Computer Languages

Transformations of the IR

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School of Information Science, Computer and Electrical Engineering

Mars 2

www2.hh.se/staff/vero/languages

Another overview of the compiler

Source: unstructured text

```
class A {
  public static void ...
     System.out.print(3);}
class B {
  int  x;
  int f(int y){
    return x+y;}}
```

Abstract syntax: strucutured

Intermediate representation

Target: unstructured text

```
main:
            subu $sp, $sp, 32
            sw $ra, 20($sp)
            sd $a0, 32($sp)
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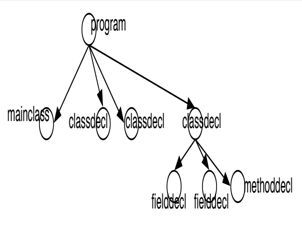

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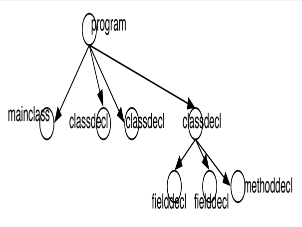

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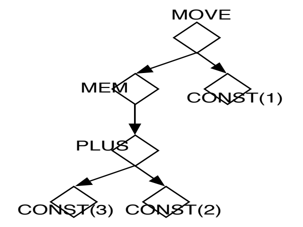

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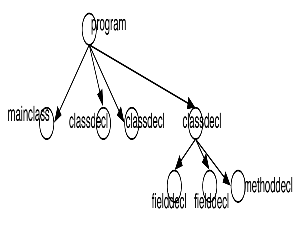

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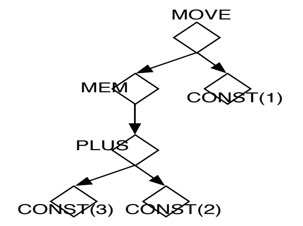

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Today I will explain things that you will not have to implement. You will be provided with the code for doing this.

However, we need to explain what kind of modifications compilers do to the IR so that it is easier to translate to assembler!

You find the details in chapter 8 of the course book.

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Mismatches between IR trees and machine-language

- $\mathrm{CJUMP}(op, e_1, e_2, l_1, l_2)$! In real machines conditional jumps fall to the next instruction!
- $\mathrm{ESEQ}(s, e)$ makes different evaluation orders yield different results!
- $\mathrm{CALL}(f, e_1, \ldots, e_n)$ too!
- $\mathrm{CALL}(f, e_1, \ldots, e_n)$ within other $\mathrm{CALL}()$ disturb using dedicated registers for parameters.

Solution

Transform the IR-trees preserving meaning but making them easier to translate to machine language!

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Overview of the transformation

Canonical Trees

The original IR-tree is transformed into a list of canonical trees without $\mathrm{SEQ}()$ or $\mathrm{ESEQ}()$ nodes

Basic Blocks

The list of canonical trees is grouped into a set of basic blocks such that there are no jumps or labels inside a block.

Traces

Finally, the basic blocks are reordered into a set of traces where each $\mathrm{CJUMP}()$ is immediatelly followed by its `false` label.

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IR-trees (short reminder)

IR-trees are the *abstract syntax* for the *abstract machine* instruction language!

Example

tree.Exp

$\mathrm{CONST}(1)$
$\mathrm{TEMP}(t_{98})$
$\mathrm{BINOP}(+,\mathrm{CONST}(1),\mathrm{TEMP}(t_{98}))$
$\mathrm{CALL}(f,\mathrm{TEMP}(t_{98}))$
$\mathrm{MEM}(\mathrm{CALL}(f,\mathrm{TEMP}(t_{98})))$
$\mathrm{ESEQ}(\mathrm{MOVE}(\mathrm{TEMP}(t_{98}),\mathrm{CONST}(1)),\mathrm{TEMP}(t_{98}))$

tree.Stm

$\mathrm{JUMP}(l_1)$
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$\textsc{call}(f,\textsc{temp}(t_{98}))$

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$\textsc{temp}(t_{98})$
$\textsc{binop}(+,\textsc{const}(1),\textsc{temp}(t_{98}))$
$\textsc{call}(f,\textsc{temp}(t_{98}))$
$\textsc{mem}(\textsc{call}(f,\textsc{temp}(t_{98})))$
$\textsc{eseq}(\textsc{move}(\textsc{temp}(t_{98}),\textsc{const}(1)),\textsc{temp}(t_{98}))$

tree.Stm

$\textsc{jump}(l_1)$
$\textsc{move}(\textsc{temp}(t_{98}),\textsc{const}(1))$
$\textsc{move}(\textsc{mem}(\textsc{call}(f,\textsc{temp}(t_{98}))),\textsc{const}(1))$

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MOVE(MEM(CALL(f,TEMP(t_{98}))),CONST(1))

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- $\mathrm{ESEQ}(s,e)$is very useful but introduces side effects when evaluating expressions!
- Many computer architectures support parallel evaluation of expressions.To exploit this, the order of evaluation of expressions should not influence the result!$\mathrm{ESEQ}(s,e)$ spoils this!
- We want to get rid of $\mathrm{ESEQ}(s,e)$ before generating code!
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Getting rid of $\mathrm{ESEQ}(s,e)$

- If $\mathrm{ESEQ}(s,e)$ is the main expression in a statement, as in

$$\mathrm{JUMP}(\mathrm{ESEQ}(s,e))$$

we might replace it by

$$\mathrm{SEQ}(s,\mathrm{JUMP}(e))$$

- So, if we manage to shift all $\mathrm{ESEQ}(s,e)$ to *top level*, then we can eliminate them! (we *transform* an IR-tree with an $\mathrm{ESEQ}(s,e)$ into another IR-tree *that achieves the same results* and does not contain the $\mathrm{ESEQ}(s,r)$)
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The algorithm

Extract subexpressions

Given a *Tree.Exp* or a *Tree.Stm* the subexpressions can be extracted calling method

abstract public LinkedList kids();

that is implemented adequately in each subclass of *Tree.Exp* and of *Tree.Stm*.

Example

CALL(NAME(*f*),CONST(*3*),MEM(CONST(*4*))).*kids()*

will yield the list

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A list of expressions can be reordered using the *rewrite rules* to one statement that does all the side effects and a list of expressions without $\mathrm{ESEQ}()$s

Example

For the list

$[e_1, e_2, \mathrm{ESEQ}(s, e_3)]$

the statement s must be pulled to the left past e_1 and e_2.

If s *commutes* with e_1 and e_2 reordering will yield

$(s, [e_1, e_2, e_3])$.

If s does not commute with e_1 and e_2 reordering will yield

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Building up

Once the expressions have been reordered they must be used to form back the corresponding *Tree.Exp* or *Tree.Stm*. That is why we find methods

- *public abstract Tree.Exp build(ExpList kids)* in class *Tree.Exp*
- *public abstract Tree.Stm build(ExpList kids)* in class *Tree.Stm*

That are implemented adequtely in each of their subclasses.

Example

