CSE P 501 – Compilers

Introduction to Optimization

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Agenda

- Optimization
  - Goals
  - Scope: local, superlocal, regional, global (intraprocedural), interprocedural
- Control flow graphs
- Value numbering
- Dominators
- Ref.: Cooper/Torczon ch. 8

Code Improvement – How?

- Pick a better algorithm(!)
- Use machine resources effectively
  - Instruction selection & scheduling
  - Register allocation

disk

mem 100-250

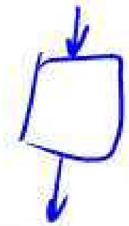
cache 5-20

cache 2

reg 1

p.f()
p.x
a[i][j*3]

Code Improvement (2)



- Local optimizations – basic blocks
  - Algebraic simplifications
  - Constant folding
  - Common subexpression elimination (i.e., redundancy elimination)
  - Dead code elimination
  - Specialize computation based on context
  - etc., etc., ...

for (—)
c[i][j] += a[i][k] *
b[k][j]

Code Improvement (3)

- Global optimizations (single functions)
  - Code motion
  - Moving invariant computations out of loops
  - Strength reduction (replace multiplications by repeated additions, for example)
  - Global common subexpression elimination
  - Global register allocation
  - Many others…

"Optimization"

- None of these improvements are truly "optimal"
  - Hard problems
  - Proofs of optimality assume artificial restrictions
- Best we can do is to improve things
  - Most (much?) (some?) of the time

c

$a[i] \equiv *(a+i)$

$= *(i+a) \equiv i[a]$

Example: A[i,j]

- Without any surrounding context, need to generate code to calculate

  address(A)
  + (i-low$_1$(A)) * (high$_2$(A)-low$_2$(a)+1) * size(A)
  + (j-low$_2$(A)) * size(A)

  - low$_i$ and high$_i$ are subscript bounds in dimension i
  - address(A) is the runtime address of first element of A
- … And we really should be checking that i, j are in bounds

Some Optimizations for A[i,j]

- With more context, we can do better
- Examples
  - If A is local, with known bounds, much of the computation can be done at compile time
  - If A[i,j] is in a loop where i and j change systematically, we probably can replace multiplications with additions each time around the loop to reference successive rows/columns
    - Even if not, we can move "loop-invariant" parts of the calculation outside the loop

Optimization Phase

- Goal
  - Discover, at compile time, information about the runtime behavior of the program, and use that information to improve the generated code

A First Running Example: Redundancy Elimination

$t = x+y$

$\cancel{x}$

p $x+y$

t

- An expression x+y is *redundant* at a program point iff, along every path from the procedure's entry, it has been evaluated and its constituent subexpressions (x and y) have not been redefined
- If the compiler can prove the expression is redundant
  - Can store the result of the earlier evaluation
  - Can replace the redundant computation with a reference to the earlier (stored) result

Common Problems in Code Improvement

- This strategy is typical of most compiler optimizations
  - First, discover opportunities through program analysis
  - Then, modify the IR to take advantage of the opportunities
    - Historically, goal usually was to decrease execution time
    - Other possibilities: reduce space, power, …

Issues (1)

- Safety – transformation must not change program meaning
  - ✓ Must generate correct results
  - ✓ Can't generate spurious errors
  - ✓ Optimizations must be conservative
  - ✓ Large part of analysis goes towards proving safety
  - Can pay off to speculate (be optimistic) but then need to recover if reality is different

t = x/y
for

x/y t

obj.m(—)
if typeof obj is t
static call t::m
else
use vtable

for (i++) {
}

for (i+=4) {
i
i+1
i+2
i+3

Issues (2)

- Profitibility
  - If a transformation is possible, is it profitable?
  - Example: loop unrolling
    - Can increase amount of work done on each iteration, i.e., reduce loop overhead
    - Can eliminate duplicate operations done on separate iterations

for(——) {

}

Issues (3)

