# Compilerconstructie

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http://www.liacs.nl/home/rvvliet/coco/

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college 8, dinsdag 12 november 2013

Code Generation

Code Optimization



## 8.6 A Simple Code Generator

Use of registers

- Operands of operation must be in registers
- To hold values of temporary variables
- To hold (global) values that are used in several blocks
- To manage run-time stack

Assumption: subset of registers available for block

Machine instructions of form

- LD *reg*, *mem*
- ST *mem*, *reg*
- *OP* *reg*, *reg*, *reg*



## Register and Address Descriptors

- Register descriptor keeps track of what is currently in register
  - Example:

    LD $R, x$ $\quad \rightarrow$ register $R$ contains $x$

  - Initially, all registers are empty
- Address descriptor keeps track of locations where current value of a variable can be found
  - Example:

    LD $R, x$ $\quad \rightarrow x$ is (also) in $R$

  - Information stored in symbol table



## The Code-Generation Algorithm

For each three-address instruction $x = y$ *op* $z$

1. Use *getReg*($x = y$ *op* $z$) to select registers $R_x, R_y, R_z$
2. If $y$ is not in $R_y$, then issue instruction LD $R_y, y'$,
   where $y'$ is a memory location for $y$
   (according to address descriptor)
3. If $z$ is not in $R_z$, ...
4. Issue instruction *OP* $R_x, R_y, R_z$

Special case: $x = y$ ...

At end of block: store all variables that are live-on-exit and not in their memory locations (according to address descriptor)



## Managing Register / Address Descriptors

1. For the instruction LD $R, x$, ...
2. For the instruction ST $x, R$, ...
3. For an operation like ADD $R_x, R_y, R_z$, implementing $x = y + z$,
   (c) Remove $R_x$ from addr. descr. of other variables
   (d) Remove $x$ from reg. descr. of other registers
   (a) Change reg. descr. for $R_x$: only $x$
   (b) Change addr. descr. for $x$: only in $R_x$ (not in $x$ itself!)
4. For the copy statement $x = y$, ...



## Managing Register / Address Descriptors

Example: $d = (a - b) + (a - c) + (a - c)$ $\quad a = \ldots$old value of $d$

```
t = a - b
    LD  R1, a
    LD  R2, b
    SUB R2, R1, R2
u = a - c
    LD  R3, c
    SUB R1, R1, R3
v = t + u
    ADD R3, R2, R1
a = d
    LD  R2, d
d = v + u
    ADD R1, R3, R1

exit
    ST  a, R2
    ST  d, R1
```

| R1 | R2 | R3 |
|---|---|---|
| | | |

| a | b | c | d | t | u | v |
|---|---|---|---|---|---|---|
| a | b | c | d | | | |



## Managing Register / Address Descriptors

Example: $d = (a - b) + (a - c) + (a - c)$ $\quad a = \ldots$old value of $d$

```
t = a - b
    LD  R1, a
    LD  R2, b
    SUB R2, R1, R2
u = a - c
    LD  R3, c
    SUB R1, R1, R3
v = t + u
    ADD R3, R2, R1
a = d
    LD  R2, d
d = v + u
    ADD R1, R3, R1

exit
    ST  a, R2
    ST  d, R1
```

| R1 | R2 | R3 |
|---|---|---|
| d | a | v |

| a | b | c | d | t | u | v |
|---|---|---|---|---|---|---|
| a,R2 | b | c | d,R1 | | | R3 |



## Function *getReg*

For each instruction $x = y$ *op* $z$

- To compute $R_y$
  1. If $y$ is in register, $\longrightarrow R_y$
  2. Else, if empty register available, $\longrightarrow R_y$
  3. Else, select occupied register
     For each register $R$ and variable $v$ in $R$
     (a) If $v$ is also somewhere else, then OK
     (b) If $v$ is $x$, and $x$ is not $z$, then OK
     (c) Else, if $v$ is not used later, then OK
     (d) Else, ST $v, R$ is required

     Take $R$ with smallest number of stores

## Function *getReg*

For each instruction $x = y \textit{ op } z$

- To compute $R_x$, similar with few differences (which?)