```
class BINOP extends Exp{
   public Exp build(ExpList kids){
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- Another issue is the possibility of using $\textsc{call}(f,args)$ as subexpressions.
- All functions return their result in the dedicated register $\mathtt{RV}$.Thus, in

$$\textsc{binop}(op,\textsc{call}(\ldots),\textsc{call}(\ldots))$$

  the second call will overwrite $\mathtt{RV}$ before the operation can be executed!
- All $\textsc{call}(f,args)$ are replaced by

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- After these transformations, $\textsc{seq}()$ nodes can only appear as children to other $\textsc{seq}()$ nodes. As no expressions remain that have statements as children, and only the $\textsc{seq}()$ statement has statements as children!
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  $$\textsc{seq}(\textsc{seq}(a,b),c) \Rightarrow \textsc{seq}(a,\textsc{seq}(b,c))$$

  can be used to linearize the sequence structure.
- Now $\textsc{seq}()$ nodes are redundant! we can as well have a list with the statements in the sequence!

IR-trees (remarks)

- After these transformations, SEQ() nodes can only appear as children to other SEQ() nodes. As no expressions remain that have statements as children, and only the SEQ() statement has statements as children!
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- Now SEQ() nodes are redundant! we can as well have a list with the statements in the sequence!

IR-trees (remarks)

- After these transformations, $\textsc{seq}()$ nodes can only appear as children to other $\textsc{seq}()$ nodes. As no expressions remain that have statements as children, and only the $\textsc{seq}()$ statement has statements as children!
- The transformation

$$\textsc{seq}(\textsc{seq}(a,b),c) \Rightarrow \textsc{seq}(a,\textsc{seq}(b,c))$$

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  - the translation phase resulted in an IR-tree statement for every method body,
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- To implement this last transformation of the list of statements,a bit of control flow analysis is done.
- First, basic blocks of statements are identified and put together. A basic block is a list of statements where
  - the first statement is a LABEL()
  - the last statement is a JUMP() or CJUMP()
  - there are no other LABEL(), JUMP() or CJUMP() in it.

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Splitting

The list of canonical IR-trees corresponding to a function body is inspected from first to last element.

- On a $\mathrm{LABEL}()$, start a new block!
- On a $\mathrm{JUMP}()$ or $\mathrm{CJUMP}()$, end a block!
- On any other statement, add it to the current block!

Completing

- If a block doesn't end with a $\mathrm{JUMP}()$ or $\mathrm{CJUMP}()$ add to it a $\mathrm{JUMP}()$ to the label of the following block.
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- Basic blocks are put together into a traces.
- A trace is a sequence of statements that *could* be executed sequentialy.
- We want to produce a set of traces such that
  - every basic block is in some trace,
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  - many JUMP()s are followed by the label they jump to (because they can then be eliminated!)
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a new label is invented l'
the CJUMP() is replaced by:
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There is an implementation of these transformations that comes with the book. For it to run with the rest of the compiler I've made some small modifications (you will get it with the distribution for part five of the project)

package canon;

Canon removes ESEQ(), assigns CALL() to registers and returns a list of atomic statements

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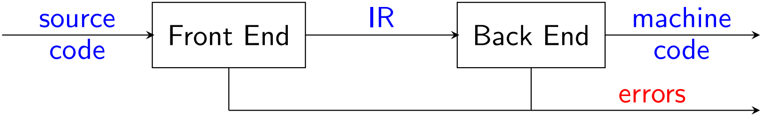

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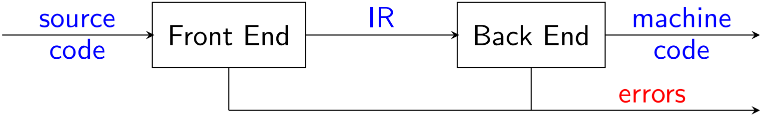

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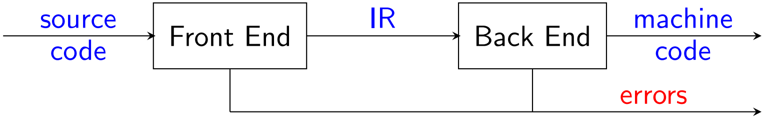

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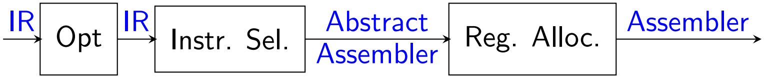

Observation

For the back-end we no longer look at *minijava*! We compile IR-trees to assembler.

A small minijava program

```
class A{
   public static void main(String[] a){
      System.out.println(new B().f(3).f());
   }
}
class B{
   int x;
   int y;
   public C f(int z){
      if(x<y) x=z+1; else x=z+x;
      return new C();
   }
}
class C{
   public int f(){return 3;}
}
```

The result of translating it

```
PROCEDURE :main
EXPS(
 CALL(
  NAME _printint,
  CONST 0,
  CALL(
   NAME C_f,
   CALL(
    NAME B_f,
    CALL(
     NAME _malloc,
     CONST 0,
     CONST 8),
    CONST 3))))
```

```
PROCEDURE :B_f
MOVE(
 TEMP t32,
 ESEQ(
  SEQ(
   SEQ(
    CJUMP(LT,
     MEM(
      BINOP(PLUS,
       TEMP t64,
       CONST 0)),
     MEM(
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       TEMP t64,
       CONST 4)),
     L0,L1),
```

```
PROCEDURE :C_f
MOVE(
 TEMP t32,
 CONST 3)
```

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PROCEDURE :B_f
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PROCEDURE :C_f
MOVE(
 TEMP t32,
 CONST 3)
```

The result of translating it

```
PROCEDURE :main
EXPS(
 CALL(
  NAME _printint,
  CONST 0,
  CALL(
   NAME C_f,
   CALL(
    NAME B_f,
    CALL(
     NAME _malloc,
     CONST 0,
     CONST 8),
    CONST 3))))
```

```
PROCEDURE :B_f
MOVE(
 TEMP t32,
 ESEQ(
  SEQ(
   SEQ(
    CJUMP(LT,
     MEM(
      BINOP(PLUS,
       TEMP t64,
       CONST 0)),
     MEM(
      BINOP(PLUS,
       TEMP t64,
       CONST 4)),
     L0,L1),
```

```
PROCEDURE :C_f
MOVE(
 TEMP t32,
 CONST 3)
```

(almost)All of `B_f`

```
MOVE(
 TEMP t32,
 ESEQ(
  SEQ(
   SEQ(
    CJUMP(LT,
     MEM(
      BINOP(PLUS,
       TEMP t64,
       CONST 0)),
     MEM(
      BINOP(PLUS,
       TEMP t64,
       CONST 4)),
     L0,L1),
```

```
SEQ(
 SEQ(
  SEQ(
   LABEL L0,
   MOVE(
    MEM(
     BINOP(PLUS,
      TEMP t64,
      CONST 0)),
    BINOP(PLUS,
     TEMP t65,
     CONST 1))),
  JUMP(
   NAME L2)),
```

```
SEQ(
 SEQ(
  LABEL L1,
  MOVE(
   MEM(
    BINOP(PLUS,
     TEMP t64,
     CONST 0)),
   BINOP(PLUS,
    TEMP t65,
    MEM(
     BINOP(PLUS,
      TEMP t64,
      CONST 0))))),
 JUMP(
  NAME L2)))),
```

(almost)All of `B_f`

```
MOVE(
 TEMP t32,
 ESEQ(
  SEQ(
   SEQ(
    CJUMP(LT,
     MEM(
      BINOP(PLUS,
       TEMP t64,
       CONST 0)),
     MEM(
      BINOP(PLUS,
       TEMP t64,
       CONST 4)),
     L0,L1),
```

```
SEQ(
 SEQ(
  SEQ(
   LABEL L0,
   MOVE(
    MEM(
     BINOP(PLUS,
      TEMP t64,
      CONST 0)),
    BINOP(PLUS,
     TEMP t65,
     CONST 1))),
  JUMP(
   NAME L2)),
```

```
SEQ(
 SEQ(
  LABEL L1,
  MOVE(
   MEM(
    BINOP(PLUS,
     TEMP t64,
     CONST 0)),
   BINOP(PLUS,
    TEMP t65,
    MEM(
     BINOP(PLUS,
      TEMP t64,
      CONST 0))))),
 JUMP(
  NAME L2))),
```

(almost)All of `B_f`

```
MOVE(
 TEMP t32,
 ESEQ(
  SEQ(
   SEQ(
    CJUMP(LT,
     MEM(
      BINOP(PLUS,
       TEMP t64,
       CONST 0)),
     MEM(
      BINOP(PLUS,
       TEMP t64,
       CONST 4)),
     L0,L1),
```

```
SEQ(
 SEQ(
  SEQ(
   LABEL L0,
   MOVE(
    MEM(
     BINOP(PLUS,
      TEMP t64,
      CONST 0)),
    BINOP(PLUS,
     TEMP t65,
     CONST 1))),
  JUMP(
   NAME L2)),
```

```
SEQ(
 SEQ(
  LABEL L1,
  MOVE(
   MEM(
    BINOP(PLUS,
     TEMP t64,
     CONST 0)),
   BINOP(PLUS,
    TEMP t65,
    MEM(
     BINOP(PLUS,
      TEMP t64,
      CONST 0))))),
 JUMP(
  NAME L2)))),
```

B_f - after the transformations

```
LABEL L6
CJUMP(LT,
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 0)),
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 4)),
 L0,L1)
```

```
LABEL L1
MOVE(
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 0)),
 BINOP(PLUS,
  TEMP t65,
  MEM(
   BINOP(PLUS,
    TEMP t64,
    CONST 0))))
```

```
LABEL L2
MOVE(
 TEMP t32,
 CALL(
  NAME _malloc,
  CONST 0,
  CONST 0))
JUMP(
 NAME L5)
```

```
LABEL L0
MOVE(
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 0)),
 BINOP(PLUS,
  TEMP t65,
  CONST 1))
JUMP(
 NAME L2)
LABEL L5
```

B_f - after the transformations

```
LABEL L6
CJUMP(LT,
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 0)),
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 4)),
 L0,L1)
```

```
LABEL L1
MOVE(
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 0)),
 BINOP(PLUS,
  TEMP t65,
  MEM(
   BINOP(PLUS,
    TEMP t64,
    CONST 0))))
```

```
LABEL L2
MOVE(
 TEMP t32,
 CALL(
  NAME _malloc,
  CONST 0,
  CONST 0))
JUMP(
 NAME L5)
```

```
LABEL L0
MOVE(
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 0)),
 BINOP(PLUS,
  TEMP t65,
  CONST 1))
JUMP(
 NAME L2)
LABEL L5
```

B_f - after the transformations

```
LABEL L6
CJUMP(LT,
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 0)),
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 4)),
 L0,L1)
```

```
LABEL L1
MOVE(
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 0)),
 BINOP(PLUS,
  TEMP t65,
  MEM(
   BINOP(PLUS,
    TEMP t64,
    CONST 0))))
```

```
LABEL L2
MOVE(
 TEMP t32,
 CALL(
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  CONST 0))
JUMP(
 NAME L5)
```

```
LABEL L0
MOVE(
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 0)),
 BINOP(PLUS,
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JUMP(
 NAME L2)
LABEL L5
```

B_f - after the transformations

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LABEL L1
MOVE(
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   TEMP t64,
   CONST 0)),
 BINOP(PLUS,
  TEMP t65,
  MEM(
   BINOP(PLUS,
    TEMP t64,
    CONST 0))))
```

```
LABEL L2
MOVE(
 TEMP t32,
 CALL(
  NAME _malloc,
  CONST 0,
  CONST 0))
JUMP(
 NAME L5)
```

```
LABEL L0
MOVE(
 MEM(
  BINOP(PLUS,
   TEMP t64,
   CONST 0)),
 BINOP(PLUS,
  TEMP t65,
  CONST 1))
JUMP(
 NAME L2)
LABEL L5
```

What is left: code generation

Purpose: Generate a file with assembler code for a target machine

Instruction Selection

- Study the instructions of the target architecture.
- Program how to match each IR statement with machine instructions.
- For each instruction keep a list of the temporaries used.

Register Allocation

- Build a *flow graph* where instructions are nodes and edges reflect usage of temporaries.
- *Color* the graph to find independent temporaries.
- Assign registers to instructions.

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