- Downside risks
  - Even if a transformation is generally worthwhile, need to factor in potential problems
  - For example:
    - Transformation might need more temporaries, putting additional pressure on registers
    - Increased code size could cause cache misses, or in bad cases, increase page working set

$(x^1 + y^2)^3$

Example: Value Numbering

- Technique for eliminating redundant expressions: assign an identifying number VN(n) to each expression
  - VN(x+y)=VN(j) if x+y and j have the same value
  - Use hashing over value numbers for effeciency
- Old idea (Balke 1968, Ershov 1954)
  - Invented for low-level, linear IRs
  - Equivalent methods exist for tree IRs, e.g., build a DAG

Uses of Value Numbers

- Improve the code
  - Replace redundant expressions
  - Simplify algebraic identities
  - Discover, fold, and propagate constant valued expressions

o x+y

Local Value Numbering

- Algorithm
  - $+$ x^3 y'
  - For each operation o = <op, o1,o2> in a block
    1. Get value numbers for operands from hash lookup
    2. Hash <op, VN(o1), VN(o2)> to get a value number for o (If op is commutative, sort VN(o1), VN(o2) first)
    3. If o already has a value number, replace o with a reference to the value
    4. If o1 and o2 are constant, evaluate o at compile time and replace with an immediate load
- If hashing behaves well, this runs in linear time

Example

Code

$a^3 = x^1 + y^2$

$b^3 = x^1 + y^2$

$a^4 = 17^4$

$c^3 = \underline{x^1} + \underline{y^2}$

Rewritten

$a^3 = x^1 + y^2$

$b^3 = a^3$

$\underline{a^4} = 17^4$

$\cancel{c^3 = a^3}$ $c^3 = b^3$

$t = a^3$

$c^3 = t$

Bug in Simple Example

- If we use the original names, we get in trouble when a name is reused
- Solutions
  - Be clever about which copy of the value to use (e.g., use c=b in last statement)
  - Create an extra temporary
  - Rename around it (best!)

a_i

Renaming

- Idea: give each value a unique name
  - a_i^j means i^{th} definition of a with VN = j
- Somewhat complex notation, but meaning is clear
- This is the idea behind SSA (Static Single Assignment)
  - Popular modern IR – exposes many opportunities for optimizations

$\boxed{x_7 =}$ $\boxed{x_9 =}$

$x_{10} = \phi(x_7, x_9)$

Example Revisited

Code

$a_0^3 = x_0^1 + y_0^2$

$b_0^3 = x_0^1 + y_0^2$

$a_1^4 = 17^4$

$c_0^3 = x_0^1 + y_0^2$

$a^4 + 1$

Rewritten

$a_0^3 = x_0^1 + y_0^2$

$b_0^3 = a_0^3$

$a_1^4 = 17$

$c_0^3 = a_0^3$

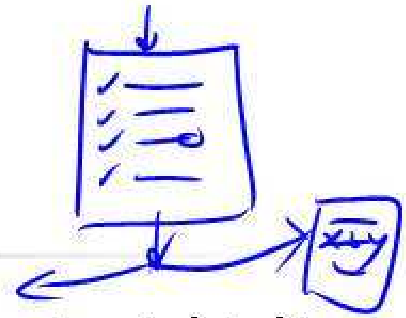
$+, 1, 2$

3

Simple Extensions to Value Numbering

- Constant folding $x+y$ 18
  - Add a bit that records when a value is constant
  - Evaluate constant values at compile time
  - Replace op with load immediate
- Algebraic identities: x+0, x*1, x-x, … 0
  - Many special cases
    - Switch on op to narrow down checks needed
    - Replace result with input VN

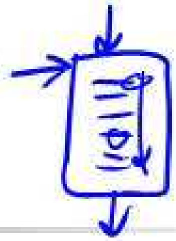
Larger Scopes



- This algorithm works on straight-line blocks of code (basic blocks)
  - Best possible results for single basic blocks
  - Loses all information when control flows to another block
- To go further we need to represent multiple blocks of code and the control flow between them