For each instruction $x = y$, choose $R_x = R_y$



**Exercise.**
(Exercise 1 one from exercise class; cf. Exercise 8.6.1/8.6.4)

Consider the following C code:

```
x = a[i] + 1;
k = x;
b[i][j] = k + y;
```

Assume
that all array elements are integers taking four bytes each,
and that $b$ is $100 \times 100$ array

**a.** Generate three-address code for this C code
**b.** Convert your three-address code into machine code, using the simple code-generation algorithm of this section, assuming three registers are available. Show the register and address descriptors after each step.



## Addressing Modes of Target Machine

(from college 7)

| Form | Address | Example |
|---|---|---|
| $r$ | $r$ | LD R1, R2 |
| $x$ | $x$ | LD R1, x |
| $a(r)$ | $a + contents(r)$ | LD R1, a(R2) |
| $c(r)$ | $c + contents(r)$ | LD R1, 100(R2) |
| $*r$ | $contents(r)$ | LD R1, *R2 |
| $*c(r)$ | $contents(c + contents(r))$ | LD R1, *100(R2) |
| $\#c$ | | LD R1, #100 |



## 8.8 Register Allocation and Assignment

So far, live variables in registers are stored at end of block

Use of registers

- Operands of operation must be in registers
- To hold values of temporary variables
- To hold (global) values that are used in several blocks
- To manage run-time stack



## Usage counts

With $x$ in register during loop $L$

- Save ... for ... use of $x$ that is not preceded by assignment in same block
- Save ... for each block, where $x$ is assigned a value and $x$ is live on exit
- $$\text{Total savings} \approx \sum_{\text{blocks } B \in L} \ldots$$

Choose variables $x$ with largest savings



## Usage counts

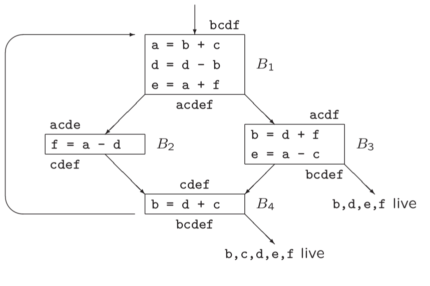
With $x$ in register during loop $L$

- Save 1 for each use of $x$ that is not preceded by assignment in same block
- Save 2 for each block, where $x$ is assigned a value and $x$ is live on exit
- $$\text{Total savings} \approx \sum_{\text{blocks } B \in L} use(x, B) + 2 * live(x, B)$$

Choose variables $x$ with largest savings



## Usage counts (Example)




Savings for $a$ are $1 + 1 + 1 * 2 = 4$



## 8.5 Optimization of Basic Blocks

To improve running time of code

- Local optimization: within block
- Global optimization: across blocks

Local optimization benefits from DAG representation of basic block

## DAG Representation of Basic Blocks

1. A node for initial value of each variable appearing in block
2. A node $N$ for each statement $s$ in block
   Children of $N$ are nodes corresponding to last definitions of operands used by $s$
3. Node $N$ is labeled by operator applied at $s$
   $N$ has list of variables for which $s$ is last definition in block
4. *Output nodes* $\approx$ live on exit

Example:

```
a = b + c
b = a - d
c = b + c
d = a - d
```



## Local Common Subexpression Elimination

- Use value-number method to detect common subexpressions
- Remove redundant computations

Example:

```
a = b + c
b = a - d
c = b + c
d = a - d
```



## Local Common Subexpression Elimination

- Use value-number method to detect common subexpressions
- Remove redundant computations

Example:

```
a = b + c        a = b + c
b = a - d        b = a - d
c = b + c        c = b + c
d = a - d        d = b
```



## Dead Code Elimination

- Remove roots with no live variables attached
- If possible, repeat

Example:

```
a = b + c
b = b - d
c = c + d
e = b + c
```

No common subexpression

If $c$ and $e$ are not live. . .



## Dead Code Elimination

- Remove roots with no live variables attached
- If possible, repeat

Example:

```
a = b + c        a = b + c
b = b - d        b = b - d
c = c + d
e = b + c
```

No common subexpression

If $c$ and $e$ are not live. . .



## Algebraic Transformations

(see assignment 3)

Algebraic identities:

$$x + 0 = 0 + x = x$$
$$x * 1 = 1 * x = x$$

Reduction in strength:

$$x^2 = x * x \quad \text{(cheaper)}$$
$$2 * x = x + x \quad \text{(cheaper)}$$
$$x/2 = x * 0.5 \quad \text{(cheaper)}$$

Constant folding:

$$2 * 3.14 = 6.28$$



## Algebraic Transformations

Common subexpressions resulting from commutativity / associativity of operators:

$$x * y = y * x$$
$$c + d + b = (b + c) + d$$

Common subexpressions generated by relational operators:

$$x > y \Leftrightarrow x - y > 0$$



## 8.7 Peephole Optimization

- Examines short sequence of instructions in a window (peephole) and replace them by faster/shorter sequence
- Applied to intermediate code or target code
- Typical optimizations
  - Redundant instruction elimination
  - Eliminating unreachable code
  - Flow-of-control optimization
  - Algebraic simplification
  - Use of machine idioms

## Redundant Instruction Elimination

Example:

```
ST  a, R0
LD  R0, a
```



## Eliminating Unreachable Code

Example:

```
     if debug == 1 goto L1
     goto L2
L1: print debugging information
L2:
```



## Eliminating Unreachable Code

Example:

```
     if debug != 1 goto L2
L1: print debugging information
L2:
```

If `debug` is set to 0 at beginning of program, . . .



## Flow-of-Control Optimizations

Example 1:

```
     goto L1
     ...
L1: goto L2
```

Example 3:

```
     goto L1
     . . .
L1: 1f a < b goto L2
L3:
```



## 9.1 The Principal Sources of Optimization

Causes of redundancy

- At source level
- Side effect of high-level programming language, e.g., $A[i][j]$



## A Running Example: Quicksort

```
void quicksort (int m, int n)
    /* recursively sorts a[m] through a[n] */
{
    int i, j;
    int v, x;

    if (n <= m) return;

    i = m-1; j = n; v = a[n];
    while (1)
    {   do i = i+1; while (a[i] < v);
        do j = j-1; while (a[j] > v);
        if (i >= j) break;
        x = a[i]; a[i] = a[j]; a[j] = x; /* swap a[i], a[j] */
    }
    x = a[i]; a[i] = a[n]; a[n] = x; /* swap a[i], a[n] */

    quicksort(m,j); quicksort(i+1,n);
}
```

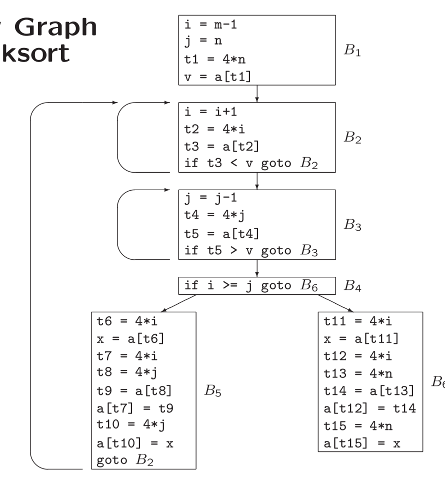


## Three-Address Code Quicksort

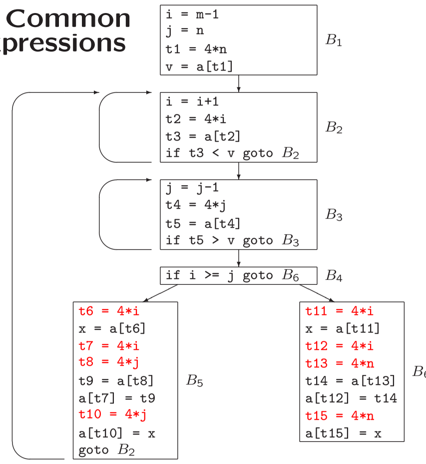
```
-->  (1)  i = m-1               (16)  t7 = 4*i
     (2)  j = n                 (17)  t8 = 4*j
     (3)  t1 = 4*n              (18)  t9 = a[t8]
     (4)  v = a[t1]             (19)  a[t7] = t9
-->  (5)  i = i+1               (20)  t10 = 4*j
     (6)  t2 = 4*i              (21)  a[t10] = x
     (7)  t3 = a[t2]            (22)  goto (5)
     (8)  if t3<v goto (5)  --> (23)  t11 = 4*i
-->  (9)  j = j-1               (24)  x = a[t11]
    (10)  t4 = 4*j              (25)  t12 = 4*i
    (11)  t5 = a[t4]            (26)  t13 = 4*n
    (12)  if t5>v goto (9)      (27)  t14 = a[t13]
--> (13)  if i>=j goto (23)     (28)  a[t12] = t14
--> (14)  t6 = 4*i              (29)  t15 = 4*n
    (15)  x = a[t6]             (30)  a[t15] = x
```



## Flow Graph Quicksort



## Local Common Subexpressions

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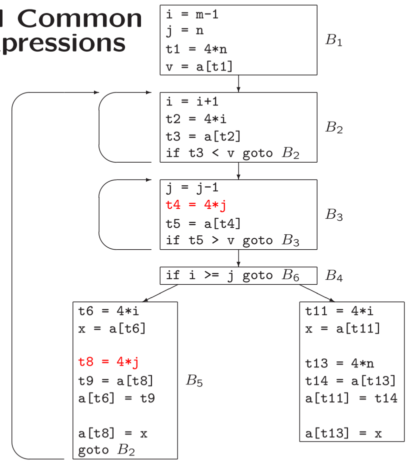
## Global Common Subexpressions

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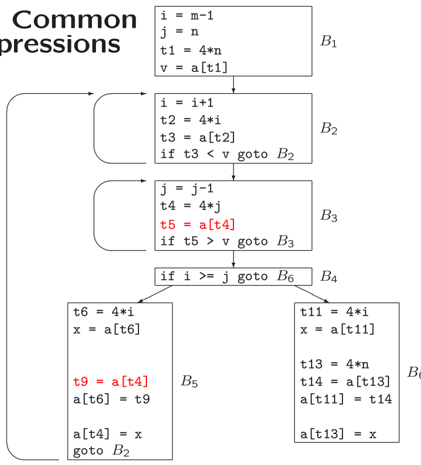
## Global Common Subexpressions

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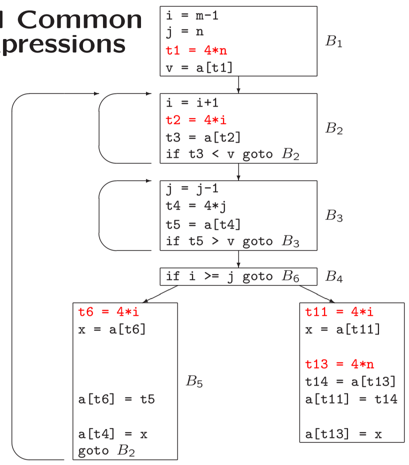
## Global Common Subexpressions

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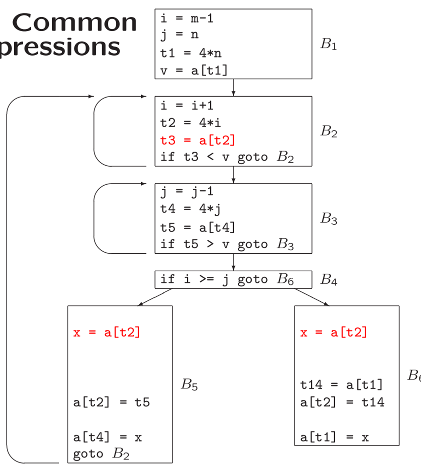
## Global Common Subexpressions

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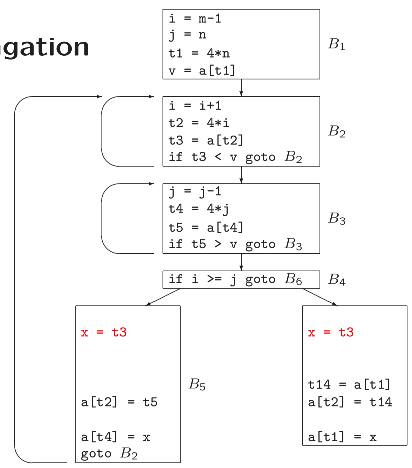
## Copy Propagation

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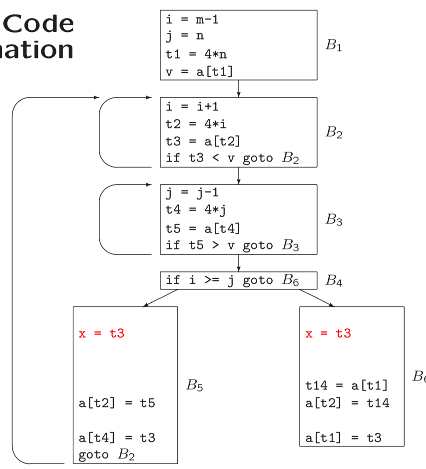
## Dead-Code Elimination

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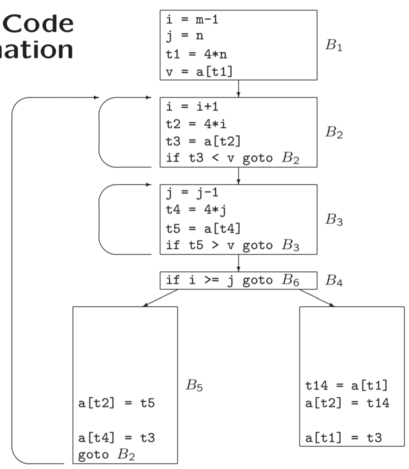
## Dead-Code Elimination

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## Code Motion

- loop-invariant computation
- compute before loop
- Example:

```
while (i <= limit-2)  /* statement does not change limit */
```

After code-motion

```
t = limit-2
while (i <= t)  /* statement does not change limit or t */
```

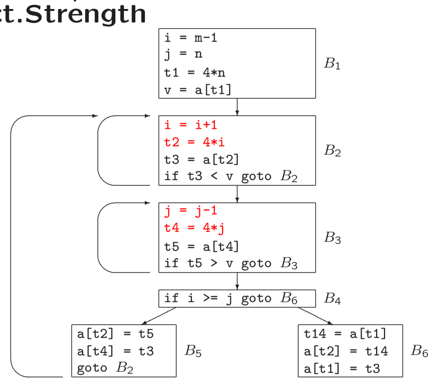


## Induction Variables and Reduction in Strength

- Induction variable: each assignment to $x$ of form $x = x + c$
- Reduction in strength: replace expensive operation by cheaper one

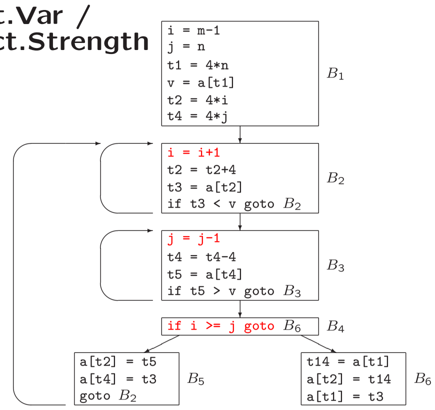


## Induct.Var / Reduct.Strength



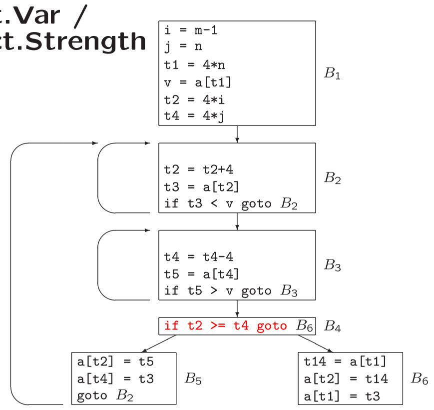



## Induct.Var / Reduct.Strength






## Induct.Var / Reduct.Strength






## En verder. . .

- Maandag 18 november: inleveren opdracht 3
- Dinsdag 19 november: practicum over opdracht 4
- Eerst naar 403, daarna naar 302/304
- Inleveren 9 december
- Dinsdag 26 november: hoor-/werkcollege in 403
- Dinsdag 3 december: practicum over opdracht 4



## Compiler constructie

college 8
Code Generation
Code Optimization

Chapters for reading:
8.5–8.5.4, 8.6–8.7, 8.8–8.8.2
9.intro, 9.1