CSC D70:
Compiler Optimization

Prof. Gennady Pekhimenko
University of Toronto
Winter 2019

The content of this lecture is adapted from the lectures of Todd Mowry and Phillip Gibbons

CSC D70: Compiler Optimization Introduction, Logistics

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Summary

- Syllabus
  - Course Introduction, Logistics, Grading
- Information Sheet
  - Getting to know each other
- Assignments
- Learning LLVM
- Compiler Basics

Syllabus: Who Are We?

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Office: BA 5232 / IC 454

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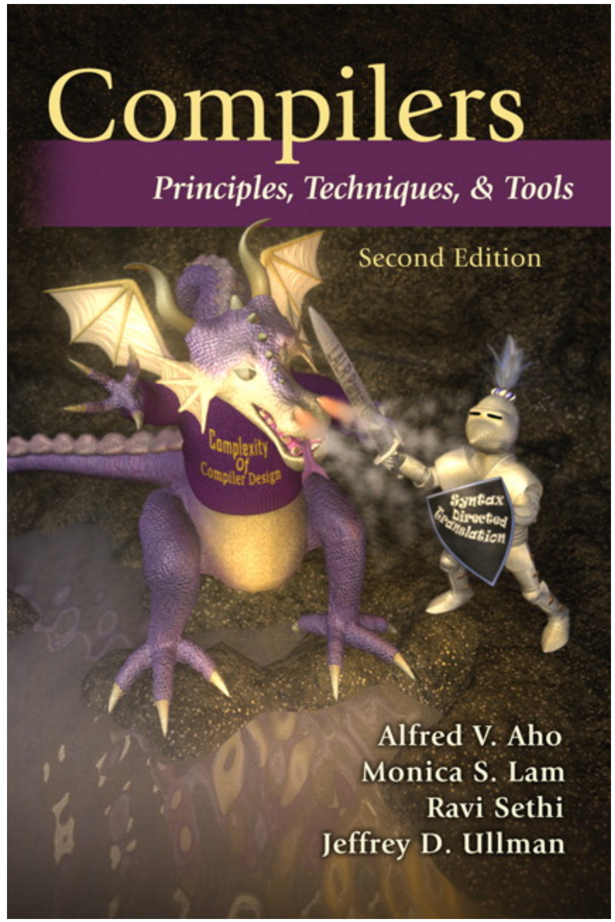
Computer Systems and Networking Group (CSNG)

EcoSystem Group

Course Information: Where to Get?

- Course Website: http://www.cs.toronto.edu/~pekhimenko/courses/cscd70-w19/
  - Announcements, Syllabus, Course Info, Lecture Notes, Tutorial Notes, Assignments
- Piazza: https://piazza.com/utoronto.ca/winter2019/cscd70/home
  - Questions/Discussions, Syllabus, Announcements
- Quercus
  - Emails/announcements
- Your email

Useful Textbook



CSC D70: Compiler Optimization Compiler Introduction

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Why Computing Matters (So Much)?

WHAT IS THE DIFFERENCE BETWEEN THE COMPUTING INDUSTRY AND THE PAPER TOWEL INDUSTRY?

Industry of replacement

1971 2017

CAN WE CONTINUE BEING AN INDUSTRY OF NEW POSSIBILITIES?

Personalized healthcare	Virtual reality	Real-time translators

Moore's Law

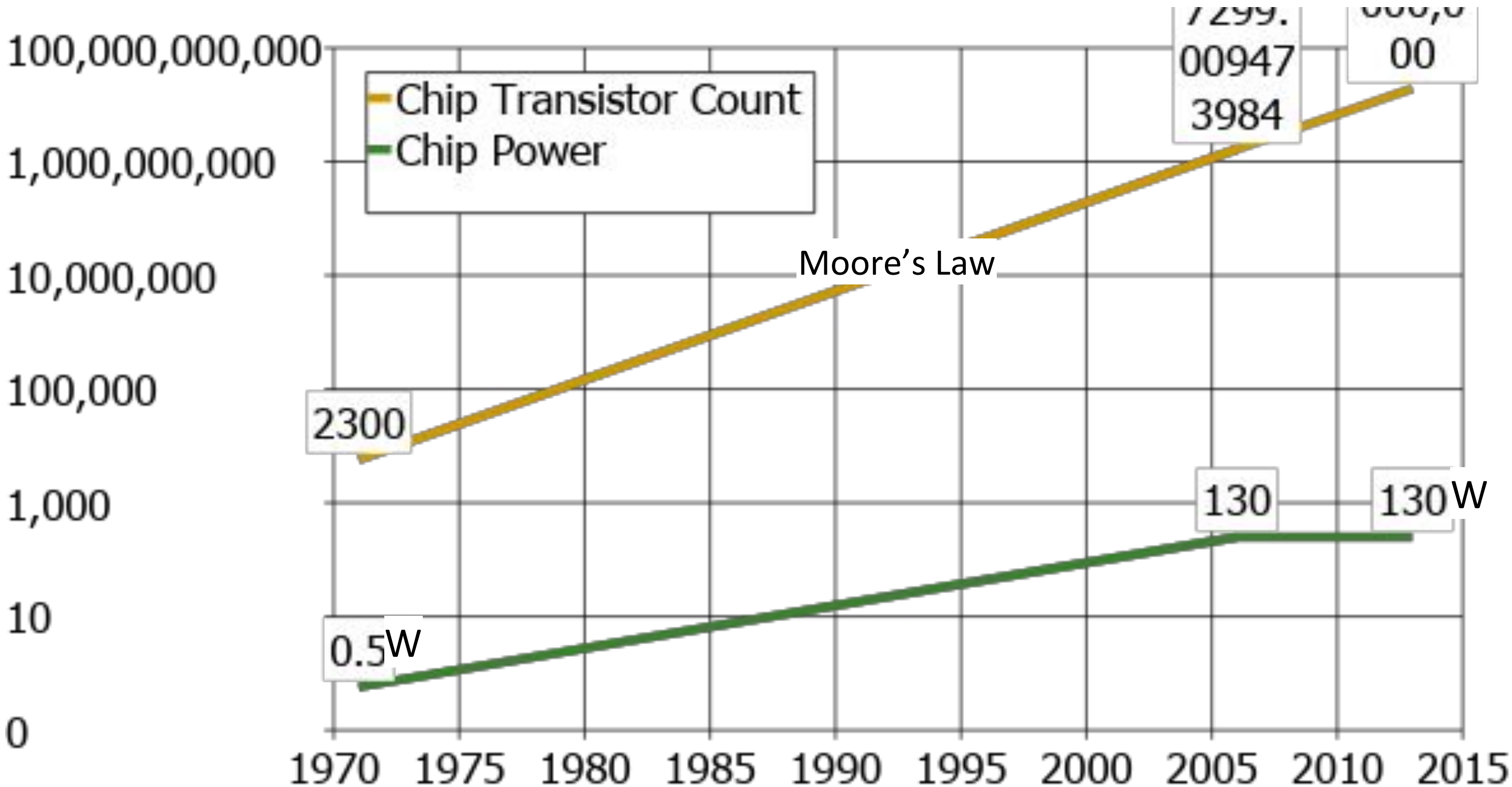
Or, how we became an industry of new possibilities

Every 2 Years

- Double the number of transistors
- Build higher performance general-purpose processors
  - Make the transistors available to masses
  - Increase performance (1.8×↑)
  - Lower the cost of computing (1.8×↓)

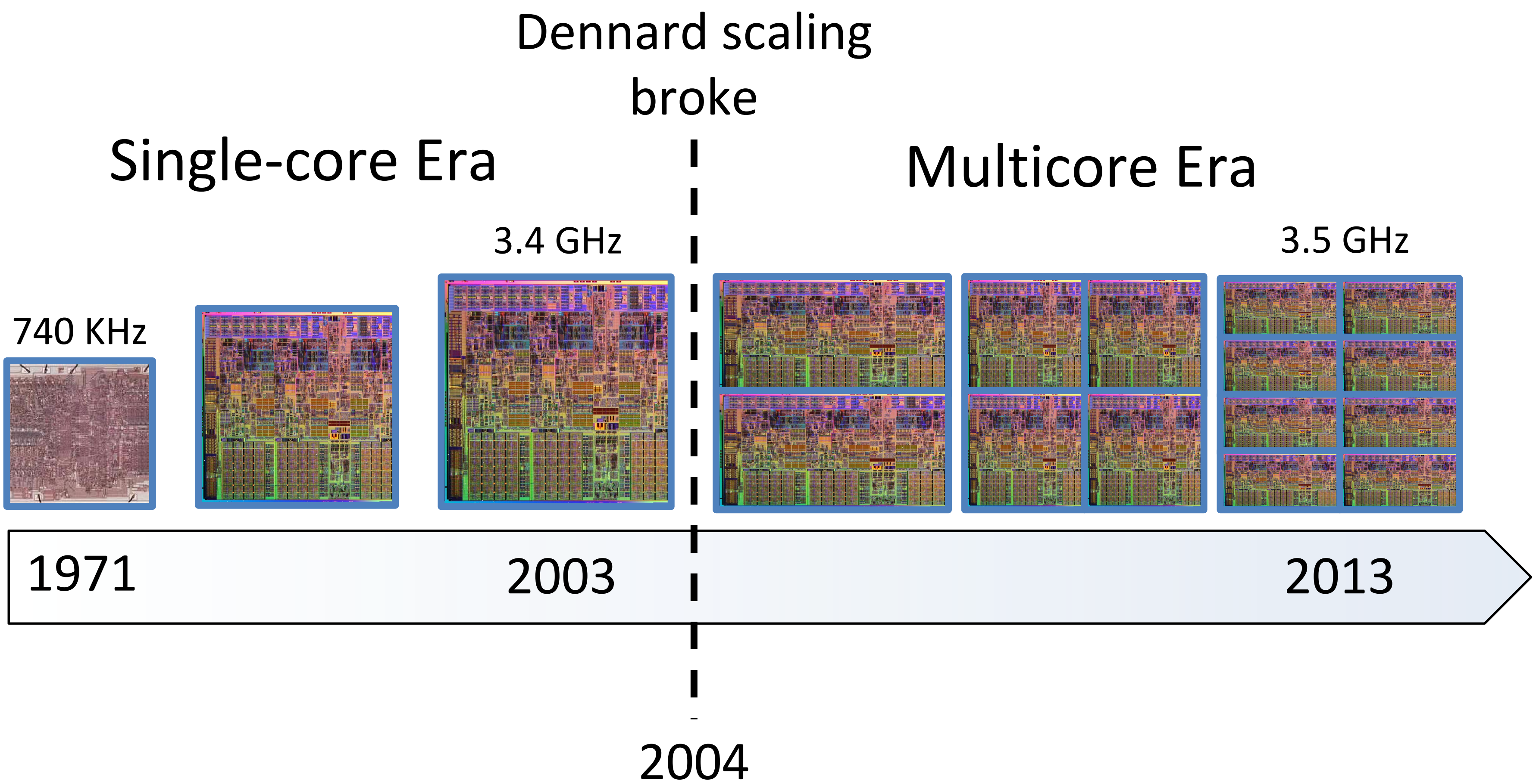
What is the catch?

Powering the transistors without melting the chip



Looking back

Evolution of processors



Any Solution Moving Forward?

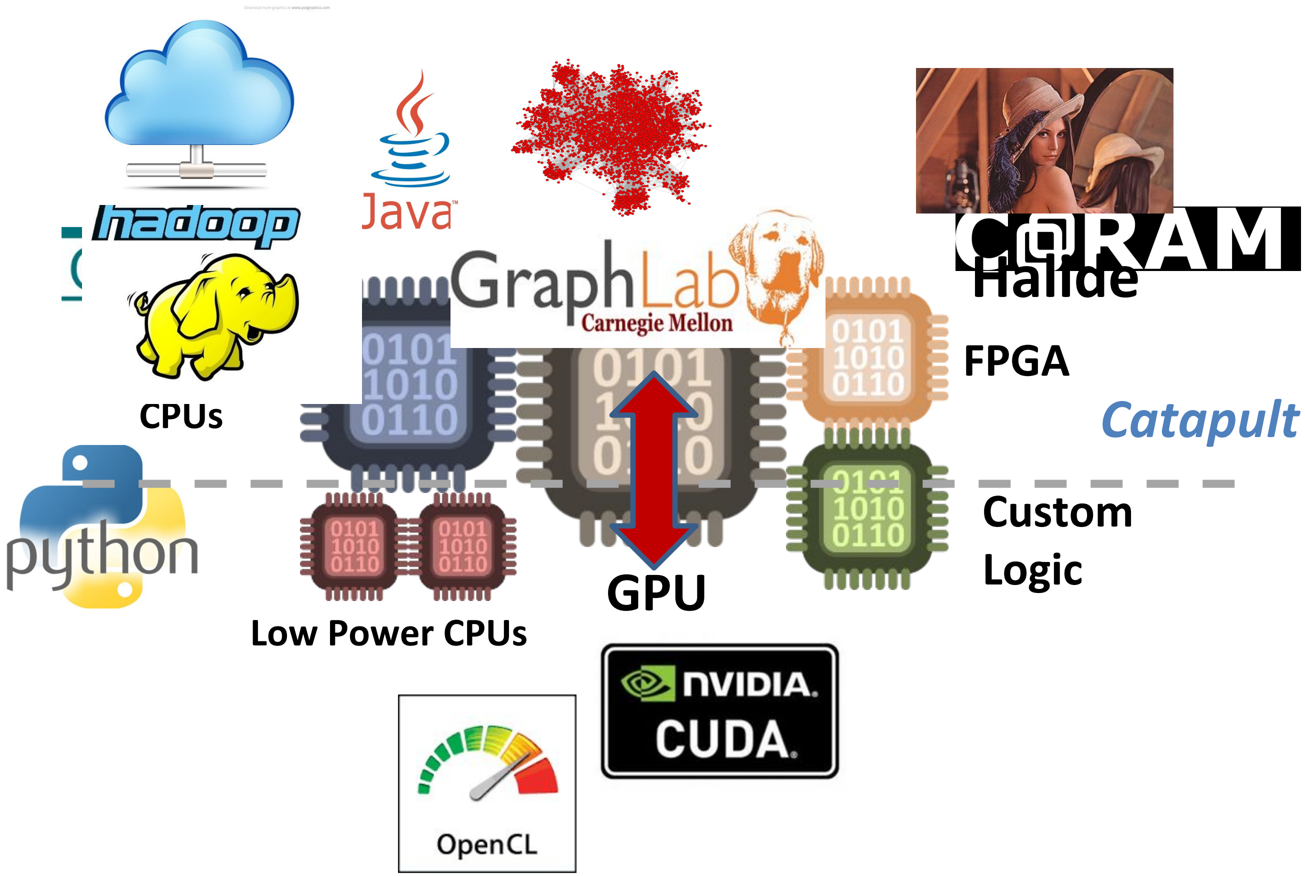
Hardware accelerators:

GPUs (Graphics Processing Units)

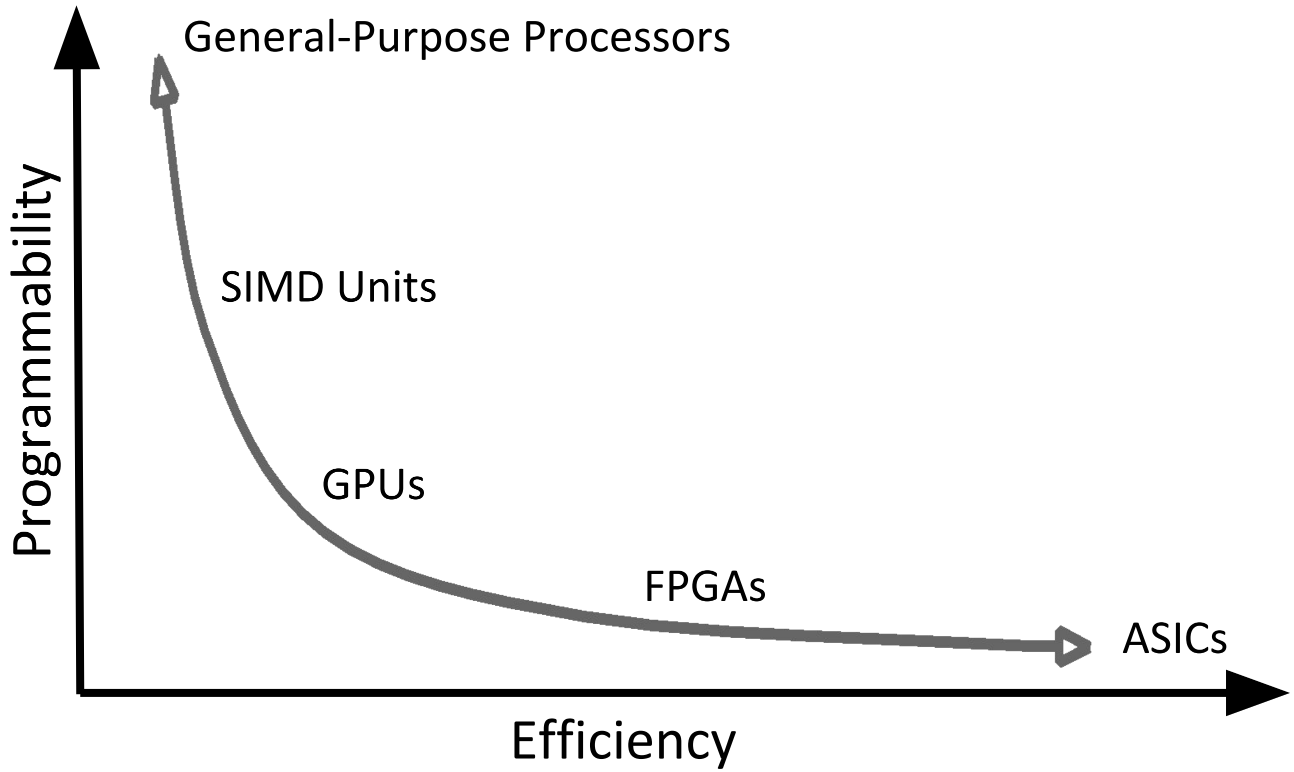
FPGAs (Field Programmable Gate Arrays)

TPUs (Tensor Processing Units)

Heterogeneity and Specialization



Programmability versus Efficiency



We need compilers!

Introduction to Compilers

- What would you get out of this course?
- Structure of a Compiler
- Optimization Example

What Do Compilers Do?

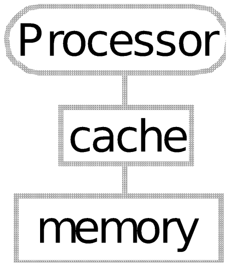
1. Translate one language into another
   - e.g., convert C++ into x86 object code
   - difficult for “natural” languages, but feasible for computer languages

2. Improve (i.e. “optimize”) the code
   - e.g., make the code run 3 times faster
     - or more energy efficient, more robust, etc.
   - driving force behind modern processor design

How Can the Compiler Improve Performance?

Execution time = **Operation count** * **Machine cycles per operation**

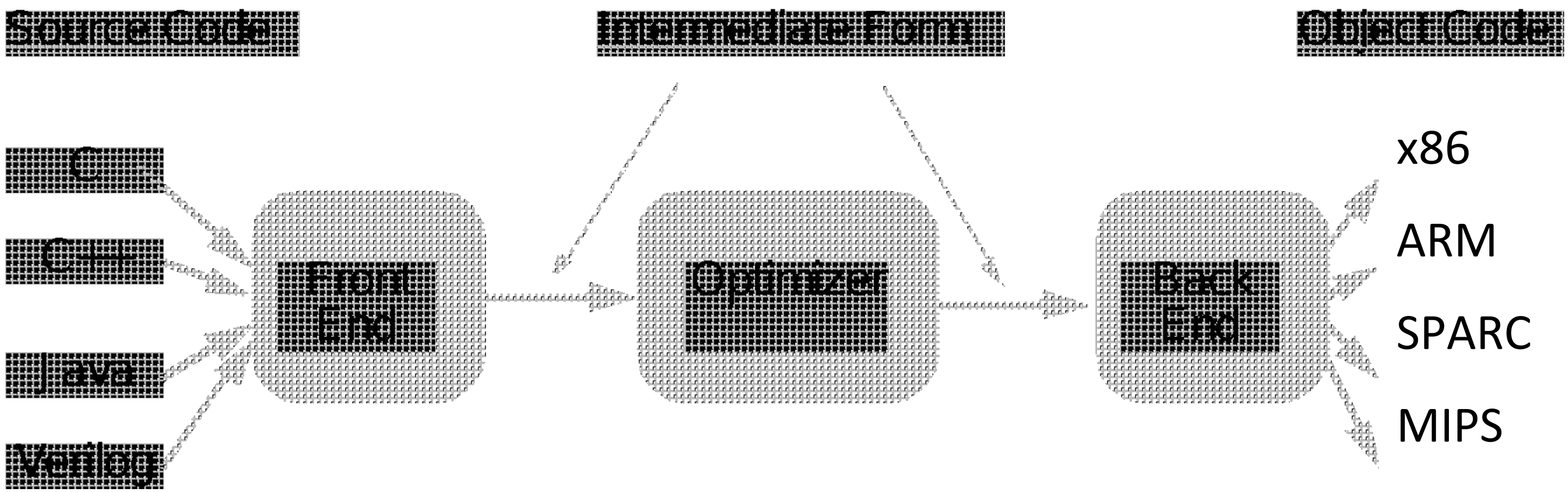
- **Minimize the number of operations**
  - arithmetic operations, memory accesses
- **Replace expensive operations with simpler ones**
  - e.g., replace 4-cycle multiplication with 1-cycle shift
- **Minimize cache misses**
  - both data and instruction accesses
- **Perform work in parallel**
  - instruction scheduling within a thread
  - parallel execution across multiple threads



What Would You Get Out of This Course?

- Basic knowledge of existing compiler optimizations
- Hands-on experience in constructing optimizations within a fully functional research compiler
- Basic principles and theory for the development of new optimizations

Structure of a Compiler

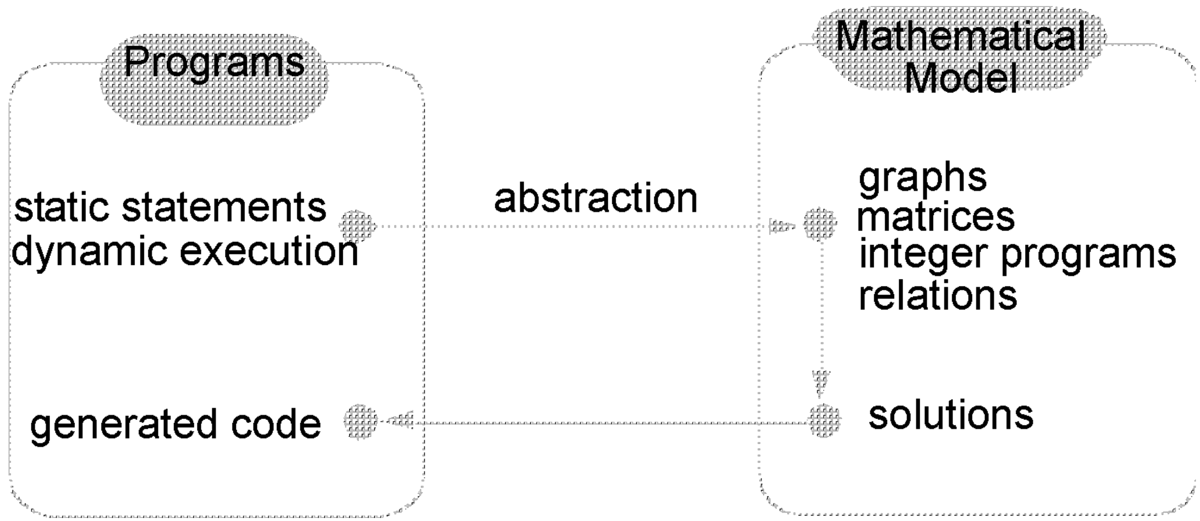


- **Optimizations are performed on an "intermediate form"**
  - similar to a generic RISC instruction set
- **Allows easy portability to multiple source languages, target machines**

Ingredients in a Compiler Optimization

- **Formulate optimization problem**
  - Identify opportunities of optimization
    - applicable across many programs
    - affect key parts of the program (loops/recursions)
    - amenable to “efficient enough” algorithm
- **Representation**
  - Must abstract essential details relevant to optimization

Ingredients in a Compiler Optimization



Ingredients in a Compiler Optimization

- **Formulate optimization problem**
  - Identify opportunities of optimization
    - applicable across many programs
    - affect key parts of the program (loops/recursions)
    - amenable to “efficient enough” algorithm
- **Representation**
  - Must abstract essential details relevant to optimization
- **Analysis**
  - Detect when it is desirable and safe to apply transformation
- **Code Transformation**

- **Experimental Evaluation (and repeat process)**

Representation: Instructions

- **Three-address code**

  `A := B op C`

  - LHS: name of variable e.g. **`x, A[t]`** (address of **`A`** + contents of **`t`**)
  - RHS: value

- **Typical instructions**

```
A := B op C
A := unaryop B
A := B
GOTO s
IF A relop B GOTO s
CALL  f
RETURN
```

Optimization Example

- **Bubblesort program that sorts an array `A` that is allocated in static storage:**
  - an element of **`A`** requires four bytes of a byte-addressed machine
  - elements of **`A`** are numbered 1 through **`n`** (**`n`** is a variable)
  - **`A[j]`** is in location **`&A+4*(j-1)`**

```
FOR i := n-1 DOWNTO 1 DO
    FOR j := 1 TO i DO
        IF A[j]> A[j+1] THEN BEGIN
         temp := A[j];
         A[j] := A[j+1];
         A[j+1] := temp
        END
```

Translated Code

```
       i  := n-1
S5:   if i<1 goto s1
       j  := 1
s4:   if j>i goto s2
       t1  := j-1
      t2  := 4*t1
      t3  := A[t2]    ;A[j]
      t4  := j+1
      t5  := t4-1
       t6  := 4*t5
       t7  := A[t6]    ;A[j+1]
      if t3<=t7 goto s3
```

```
FOR i  := n-1 DOWNTO 1 DO
  FOR j  := 1 TO i DO
    IF A[j]> A[j+1] THEN BEGIN
   temp  := A[j];
   A[j]  := A[j+1];
   A[j+1]  := temp
    END
```

```
      t8  :=j-1
      t9  := 4*t8
      temp  := A[t9]   ;A[j]
      t10  := j+1
      t11:= t10-1
      t12 := 4*t11
      t13  := A[t12]   ;A[j+1]
      t14  := j-1
      t15  := 4*t14
      A[t15]  := t13 ;A[j]:=A[j+1]
      t16  := j+1
      t17  := t16-1
      t18  := 4*t17
      A[t18]:=temp   ;A[j+1]:=temp
s3:   j  := j+1
      goto S4
S2:   i  := i-1
       goto s5
s1:
```

Representation: a Basic Block

- **Basic block = a sequence of 3-address statements**
  - only the first statement can be reached from outside the block (no branches into middle of block)
  - all the statements are executed consecutively if the first one is (no branches out or halts except perhaps at end of block)
- **We require basic blocks to be *maximal***
  - they cannot be made larger without violating the conditions
- **Optimizations within a basic block are *local* optimizations**

Flow Graphs

- **Nodes: basic blocks**

- **Edges: B_i -> B_j, iff B_j can follow B_i immediately in *some* execution**
  – Either first instruction of B_j is target of a goto at end of B_i
  – Or, B_j physically follows B_i, which does not end in an unconditional goto.

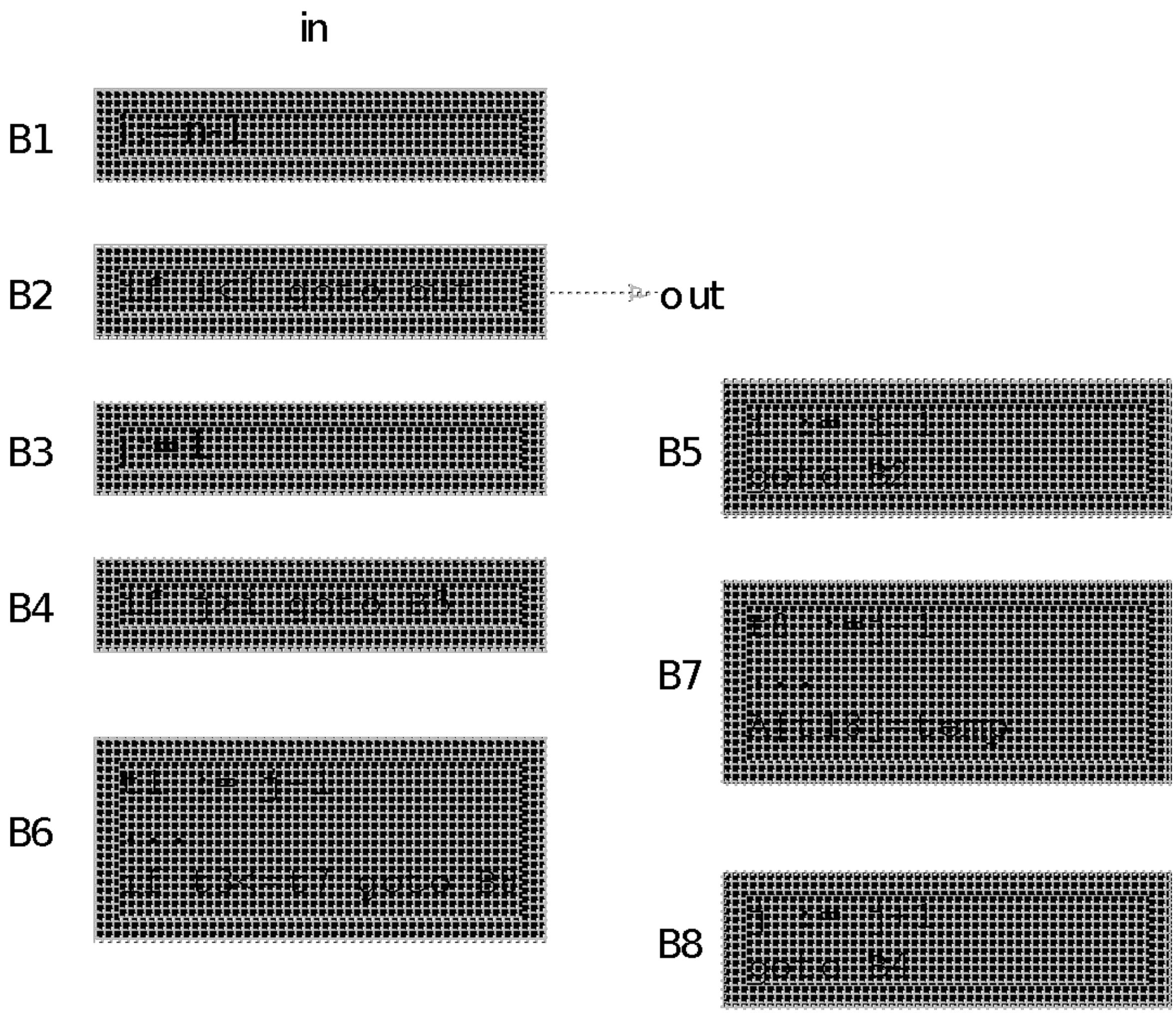
- **The block led by first statement of the program is the *start*, or *entry* node.**

Find the Basic Blocks

```
      i := n-1
S5:  if i<1 goto s1
      j := 1
s4:  if j>i goto s2
      t1 := j-1
     t2 := 4*t1
     t3 := A[t2]    ;A[j]
     t4 := j+1
     t5 := t4-1
      t6 := 4*t5
      t7 := A[t6]    ;A[j+1]
     if t3<=t7 goto s3
```

```
     t8 :=j-1
     t9 := 4*t8
     temp := A[t9]   ;A[j]
     t10 := j+1
     t11:= t10-1
     t12 := 4*t11
     t13 := A[t12]   ;A[j+1]
     t14 := j-1
     t15 := 4*t14
     A[t15] := t13 ;A[j]:=A[j+1]
     t16 := j+1
     t17 := t16-1
     t18 := 4*t17
     A[t18]:=temp  ;A[j+1]:=temp
s3:  j := j+1
     goto S4
S2:  i := i-1
      goto s5
s1:
```

Basic Blocks from Example

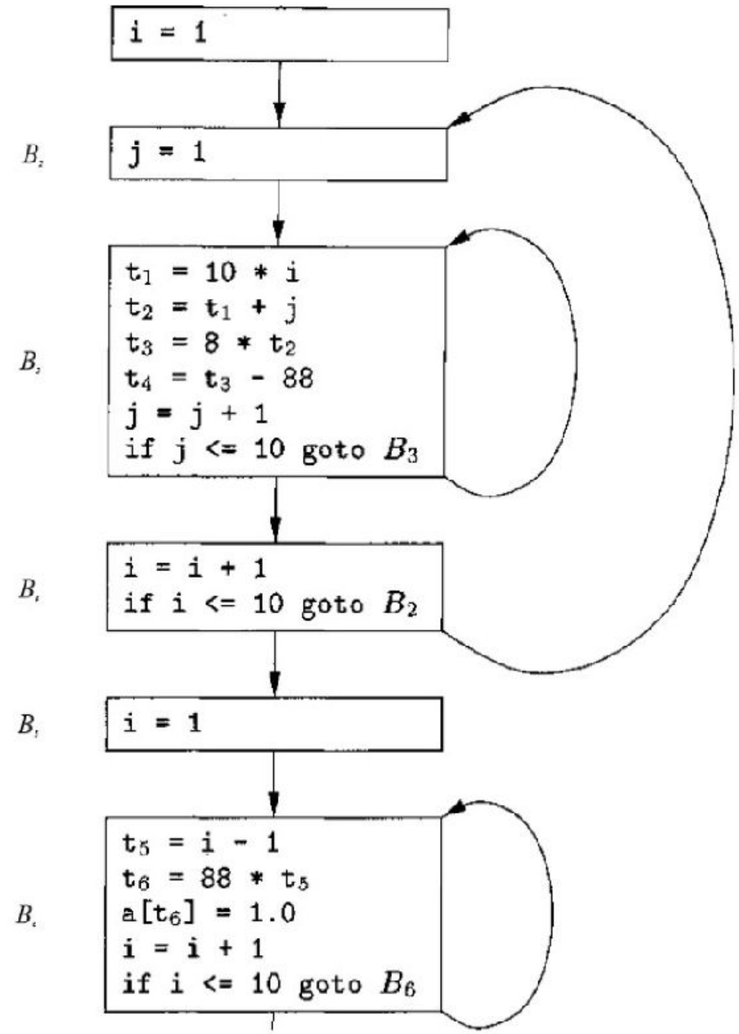


Partitioning into Basic Blocks

- Identify the leader of each basic block
  - First instruction
  - Any target of a jump
  - Any instruction immediately following a jump
- Basic block starts at leader & ends at instruction immediately before a leader (or the last instruction)

```
★ 1)  i = 1
★ 2)  j = 1
★ 3)  t1 = 10 * i
  4)  t2 = t1 + j
  5)  t3 = 8 * t2
  6)  t4 = t3 - 88
  7)  a[t4] = 0.0
  8)  j = j + 1
  9)  if j <= 10 goto (3)
★10)  i = i + 1
 11)  if i <= 10 goto (2)
★12)  i = 1
★13)  t5 = i - 1
 14)  t6 = 88 * t5
 15)  a[t6] = 1.0
 16)  i = i + 1
 17)  if i <= 10 goto (13)
```

★ = Leader



ALSU pp. 529-531

Sources of Optimizations

- **Algorithm optimization**

- **Algebraic optimization**

  `A := B+0        =>        A := B`

- **Local optimizations**
  - within a basic block -- across instructions
- **Global optimizations**
  - within a flow graph -- across basic blocks
- **Interprocedural analysis**
  - within a program -- across procedures (flow graphs)

Local Optimizations

- **Analysis & transformation performed within a basic block**
- **No control flow information is considered**
- **Examples of local optimizations:**
  - local common subexpression elimination
    analysis: same expression evaluated more than once in b.
    transformation: replace with single calculation
  - local constant folding or elimination
    analysis: expression can be evaluated at compile time
    transformation: replace by constant, compile-time value
  - dead code elimination

Example

```
     i  := n-1
S5:  if i<1 goto s1
     j  := 1
s4:  if j>i goto s2
     t1  := j-1
     t2  := 4*t1
     t3  := A[t2]     ;A[j]
     t4  := j+1
     t5  := t4-1
     t6  := 4*t5
     t7  := A[t6]     ;A[j+1]
     if t3<=t7 goto s3

     t8  :=j-1
     t9  := 4*t8
     temp  := A[t9]   ;A[j]
     t10  := j+1
     t11:= t10-1
     t12 := 4*t11
     t13  := A[t12]   ;A[j+1]
     t14  := j-1
     t15  := 4*t14
     A[t15]  := t13   ;A[j]:=A[j+1]
     t16  := j+1
     t17  := t16-1
     t18  := 4*t17
     A[t18]:=temp     ;A[j+1]:=temp
s3:  j  := j+1
     goto S4
S2:  i  := i-1
     goto s5
s1:
```

Example

```
B1: i  := n-1
B2: if i<1 goto out
B3: j  := 1
B4: if j>i goto B5
B6: t1  := j-1
    t2  := 4*t1
    t3  := A[t2]       ;A[j]
    t6  := 4*j
    t7  := A[t6]      ;A[j+1]
    if t3<=t7 goto B8
```

```
B7: t8  :=j-1
    t9  := 4*t8
    temp  := A[t9]   ;temp:=A[j]
    t12  := 4*j
    t13  := A[t12]   ;A[j+1]
    A[t9]:= t13      ;A[j]:=A[j+1]
    A[t12]:=temp     ;A[j+1]:=temp
B8: j  := j+1
    goto B4
B5: i  := i-1
    goto B2
out:
```

(Intraprocedural) Global Optimizations

- **Global versions of local optimizations**
  - global common subexpression elimination
  - global constant propagation
  - dead code elimination
- **Loop optimizations**
  - reduce code to be executed in each iteration
  - code motion
  - induction variable elimination
- **Other control structures**
  - Code hoisting: eliminates copies of identical code on parallel paths in a flow graph to reduce code size.

Example

```
B1: i := n-1
B2: if i<1 goto out
B3: j := 1
B4: if j>i goto B5
B6: t1 := j-1
    t2 := 4*t1
    t3 := A[t2]       ;A[j]
    t6 := 4*j
    t7 := A[t6]      ;A[j+1]
    if t3<=t7 goto B8
```

```
B7: t8 :=j-1
    t9 := 4*t8
    temp := A[t9]  ;temp:=A[j]
    t12 := 4*j
     t13 := A[t12]  ;A[j+1]
    A[t9]:= t13    ;A[j]:=A[j+1]
    A[t12]:=temp   ;A[j+1]:=temp
B8: j := j+1
    goto B4
B5: i := i-1
    goto B2
out:
```

Example (After Global CSE)

```
B1: i := n-1
B2: if i<1 goto out
B3: j := 1
B4: if j>i goto B5
B6: t1 := j-1
    t2 := 4*t1
    t3 := A[t2]      ;A[j]
    t6 := 4*j
    t7 := A[t6]     ;A[j+1]
    if t3<=t7 goto B8
B7: A[t2] := t7
    A[t6] := t3
B8: j := j+1
    goto B4
B5: i := i-1
    goto B2
out:
```

Induction Variable Elimination

- **Intuitively**
  - Loop indices are induction variables
    (counting iterations)
  - Linear functions of the loop indices are also induction variables
    (for accessing arrays)

- **Analysis: detection of induction variable**

- **Optimizations**
  - strength reduction:
    - replace multiplication by additions
  - elimination of loop index:
    - replace termination by tests on other induction variables

Example

```
B1: i := n-1
B2: if i<1 goto out
B3: j := 1
B4: if j>i goto B5
B6: t1 := j-1
    t2 := 4*t1
    t3 := A[t2]      ;A[j]
    t6 := 4*j
    t7 := A[t6]     ;A[j+1]
    if t3<=t7 goto B8
```

```
B7: A[t2] := t7
    A[t6] := t3
B8: j := j+1
    goto B4
B5: i := i-1
    goto B2
out:
```

Example (After IV Elimination)

```
B1:  i := n-1
B2:  if i<1 goto out
B3:  t2 := 0
     t6 := 4
B4:  t19 := 4*I
     if t6>t19 goto B5
B6:  t3 := A[t2]
     t7 := A[t6]   ;A[j+1]
     if t3<=t7 goto B8
```

```
B7:  A[t2] := t7
     A[t6] := t3
B8:  t2 := t2+4
     t6 := t6+4
     goto B4
B5:  i := i-1
     goto B2
out:
```

Loop Invariant Code Motion

- **Analysis**
  - a computation is done within a loop and
  - result of the computation is the same as long as we keep going around the loop

- **Transformation**
  - move the computation outside the loop

Machine Dependent Optimizations

- Register allocation
- Instruction scheduling
- Memory hierarchy optimizations
- etc.

Local Optimizations (More Details)

- **Common subexpression elimination**
  - array expressions
  - field access in records
  - access to parameters

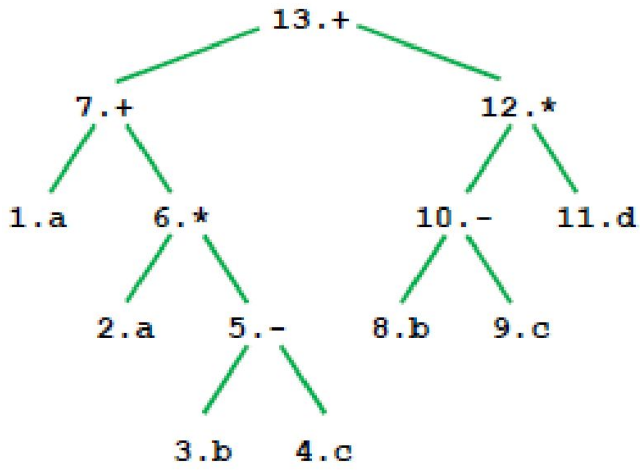
Graph Abstractions

Example 1:

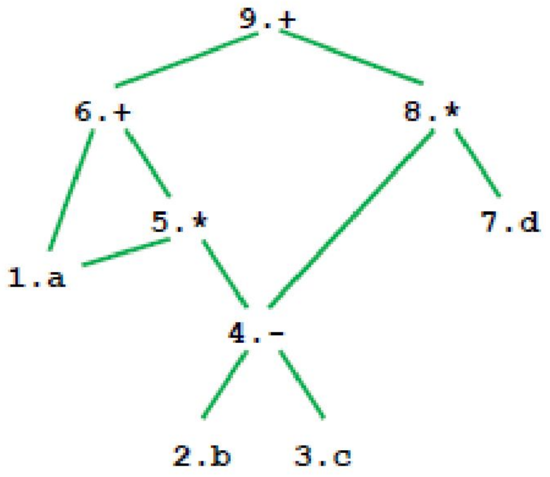
- grammar (for bottom-up parsing):

E -> E + T | E – T | T, T -> T*F | F, F -> (E) | id

- expression: a+a*(b-c)+(b-c)*d



Parse tree



Expression DAG

Graph Abstractions

Example 1: an expression

`a+a*(b-c)+(b-c)*d`

Optimized code:

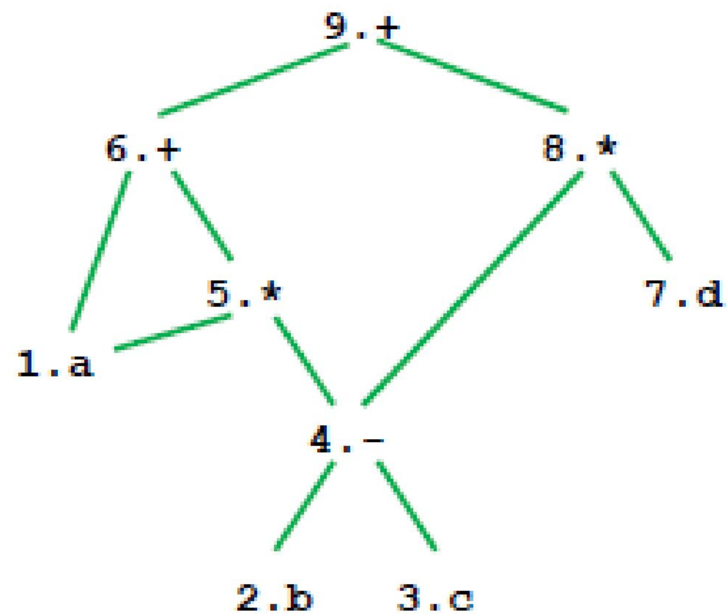
t1 = b - c

t2 = a * t1

t3 = a + t2

t4 = t1 * d

t5 = t3 + t4

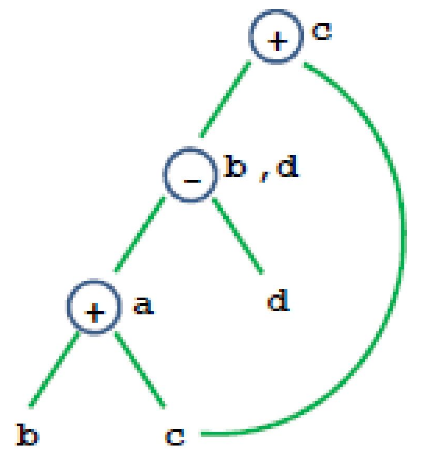


How well do DAGs hold up across statements?

DAG – directed acyclic graph

- **Example 2**

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



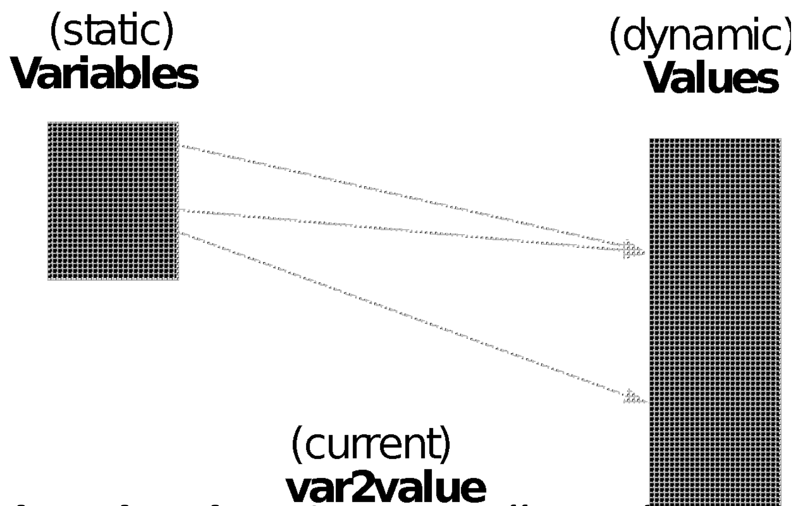

```
Is this optimized code correct?
a = b+c;
d = a-d;
c = d+c;
```

Critique of DAGs

- **Cause of problems**
  - Assignment statements
  - Value of variable depends on TIME
- **How to fix problem?**
  - build graph in order of execution
  - attach variable name to latest value
- **Final graph created is not very interesting**
  - Key: variable->value mapping across time
  - loses appeal of abstraction

Value Number: Another Abstraction

- More explicit with respect to VALUES, and TIME



- **each value has its own "number"**
  - **common subexpression means same value number**
- var2value: current map of variable to value
  - used to determine the value number of current expression

r1 + r2 => var2value(r1)+var2value(r2)

Algorithm

```
Data structure:
     VALUES = Table of
        expression     //[OP, valnum1, valnum2}
        var            //name of variable currently holding expression

For each instruction (dst = src1 OP src2) in execution order

  valnum1 = var2value(src1); valnum2 = var2value(src2);

  IF [OP, valnum1, valnum2] is in VALUES
     v = the index of expression
     Replace instruction with CPY dst = VALUES[v].var
  ELSE
     Add
        expression = [OP, valnum1, valnum2]
        var        = dst
     to VALUES
     v = index of new entry; tv is new temporary for v
     Replace instruction with: tv = VALUES[valnum1].var OP VALUES[valnum2].var
                               dst = tv;

  set_var2value (dst, v)
```

More Details

- **What are the initial values of the variables?**
  – values at beginning of the basic block

- **Possible implementations:**
  – Initialization: create “initial values” for all variables
  – Or dynamically create them as they are used

- **Implementation of VALUES and var2value: hash tables**

Example

```
Assign: a->r1,b->r2,c->r3,d->r4
a = b+c;        ADD t1 = r2,r3
                CPY r1 = t1
b = a-d;        SUB t2 = r1,r4
                CPY r2 = t2
c = b+c;        ADD t3 = r2,r3
                CPY r3 = t3
d = a-d;        SUB t4 = r1,r4
                CPY r4 = t4
```

Conclusions

- **Comparisons of two abstractions**
  - DAGs
  - Value numbering

- **Value numbering**
  - VALUE: distinguish between variables and VALUES
  - TIME
    - Interpretation of instructions in order of execution
    - Keep dynamic state information

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