Helmut Seidl

Program Optimization

TU München

Winter 2008/09

Organization

Dates:	Lecture:	Monday, 12-14
		Tuesday, 12-14
	Tutorials:	Friday, 12-14
		Vesal Vojdani: `vojdanig@in.tum.de`
	Material:	slides, recording :-)
		simulator environment

Grades:

- Bonus for homeworks
- written exam

Proposed Content:

1. Avoiding redundant computations
    - → available expressions
    - → constant propagation/array-bound checks
    - → code motion
2. Replacing expensive with cheaper computations
    - → peep hole optimization
    - → inlining
    - → reduction of strength

    ...

3. Exploiting Hardware

→ Instruction selection

→ Register allocation

→ Scheduling

→ Memory management

0 Introduction

Observation 1: Intuitive programs often are inefficient.

Example:

```
void swap (int i, int j) {
     int t;
     if (a[i] > a[j]) {
         t = a[j];
         a[j] = a[i];
         a[i] = t;
        }
     }
```

Inefficiencies:

- Addresses `a[i]`, `a[j]` are computed three times :-(
- Values `a[i]`, `a[j]` are loaded twice :-(

Improvement:

- Use a pointer to traverse the array `a`;
- store the values of `a[i]`, `a[j]`!

```
void swap (int *p, int *q) {
     int t, ai, aj;
     ai = *p; aj = *q;
     if (ai > aj) {
         t = aj;
         *q = ai;
         *p = t;    // t can also be
        }           // eliminated!
     }
```

Observation 2:

Higher programming languages (even C :-) abstract from hardware and efficiency.

It is up to the compiler to adapt intuitively written program to hardware.

Examples:

... Filling of delay slots;

... Utilization of special instructions;

... Re-organization of memory accesses for better cache behavior;

... Removal of (useless) overflow/range checks.

Observation 3:

Programm-Improvements need not always be correct :-(

Example:

`y = f() + f();` ⟹ `y = 2 * f();`

Idea:

Save second evaluation of `f()` ...

Observation 3:

Programm-Improvements need not always be correct :-(

Example:

`y = f() + f();` $\Longrightarrow$ `y = 2 * f();`

Idea: Save the second evaluation of `f()` ???

Problem: The second evaluation may return a result different from the first; (e.g., because `f()` reads from the input :-)

Consequences:

$\Longrightarrow$ Optimizations have assumptions.

$\Longrightarrow$ The assumption must be:

- formalized,
- checked :-)

$\Longrightarrow$ It must be proven that the optimization is correct, i.e., preserves the semantics !!!

Observation 4:

Optimization techniques depend on the programming language:

→ which inefficiencies occur;

→ how analyzable programs are;

→ how difficult/impossible it is to prove correctness ...

Example: Java

Unavoidable Inefficiencies:

- $*$ Array-bound checks;
- $*$ Dynamic method invocation;
- $*$ Bombastic object organization ...

Analyzability:

- $+$ no pointer arithmetic;
- $+$ no pointer into the stack;
- $-$ dynamic class loading;
- $-$ reflection, exceptions, threads, ...

Correctness proofs:

+ more or less well-defined semantics;

− features, features, features;

− libraries with changing behavior ...

... in this course:

a simple imperative programming language with:

- variables // registers
- $R = e;$ // assignments
- $R = M[e];$ // loads
- $M[e_1] = e_2;$ // stores
- if (e) s_1 else s_2 // conditional branching
- goto $L;$ // no loops :-)

Note:

- For the beginning, we omit procedures :-)
- External procedures are taken into account through a statement $f()$ for an unknown procedure f.

  $\Longrightarrow$ intra-procedural

  $\Longrightarrow$ kind of an intermediate language in which (almost) everything can be translated.

Example: `swap()`

```
0:   $A_1 = A_0 + 1 * i;$        // $A_0 == \&a$
1:   $R_1 = M[A_1];$             // $R_1 == a[i]$
2:   $A_2 = A_0 + 1 * j;$
3:   $R_2 = M[A_2];$             // $R_2 == a[j]$
4:   if $(R_1 > R_2)$ {
5:       $A_3 = A_0 + 1 * j;$
6:       $t = M[A_3];$
7:       $A_4 = A_0 + 1 * j;$
8:       $A_5 = A_0 + 1 * i;$
9:       $R_3 = M[A_5];$
10:      $M[A_4] = R_3;$
11:      $A_6 = A_0 + 1 * i;$
12:      $M[A_6] = t;$
     }
```

