# Control-Flow Graph and Local Optimizations - Part 2

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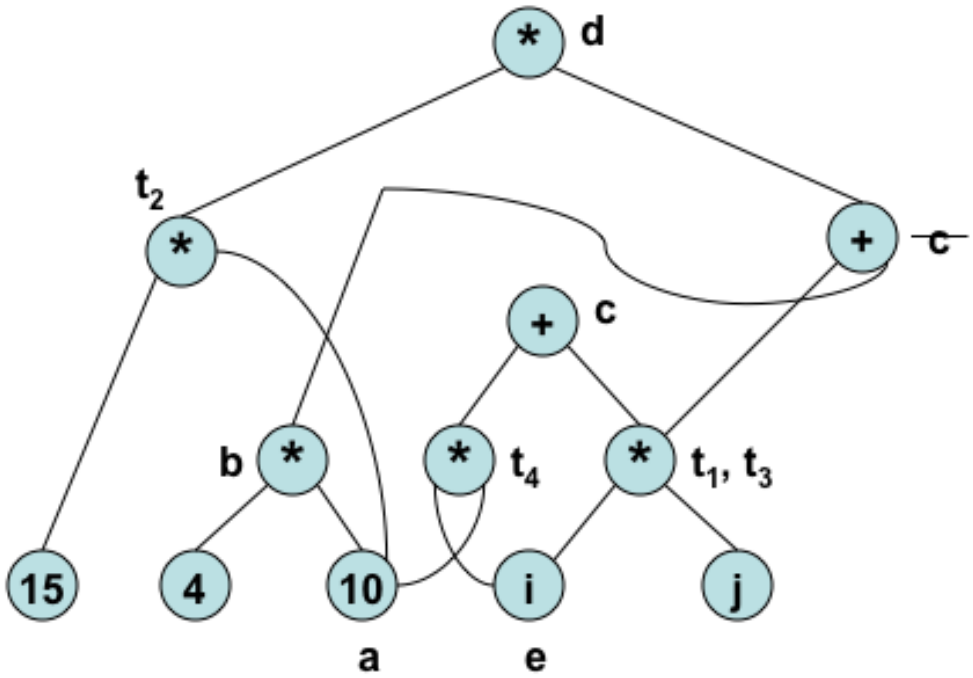
# Outline of the Lecture

- What is code optimization and why is it needed? (in part 1)
- Types of optimizations (in part 1)
- Basic blocks and control flow graphs (in part 1)
- Local optimizations (in part 1)
- Building a control flow graph (in part 1)
- Directed acyclic graphs and value numbering

# Example of a Directed Acyclic Graph (DAG)

1. $a = 10$
2. $b = 4 * a$
3. $t1 = i * j$
4. $c = t1 + b$
5. $t2 = 15 * a$
6. $d = t2 * c$
7. $e = i$
8. $t3 = e * j$
9. $t4 = i * a$
10. $c = t3 + t4$



# Value Numbering in Basic Blocks

- A simple way to represent DAGs is via *value-numbering*
- While searching DAGs represented using pointers etc., is inefficient, *value-numbering* uses hash tables and hence is very efficient
- Central idea is to assign numbers (called value numbers) to expressions in such a way that two expressions receive the same number if the compiler can prove that they are equal for all possible program inputs
- We assume quadruples with binary or unary operators
- The algorithm uses three tables indexed by appropriate hash values:
  *HashTable, ValnumTable,* and *NameTable*
- Can be used to eliminate common sub-expressions, do constant folding, and constant propagation in basic blocks
- Can take advantage of commutativity of operators, addition of zero, and multiplication by one

# Data Structures for Value Numbering

In the field *Namelist*, first name is the defining occurrence and replaces all other names with the same value number with itself (or its constant value)

HashTable entry
(indexed by expression hash value)

| Expression | Value number |
|---|---|

ValnumTable entry
(indexed by name hash value)

| Name | Value number |
|---|---|

NameTable entry
(indexed by value number)

| Name list | Constant value | Constflag |
|---|---|---|

# Example of Value Numbering

| HLL Program | Quadruples before Value-Numbering | Quadruples after Value-Numbering |
|---|---|---|
| $a = 10$ | 1. $a = 10$ | 1. $a = 10$ |
| $b = 4 * a$ | 2. $b = 4 * a$ | 2. $b = 40$ |
| $c = i * j + b$ | 3. $t1 = i * j$ | 3. $t1 = i * j$ |
| $d = 15 * a * c$ | 4. $c = t1 + b$ | 4. $c = t1 + 40$ |
| $e = i$ | 5. $t2 = 15 * a$ | 5. $t2 = 150$ |
| $c = e * j + i * a$ | 6. $d = t2 * c$ | 6. $d = 150 * c$ |
| | 7. $e = i$ | 7. $e = i$ |
| | 8. $t3 = e * j$ | 8. $t3 = i * j$ |
| | 9. $t4 = i * a$ | 9. $t4 = i * 10$ |
| | 10. $c = t3 + t4$ | 10. $c = t1 + t4$ (Instructions 5 and 8 can be deleted) |

# Running the algorithm through the example (1)

1. $a = 10$ :
   - $a$ is entered into *ValnumTable* (with a *vn* of 1, say) and into *NameTable* (with a constant value of 10)
2. $b = 4 * a$ :
   - $a$ is found in *ValnumTable*, its constant value is 10 in *NameTable*
     - We have performed *constant propagation*
     - $4 * a$ is evaluated to 40, and the quad is rewritten
     - We have now performed *constant folding*
     - $b$ is entered into *ValnumTable* (with a *vn* of 2) and into *NameTable* (with a constant value of 40)
3. $t1 = i * j$ :
   - $i$ and $j$ are entered into the two tables with new *vn* (as above), but with no constant value
   - $i * j$ is entered into *HashTable* with a new *vn*
   - $t1$ is entered into *ValnumTable* with the same *vn* as $i * j$

# Running the algorithm through the example (2)

4. Similar actions continue till $e = i$
   - $e$ gets the same *vn* as $i$
5. $t3 = e * j$ :
   - $e$ and $i$ have the same *vn*
   - hence, $e * j$ is detected to be the same as $i * j$
   - since $i * j$ is already in the HashTable, we have found a *common subexpression*
   - from now on, all uses of $t3$ can be replaced by $t1$
   - quad $t3 = e * j$ can be deleted
6. $c = t3 + t4$ :
   - $t3$ and $t4$ already exist and have *vn*
   - $t3 + t4$ is entered into *HashTable* with a new *vn*
   - this is a reassignment to $c$
   - $c$ gets a different *vn*, same as that of $t3 + t4$
7. Quads are renumbered after deletions

# Example: *HashTable* and *ValNumTable*

HashTable

| Expression | Value-Number |
|---|---|
| $i * j$ | 5 |
| $t1 + 40$ | 6 |
| $150 * c$ | 8 |
| $i * 10$ | 9 |
| $t1 + t4$ | 11 |

ValNumTable

| Name | Value-Number |
|---|---|
| $a$ | 1 |
| $b$ | 2 |
| $i$ | 3 |
| $j$ | 4 |
| $t1$ | 5 |
| $c$ | 6,11 |
| $t2$ | 7 |
| $d$ | 8 |
| $e$ | 3 |
| $t3$ | 5 |
| $t4$ | 10 |

# Handling Commutativity etc.

- When a search for an expression $i + j$ in *HashTable* fails, try for $j + i$
- If there is a quad $x = i + 0$, replace it with $x = i$
- Any quad of the type, $y = j * 1$ can be replaced with $y = j$
- After the above two types of replacements, value numbers of $x$ and $y$ become the same as those of $i$ and $j$, respectively
- Quads whose LHS variables are used later can be marked as *useful*
- All unmarked quads can be deleted at the end

# Handling Array References

Consider the sequence of quads:

1. $X = A[i]$
2. $A[j] = Y$: $i$ and $j$ could be the same
3. $Z = A[i]$: in which case, $A[i]$ is not a common subexpression here

- The above sequence cannot be replaced by: $X = A[i];\ A[j] = Y;\ Z = X$
- When $A[j] = Y$ is processed during value numbering, ALL references to array $A$ so far are searched in the tables and are marked KILLED - this kills quad 1 above
- When processing $Z = A[i]$, killed quads not used for CSE
- Fresh table entries are made for $Z = A[i]$
- However, if we know apriori that $i \neq j$, then $A[i]$ can be used for CSE

# Handling Pointer References

Consider the sequence of quads:

1. $X = *p$
2. $*q = Y$: $p$ and $q$ could be pointing to the same object
3. $Z = *p$: in which case, $*p$ is not a common subexpression here

- The above sequence cannot be replaced by: $X = *p;\ *q = Y;\ Z = X$
- Suppose no pointer analysis has been carried out
  - $p$ and $q$ can point to *any* object in the basic block
  - Hence, When $*q = Y$ is processed during value numbering, ALL table entries created so far are marked KILLED - this kills quad 1 above as well
  - When processing $Z = *p$, killed quads not used for CSE
  - Fresh table entries are made for $Z = *p$

# Handling Pointer References and Procedure Calls

- However, if we know apriori which objects *p* and *q* point to, then table entries corresponding to only those objects need to killed
- Procedure calls are similar
- With no dataflow analysis, we need to assume that a procedure call can modify any object in the basic block
  - changing call-by-reference parameters and global variables within procedures will affect other variables of the basic block as well
- Hence, while processing a procedure call, ALL table entries created so far are marked KILLED
- Sometimes, this problem is avoided by making a procedure call a separate basic block