Code Generation and Optimization

ALSU Textbook Chapters 8.4, 8.5, 8.7, 8.8, 9.1

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Introduction

- **For some compiler, the intermediate code is a pseudo code of a virtual machine.**
  - **Interpreter of the virtual machine is invoked to execute the intermediate code.**
  - **No machine-dependent code generation is needed.**
  - **Usually with great overhead.**
  - **Example:**
    - ***Pascal: P-code for the virtual P machine.***
    - ***JAVA: Byte code for the virtual JAVA machine.***
- **Motivation:**
  - **Statement by statement translation might generate redundant codes.**
  - **Locally improve the target code performance by examine a short sequence of target instructions (called a peephole) and do optimization on this sequence.**
  - **Note: Complexity depends on the "window size."**
- **Optimization.**
  - **Machine-dependent issues.**
  - **Machine-independent issues.**

Machine-dependent issues (1/2)

- **Input and output formats:**
  - **The formats of the intermediate code and the target program.**
- **Memory management:**
  - **Alignment, indirect addressing, paging, segment, . . .**
  - **Those you learned from your assembly language class.**
- **Instruction cost:**
  - **Special machine instructions to speed up execution.**
  - **Example:**
    - ▷ ***Increment by 1.***
    - ▷ ***Multiplying or dividing by 2.***
    - ▷ ***Bit-wise manipulation.***
    - ▷ ***Operators applied on a continuous block of memory space.***
  - **Pick a fastest instruction combination for a certain target machine.**

Machine-dependent issues (2/2)

- **Register allocation: in-between machine dependent and independent issues.**
  - **C language allows the user to management a pool of registers.**
  - **Some language leaves the task to compiler.**
  - **Idea: save mostly used intermediate result in a register. However, finding an optimal solution for using a limited set of registers is NP-hard.**
  - **Example:**

```
t := a + b            load  R0,a            load   R0,a
                      load  R1,b            add    R0,b
                      add   R0,R1           store  R0,T
                      store R0,T
```

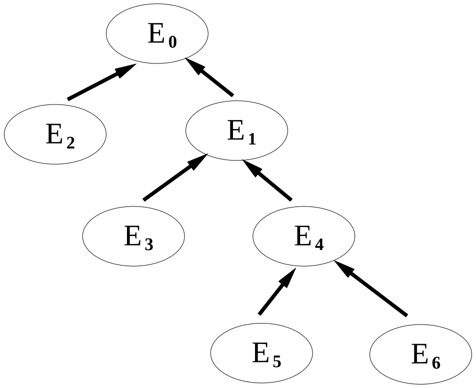
  - **Heuristic solutions: similar to the ones used for the swapping problem.**

Machine-independent issues

- **Techniques.**
    - **Analysis of dependence graphs.**
    - **Analysis of basic blocks and flow graphs.**
    - **Semantics-preserving transformations.**
    - **Algebraic transformations.**

Dependence graphs

- **Issues:**
  - In an expression, assume its **dependence graph** is given.
  - We can evaluate this expression using any topological ordering.
  - There are many legal topological orderings.
  - Pick one to increase its efficiency.
- **Example:**

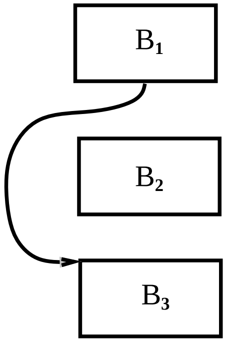


order#1	reg#	order#2	reg#
E2	1	E6	1
E3	2	E5	2
E5	3	E4	1
E6	4	E3	2
E4	3	E1	1
E1	2	E2	2
E0	1	E0	1

- On a machine with only 2 free registers, some of the intermediate results in order#1 must be stored in the temporary space.
  - STORE/LOAD takes time.

Basic blocks and flow graphs

- **Basic block** : a sequence of code such that
  - jump statements, if any, are at the end of the sequence;
  - codes in other basic block can only jump to the beginning of this sequence, but not in the middle.
  - Example:
    - ▷ $t_1 := a * a$
    - ▷ $t_2 := a * b$
    - ▷ $t_3 := 2 * t_2$
    - ▷ $goto\ outter$
  - Single entry, single exit.
- **Flow graph** : Using a flow chart-like graph to represent a program where nodes are basic blocks and edges are flow of control.



How to find basic blocks

- **How to find leaders, which are the first statements of basic blocks?**
  - **The first statement of a program is a leader.**
  - **For each conditional and unconditional goto,**
    - ▷ *its target is a leader;*
    - ▷ *its next statement is also a leader.*
- **Using leaders to partition the program into basic blocks.**
- **Ideas for optimization:**
  - **Two basic blocks are equivalent if they compute the same expression.**
  - **Use transformation techniques below to perform machine-independent optimization.**

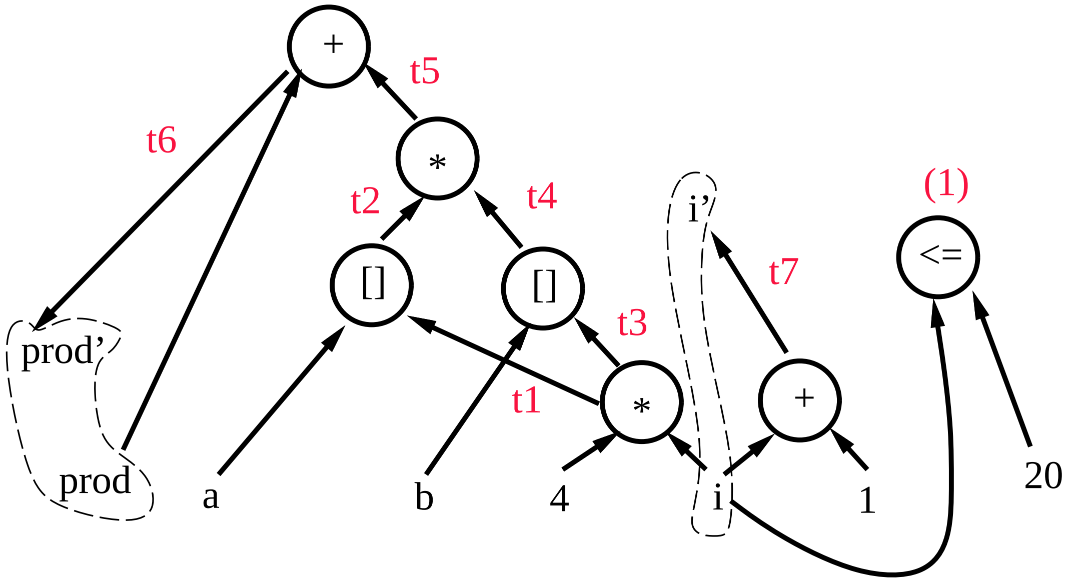
Finding basic blocks — examples

- **Example: Three-address code for computing the dot product of two vectors a and b.**
    - $prod := 0$
    - $i := 1$
    - ***loop:***
    - $t_1 := 4 * i$
    - $t_2 := a[t_1]$
    - $t_3 := 4 * i$
    - $t_4 := b[t_3]$
    - $t_5 := t_2 * t_4$
    - $t_6 := prod + t_5$
    - $prod := t_6$
    - $t_7 := i + 1$
    - $i := t_7$
    - ***if*** $i \leq 20$ ***goto loop***
    - $\cdots$
- **There are three blocks in the above example.**

DAG representation of a basic block

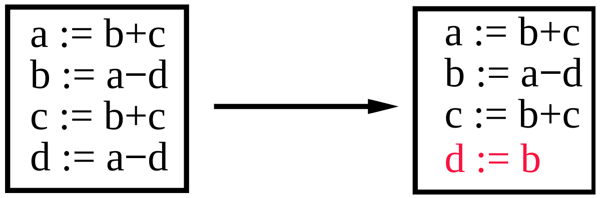
- **Inside a basic block:**
  - **Expressions can be expressed using a DAG that is similar to the idea of a dependence graph.**
  - **Graph might not be connected.**
- **Example:**

(1) $t_1 := 4 * i$
(2) $t_2 := a[t_1]$
(3) $t_3 := 4 * i$
(4) $t_4 := b[t_3]$
(5) $t_5 := t_2 * t_4$
(6) $t_6 := prod + t_5$
(7) $prod := t_6$
(8) $t_7 := i + 1$
(9) $i := t_7$
(10) if $i \leq 20$ **goto (1)**



Semantics-preserving transformations (1/3)

- **Techniques: using the information contained in the flow graph and DAG representation of basic blocks to do optimization.**
  - **Common sub-expression elimination.**



```
a := b+c
b := a−d
c := b+c
d := a−d
```

```
a := b+c
b := a−d
c := b+c
d := b
```

  - **Dead-code elimination: remove unreachable codes.**
  - **Remove redundant codes such as loads and stores.**
    - *MOV* R_0, a
    - *MOV* a, R_0
  - **Code motion.**
    - *Find loop-invariants inside a loop.*
    - *Obtain the values of loop-invariants outside the loop.*
    - *Example:*

```
while(i <= limit - 2)
    ...
```

```
t = limit - 2
while (i <= t)
    ...
```

  - **Renaming temporary variables: better usage of registers and avoiding using unneeded temporary variables.**

Semantics-preserving transformations (2/3)

- **More techniques:**
    - **Copy propagation:**
        - ▷ *De-reference a chain of variable copies.*
        - ▷ *Example:*

```
a = x;                          a = x;
y = a;                          y = x;
b = y;                          b = x;
```

    - **Flow of control simplification:**
        - ▷ *De-reference a chain of goto's.*
        - ▷ *Example:*

```
goto L1                 goto L2

...                     ...

L1: goto L2             L1: goto L2
```

Semantics-preserving transformations (3/3)

- **Interchange of two independent adjacent statements, which might be useful in discovering the above transformations.**
  - **Same expressions that are too far away to store E_1 into a register.**
    - ▷ ***Example:***

```
t1 := E1                                t1 := E1
t2 := const                             tn := E1 // swap t2 and tn
... // value of tn is not used          ...
tn := E1                                t2 := const
```

    - ▷ ***In the example above, we can swap t2 and tn since there is no dependence between t2 and tn.***
    - ▷ ***After the swapping, we can use the register stroing $E1$ twice.***
  - **Note: The order of dependence cannot be altered after the exchange.**
    - ▷ ***Example:***

```
t1 := E1
t2 := t1 + tn // cannot swap t2 and tn
...
tn := E1
```

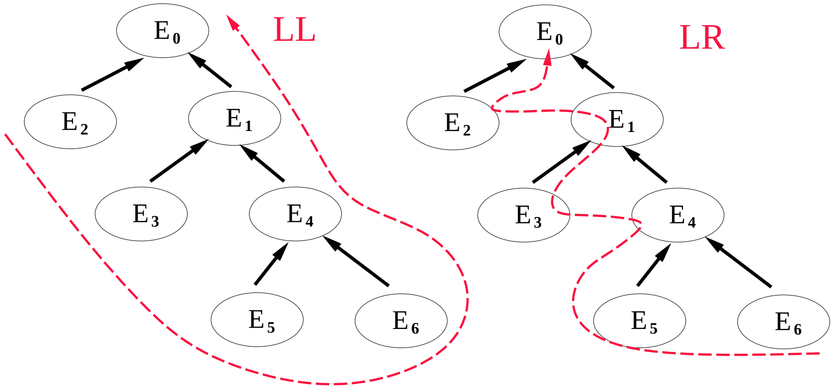
    - ▷ ***In the example above, we cannot swap t2 and tn because t2 needs to be executed before tn.***

Algebraic transformations

- **Algebraic identities:**
  - $x + 0 \equiv 0 + x \equiv x$
  - $x - 0 \equiv x$
  - $x * 1 \equiv 1 * x \equiv x$
  - $x/1 \equiv x$
- **Reduction in strength:**
  - $x^2 \equiv x * x$
  - $2.0 * x \equiv x + x$
  - $x/2 \equiv x * 0.5$
- **Constant folding:**
  - $2 * 3.14 \equiv 6.28$
- **Standard representation for subexpression by commutativity and associativity:**
  - $n * m \equiv m * n$.
  - $b < a \equiv a > b$.

Correctness after optimization

- **When side effects are expected, different evaluation orders may produce different results for expressions.**



  - **Assume E_5 is a procedure call with the side effect of changing some values in E_6.**
  - **LL and LR parsing produce different results.**
- **Watch out precisions when doing algebraic transformations.**
  - **if** $(x = 321.00000123456789 - 321.00000123456788) > 0$ **then** $\cdots$
- **Need to make sure code before and after optimization produce the same result.**
- **Complications arise when debugger is involved.**