Optimization 1: $1 * R \implies R$

Optimization 2: Reuse of subexpressions

$$A_1 == A_5 == A_6$$
$$A_2 == A_3 == A_4$$

$$M[A_1] == M[A_5]$$
$$M[A_2] == M[A_3]$$

$$R_1 == R_3$$

By this, we obtain:

$$
\begin{array}{lcl}
A_1 & = & A_0 + i; \\
R_1 & = & M[A_1]; \\
A_2 & = & A_0 + j; \\
R_2 & = & M[A_2]; \\
\multicolumn{3}{l}{\mathsf{if}\ (R_1 > R_2)\ \{} \\
\end{array}
$$

$$
\begin{array}{lcl}
t & = & R_2; \\
M[A_2] & = & R_1; \\
M[A_1] & = & t; \\
\}
\end{array}
$$

Optimization 3: Contraction of chains of assignments :-)

Gain:

	before	after
$+$	6	2
$*$	6	0
load	4	2
store	2	2
$>$	1	1
$=$	6	2

1 Removing superfluous computations

1.1 Repeated computations

Idea:

If the same value is computed repeatedly, then

→ store it after the first computation;

→ replace every further computation through a look-up!

$\Longrightarrow$ Availability of expressions

$\Longrightarrow$ Memoization

Problem: Identify repeated computations!

Example:

$$\begin{array}{lrcl} & z & = & 1; \\ & y & = & M[17]; \\ A: & x_1 & = & \boxed{y+z}; \\ & & & \dots \\ B: & x_2 & = & \boxed{y+z}; \end{array}$$

Note:

B is is a repeated computation of the value of $\boxed{y + z}$, if:

(1) A is always executed before B; and

(2) y and z at B have the same values as at A :-)

$\Longrightarrow$ We need:

$\rightarrow$ an operational semantics :-)

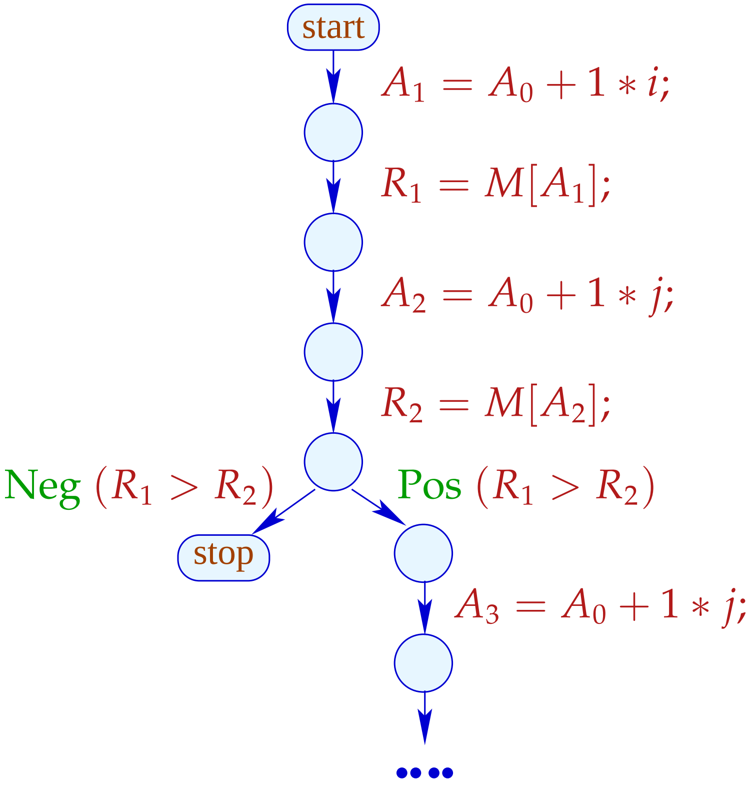
$\rightarrow$ a method which identifies at least some repeated computations ...

Background 1: An Operational Semantics

we choose a small-step operational approach.

Programs are represented as control-flow graphs.

In the example:



Thereby, represent:

vertex	program point
start	programm start
stop	program exit
edge	step of computation

Thereby, represent:

vertex	program point
start	programm start
stop	program exit
edge	step of computation

Edge Labelings:

Test : Pos (e) or Neg (e)

Assignment : $R = e;$

Load : $R = M[e];$

Store : $M[e_1] = e_2;$

Nop : $;$

Computations follow paths.

Computations transform the current state

$$s = (\rho, \mu)$$

where:

$\rho : \mathit{Vars} \to \mathbf{int}$	contents of registers
$\mu : \mathbb{N} \to \mathbf{int}$	contents of storage

Every edge $k = (u, \mathit{lab}, v)$ defines a partial transformation

$$[\![k]\!] = [\![\mathit{lab}]\!]$$

of the state: