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Program Optimization

TU München

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Organization

Dates:	Lecture:	Monday, 14:00-15:30
		Wednesday, 8:30-10:00
	Tutorials:	Tuesday/Wednesday, 10:00-12:00
		Kalmer Apinis: `apinis@in.tum.de`
	Material:	slides, recording :-)
		Moodle
		Program Analysis and Transformation
		Springer, 2012

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();    ==>    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:

- $\rightarrow$ which inefficiencies occur;
- $\rightarrow$ how analyzable programs are;
- $\rightarrow$ 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()`

$$
\begin{array}{llllll}
A_1 & = & A_0 + 1 * i; & // & A_0 == \&a \\
R_1 & = & M[A_1]; & // & R_1 == a[i] \\
A_2 & = & A_0 + 1 * j; & & \\
R_2 & = & M[A_2]; & // & R_2 == a[j] \\
\multicolumn{5}{l}{\textsf{if } (R_1 > R_2)\ \{}
\end{array}
$$

$$
\begin{array}{lll}
\quad A_3 & = & A_0 + 1 * j; \\
\quad t & = & M[A_3]; \\
\quad A_4 & = & A_0 + 1 * j; \\
\quad A_5 & = & A_0 + 1 * i; \\
\quad R_3 & = & M[A_5]; \\
\quad M[A_4] & = & R_3; \\
\quad A_6 & = & A_0 + 1 * i; \\
\quad M[A_6] & = & t; \\
\quad \} & &
\end{array}
$$

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:

$$
\begin{aligned}
A_1 &= A_0 + i; \\
R_1 &= M[A_1]; \\
A_2 &= A_0 + j; \\
R_2 &= M[A_2]; \\
&\textsf{if } (R_1 > R_2)\ \{ \\
&\qquad \begin{aligned} t &= R_2; \\ M[A_2] &= R_1; \\ M[A_1] &= t; \end{aligned} \\
&\qquad \}
\end{aligned}
$$

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

$\rightarrow$ store it after the first computation;

$\rightarrow$ replace every further computation through a look-up!

$\Longrightarrow$ Availability of expressions

$\Longrightarrow$ Memoization

Problem: Identify repeated computations!

Example:

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

Note:

B 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 :-)

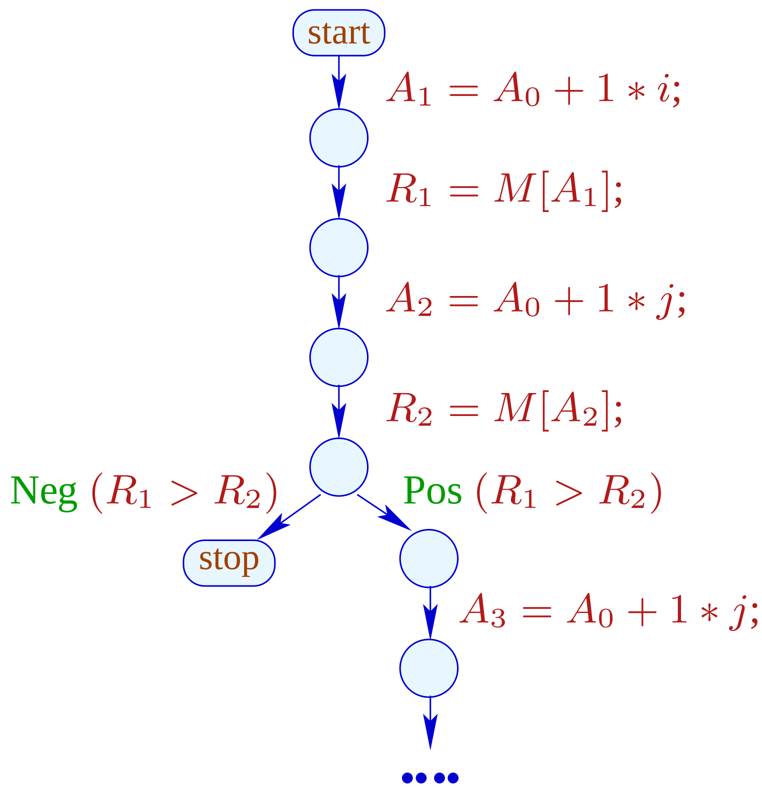
$\rightarrow$ a method which identifies at least some repeated computations ...

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 $k = (u, lab, v)$ defines a partial transformation

$$[\![k]\!] = [\![lab]\!]$$

of the state:

$$\llbracket ; \rrbracket (\rho, \mu) = (\rho, \mu)$$

$$\llbracket \mathrm{Pos}\,(e) \rrbracket (\rho, \mu) = (\rho, \mu) \quad \text{if } \llbracket e \rrbracket \rho \neq 0$$

$$\llbracket \mathrm{Neg}\,(e) \rrbracket (\rho, \mu) = (\rho, \mu) \quad \text{if } \llbracket e \rrbracket \rho = 0$$

$$
\begin{aligned}
[\![;]\!]\,(\rho, \mu) &= (\rho, \mu) \\
\\
[\![\mathrm{Pos}\,(e)]\!]\,(\rho, \mu) &= (\rho, \mu) && \text{if } [\![e]\!]\,\rho \neq 0 \\
[\![\mathrm{Neg}\,(e)]\!]\,(\rho, \mu) &= (\rho, \mu) && \text{if } [\![e]\!]\,\rho = 0
\end{aligned}
$$

// $[\![e]\!]$: evaluation of the expression e, e.g.

// $[\![x + y]\!]\,\{x \mapsto 7, y \mapsto -1\} = 6$

// $[\![!(x == 4)]\!]\,\{x \mapsto 5\} = 1$

$$[\![;]\!]\,(\rho,\mu) \quad = \quad (\rho,\mu)$$

$$[\![\text{Pos}\,(e)]\!]\,(\rho,\mu) \quad = \quad (\rho,\mu) \qquad \text{if } [\![e]\!]\,\rho \neq 0$$

$$[\![\text{Neg}\,(e)]\!]\,(\rho,\mu) \quad = \quad (\rho,\mu) \qquad \text{if } [\![e]\!]\,\rho = 0$$

// $[\![e]\!]$: evaluation of the expression e, e.g.

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$$[\![R = e;]\!]\,(\rho,\mu) \quad = \quad (\boxed{\rho \oplus \{R \mapsto [\![e]\!]\,\rho\}}, \mu)$$

// where “$\oplus$” modifies a mapping at a given argument