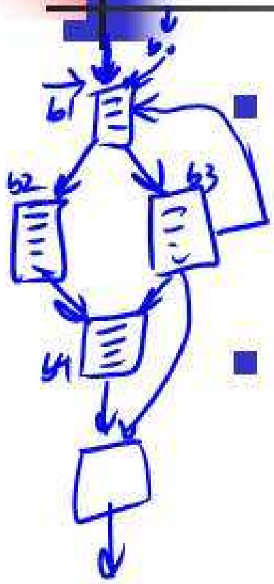
Basic Blocks

leader



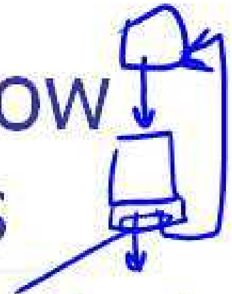
- Definition: A *basic block* is a maximal length sequence of straight-line code
- Properties
  - Statements are executed sequentially
  - If any statement executes, they all do
    (baring exceptions)
- In a linear IR, the first statement of a basic block is often called the *leader*

Control Flow Graph (CFG)

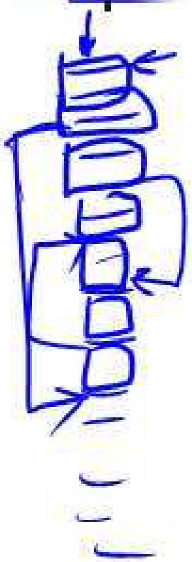


- Nodes: basic blocks
  - Possible representations: linear 3-address code, expression-level AST, DAG
- Edges: include a directed edge from n1 to n2 if there is *any* possible way for control to transfer from block n1 to n2 during execution

Constructing Control Flow Graphs from Linear IRs



cjmp(cond, Ltrue, Lfalse)

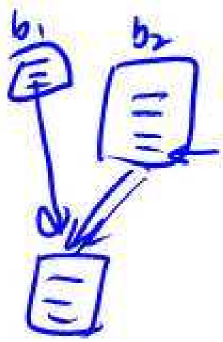


- Algorithm
  - Pass 1: Identify basic block leaders with a linear scan of the IR
  - Pass 2: Identify operations that end a block and add appropriate edges to the CFG to all possible successors
  - See your favorite compiler book for details
- **For convenience, ensure that every block ends with conditional or unconditional jump**
  - Code generator can pick the most convenient "fall-through" case later and eliminate unneeded jumps

Scope of Optimizations

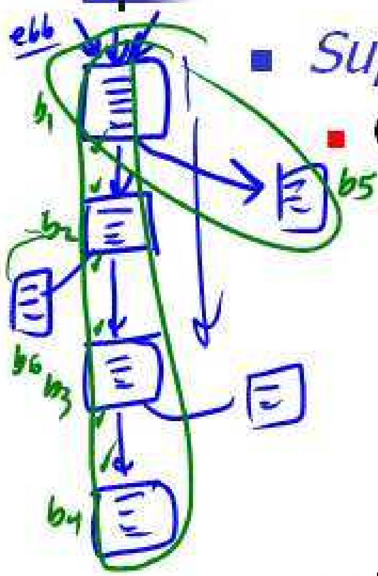
- Optimization algorithms can work on units as small as a basic block or as large as a whole program
- Local information is generally more precise and can lead to locally optimal results
- Global information is less precise (lose information at join points in the graph), but exposes opportunities for improvements across basic blocks

Optimization Categories (1)



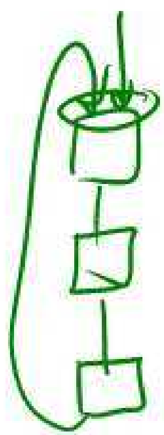
- *Local methods*
  - Usually confined to basic blocks
  - Simplest to analyze and understand
  - Most precise information

Optimization Categories (2)



- *Superlocal methods*
  - Operate over *Extended Basic Blocks* (EBBs)
    - An EBB is a set of blocks b_1, b_2, …, b_n where b_1 has multiple predecessors and each of the remaining blocks b_i ($2 \le i \le n$) have only b_{i-1} as its unique predecessor
    - The EBB is entered only at b_1, but may have multiple exits
    - A single block b_i can be the head of multiple EBBs (these EBBs form a tree rooted at b_i)
  - Use information discovered in earlier blocks to improve code in successors

Optimization Categories (3)



- *Regional methods*
  - Operate over scopes larger than an EBB but smaller than an entire procedure/ function/method
  - Typical example: loop body
  - Difference from superlocal methods is that there may be merge points in the graph (i.e., a block with two or more predecessors)

Optimization Categories (4)

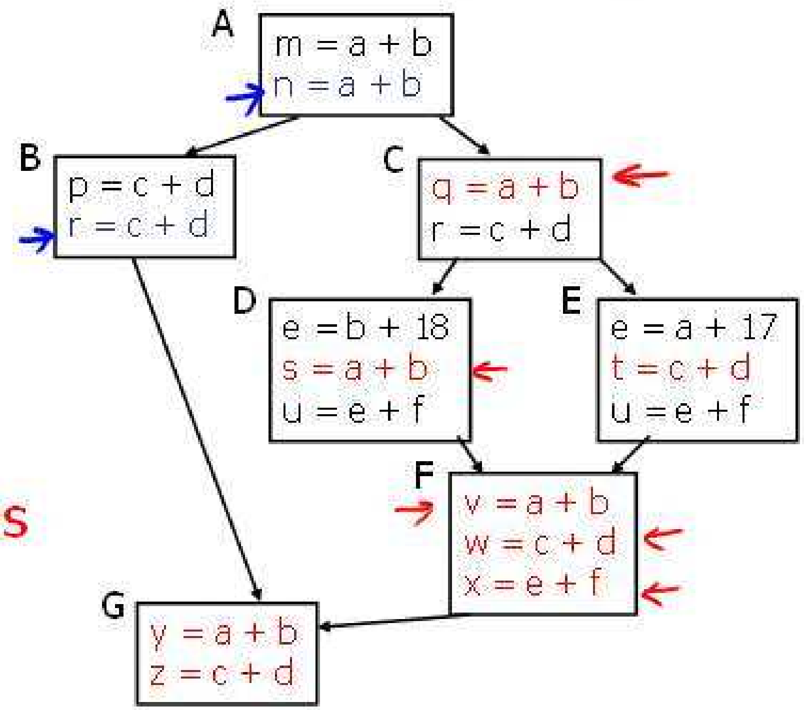
- *Global methods*
  - Operate over entire procedures
  - Sometimes called *intraprocedural* methods
  - Motivation is that local optimizations sometimes have bad consequences in larger context
  - Procedure/method/function is a natural unit for analysis, separate compilation, etc.
  - Almost always need global *data-flow* analysis information for these

Optimization Categories (5)

- *Whole-program methods*
  - Operate over more than one procedure
  - Sometimes called *interprocedural* methods
  - Challenges: name scoping and parameter binding issues at procedure boundaries
  - Classic examples: inline method substitution, interprocedural constant propagation
  - Common in aggressive JIT compilers and optimizing compilers for object-oriented languages

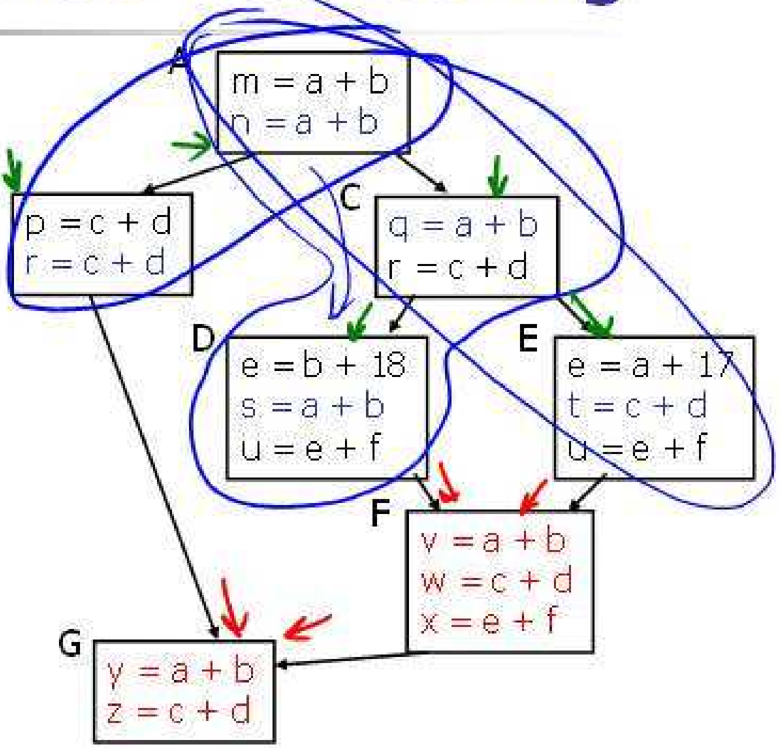
Value Numbering Revisited

- Local Value Numbering
  - 1 block at a time
  - Strong local results
  - No cross-block effects
- Missed opportunities



Superlocal Value Numbering

- Idea: apply local method to EBBs
  - {A,B}, {A,C,D}, {A,C,E}
- Final info from A is initial info for B, C; final info from C is initial for D, E
- Gets reuse from ancestors
- Avoid reanalyzing A, C
- Doesn't help with F, G



SSA Name Space (from before)

Code	Rewritten
$a_0^3 = x_0^1 + y_0^2$	$a_0^3 = x_0^1 + y_0^2$
$b_0^3 = x_0^1 + y_0^2$	$b_0^3 = a_0^3$
$a_1^4 = 17$	$a_1^4 = 17$
$c_0^3 = x_0^1 + y_0^2$	$c_0^3 = a_0^3$

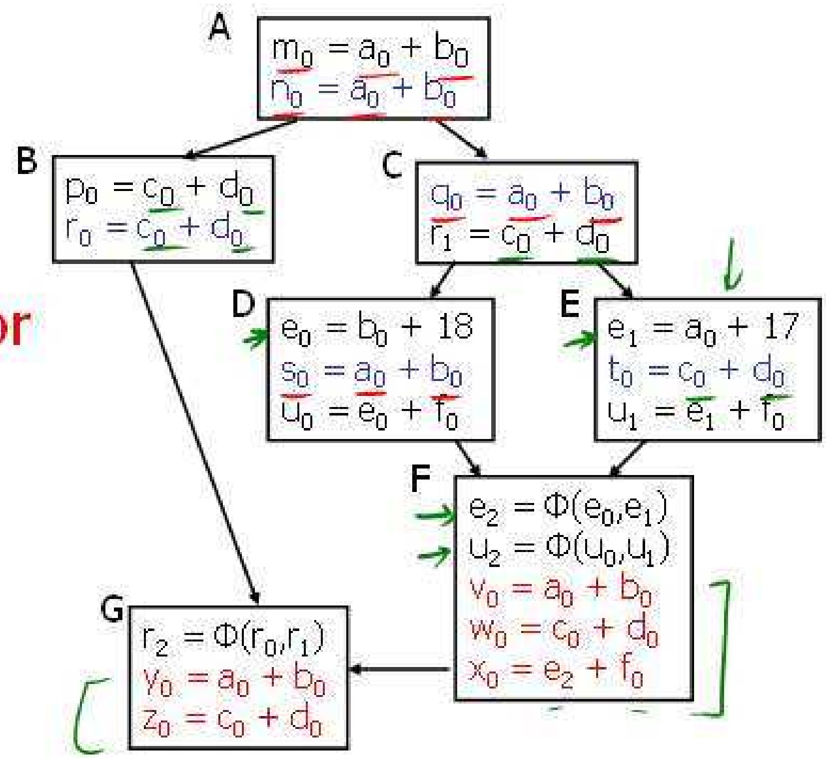
- Unique name for each definition
- Name $\Leftrightarrow$ VN
- a_0^3 is available to assign to c_0^3

