ExCtx (Exp e)     {exp = e;}
  Exp unEx()        {return exp;}
  Stm unNx()        {return new EXP(exp);}
  Stm unCx(Label t, Label f)
  { ... ? ... } // homework ;)
}
```

Implementation

```
class NxCtx implements Ctx {
  Stm stm;
  NxCtx (Stm s)    {stm = s;}
  Exp unEx()       { ... ? ... } // never needed in MiniJav
  Stm unNx()       {return stm;}
  Stm unCx(Label t, Label f)
  { ... ? ... } // never needed in MiniJava
}
```

Implementation

```
abstract class CxCtx implements Ctx {
  Exp unEx()       { ... ? ... }  // next slide
  Stm unNx()       { ... ? ... }  // homework ;)
  abstract Stm unCx(Label t, Label f);
}
```

Implementation

```
abstract class CxCtx implements Ctx {
  Exp unEx() {
    Temp r  = new Temp();
    Label t = new Label();
    Label f = new Label();
    return ESEQ(
    SEQ( MOVE (TEMP(r), CONST(1)),
    SEQ( this.unCx(t,f),
    SEQ( LABEL(f),
    SEQ( MOVE (TEMP(r), CONST(0)),
    LABEL(t))))),
    TEMP(r)));
  }
  Stm unNx()      { ... ? ... }  // homework ;)
  abstract Stm unCx(Label t, Label f);
}
```

Implementation

For comparisons (e.g. `x < 5`):

```
class RelCxCtx extends CxCtx {
  RelOp o; Exp left; Exp right;
  RelCxCtx (RelOp o, Exp left, Exp right )   {...}
  Stm unCx(Label t, Label f) {
    return CJUMP(o,left,right,t,f);
  }
}
```

Implementation

Translate short-circuiting boolean operators as if they were conditionals. May use if-then-else construct/conditional expression $e_1 ? e_2 : e_3$.

Example

`x < 5 && y > 0` is treated as

```
(x < 5) ?  (y > 0) :  0
```

We translate $e_1 ? e_2 : e_3$ into an IfThenElseCtx(e_1,e_2,e_3) :

```
class IfThenElseCtx implements Ctx{
  Exp e1; Exp e2; Exp e3;
  IfThenElseCtx (Exp e1, Exp e2, Exp e3)
  {this.e1 = e1; this.e2 = e2; this.e3 = e3;}
  Exp unEx()      { ... ? ... }
  Stm unNx()      { ... ? ... }
  Stm unCx(Label t, Label f)
  { ... ? ... }
}
```

Implementation

When using a IfThenElseCtx as an expression:

```
    Exp unEx(){
      Label t = new Label();
      Label f = new Label();
      Temp  r = new Temp();
      return ESEQ(
      SEQ( e1.unCx(t,f),
      SEQ( SEQ (LABEL (t),
      SEQ( MOVE ( TEMP(r), e2.unEx()),
      JUMP (j))),
      SEQ ( LABEL(f), SEQ( MOVE (TEMP(r), e3.unEx()),
      JUMP (j)))),
      LABEL(j)),
      TEMP (r));
    }
  }
```

Implementation

When using a IfThenElseCtx as a conditional:

```
Stm unCx(Label t, Label f) {
  Label tt = new Label();
  Label ff = new Label();
  return SEQ ( e1.unCx(tt,ff),
  SEQ(SEQ (LABEL(tt),e2.unCx(t,f)),
  SEQ(LABEL(ff), e3.unCx(t,f))));
}
```

Outline

Motivation

Mismatches between IR and machine code

- Evaluation order of `ESEQ`'s within expressions must be made explicit, same for `CALL` nodes.
- `CALL` nodes at argument expression of other `CALL`s cause problems with registers.
- `CJUMP` may jump to either of two labels, conditional jumps of machines “fall through” if condition is false.

Motivation

Idea

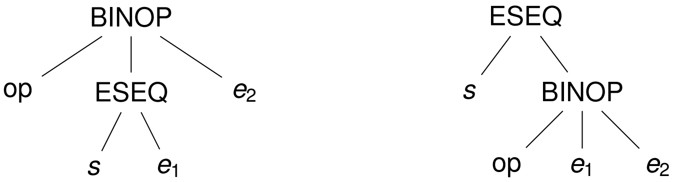
Yet another tree re-writing step!

- Eliminate `SEQ` and `ESEQ` nodes $\Rightarrow$ simple list of statements!
- `CALL` can only be subtree of `EXP(...)` or `MOVE(TEMP t,...)`.
- Group sequences into basic blocks without internal jumps or labels.
- Arrange basic blocks where every `CJUMP` is followed by false branch.

Re-writing of `ESEQ`(1)

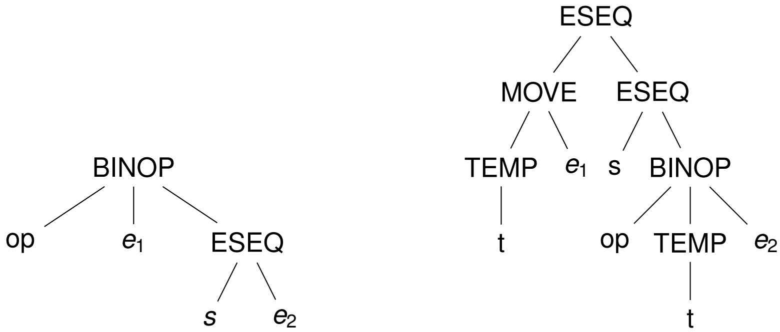
$$\text{ESEQ}(s_1, \text{ESEQ}(s_2, e)) \quad \Rightarrow \quad \text{ESEQ}(\text{SEQ}(s_1, s_2), e)$$

Re-writing of `ESEQ`(2)



BINOP(op, ESEQ(s,e_1),e_2)	$\Rightarrow$	ESEQ(s,BINOP(op,e_1,e_2))
MEM(ESEQ(s,e_1))	$\Rightarrow$	ESEQ(s,MEM(e_1))
JUMP(ESEQ(s,e_1))	$\Rightarrow$	ESEQ(s,JUMP(e_1))
CJUMP(op,ESEQ(s,e_1),e_2,l_1,l_2)	$\Rightarrow$	SEQ(s,CJUMP(op,e_1,e_2,l_1,l_2))

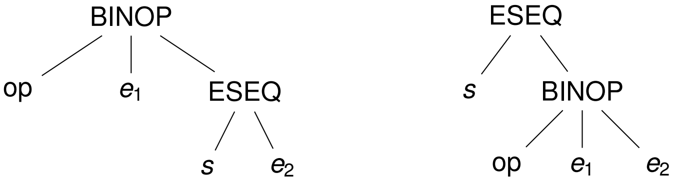
Re-writing of `ESEQ`(3)



BINOP(op, e_1,ESEQ(s,e_2))	$\Rightarrow$	ESEQ(MOVE(TEMP t,e_1), ESEQ(s, BINOP(op,TEMP t,e_2)))
CJUMP(op,e_1,ESEQ(s,e_2),l_1,l_2)	$\Rightarrow$	SEQ(MOVE(TEMP t,e_1), SEQ(s, CJUMP(op,TEMP t,e_2,l_1,l_2)))

Re-writing of ESEQ(4)

If s and e_1 commute, the move instruction is not needed:



BINOP(op, e_1,ESEQ(s,e_2))	$\Rightarrow$	ESEQ(s,BINOP(op,e_1,e_2))
CJUMP(op,e_1,ESEQ(s,e_2),l_1,l_2)	$\Rightarrow$	SEQ(s,CJUMP(op,e_1,e_2,l_1,l_2))

Example

- MOVE(MEM(x),y) commutes with MEM(z) iff $x \neq z$.
- Any statement commutes with CONST(n).

General Rewriting Rules

From the examples so far, we can derive this somewhat general approach:

- Extract recursively all `ESEQ`'s out of all subexpressions.
- Generate statement sequences where sub-expressions are evaluated into temporaries.
- Rebuild original construct.

Use similar technique to eliminate nested function calls:

$$\text{CALL}(f,\mathit{args}) \Rightarrow \text{ESEQ}(\text{MOVE}(\text{TEMP t, CALL}(f,\mathit{args})),\text{TEMP t})$$

Basic Blocks and Traces

A basic block

- starts with a LABEL,
- end with a JUMP or CJUMP, and
- there are no other LABELs, JUMPs, or CJUMPs

A trace

- is a sequence of statements that could be consecutively executed in the program.

Arrange the blocks to get “optimal” traces!

Generating Traces

- Divide the list of statements of a function body into blocks.
- Put all the blocks into a list Q.
- While Q is not empty:
  - Start new (empty) trace T.
  - Remove head element b from Q.
  - While b is not marked:
    - Mark b.
    - Append b to the end of the current trace T.
    - Examine the blocks to which b branches:
      If there is any unmarked successor c, let it be the next b.
  - End the current trace T.

Finishing up

- Make sure that every CJUMP is followed by its false label.
  - If followed by true label, negate condition and swap labels.
  - If followed by neither label, insert dummy label f' and jump.

```
CJUMP(cond,a,b,t,f')
LABEL f'
JUMP(NAME f)
```

- Remove jumps that are immediately followed by their target label.

Building Traces of Basic Blocks

prologue statements	*prologue statements*	*prologue statements*
~~JUMP(NAME(test))~~	~~JUMP(NAME(test))~~	JUMP(NAME test)
LABEL(test)	LABEL(test)	LABEL(body)
CJUMP($>$,i, N,done,body)	CJUMP($\leq$,i, N,body,done)	*loop body statements*
LABEL(body)	LABEL(done)	~~JUMP(NAME(test))~~
loop body statements	*epilogue statements*	LABEL(test)
JUMP(NAME test)	LABEL(body)	CJUMP($\leq$,i, N,body,done)
LABEL(done)	*loop body statements*	LABEL(done)
epilogue statements	JUMP(NAME test)	*epilogue statements*

Alternative Intermediate Representations

- Directed acyclic graphs (DAGs): identifies common subexpression
- Three-address code: at most one operator at the right side of an instruction
- Static single assignment form (SSA): all assignments are to variables with distinct names (later in course)