SSA Name Space

- Two Principles
  - Each name is defined by exactly one operation
  - Each operand refers to exactly one definition
- Need to deal with merge points
  - Add Φ functions at merge points to reconcile names
  - Use subscripts on variable names for uniqueness

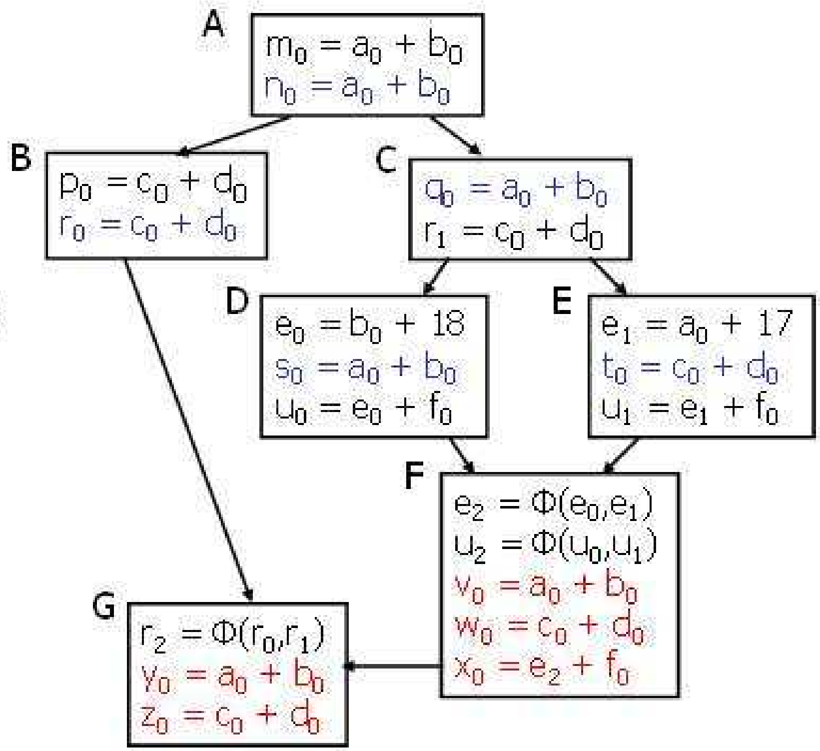
Superlocal Value Numbering with All Bells & Whistles

- Finds more redundancies
- Little extra cost
- Still does nothing for F and G

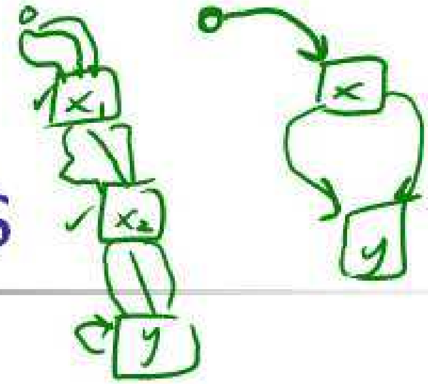


Larger Scopes

- Still have not helped F and G
- Problem: multiple predecessors
- Must decide what facts hold in F and in G
  - For G, combine B & F?
  - Merging states is expensive
  - Fall back on what we know

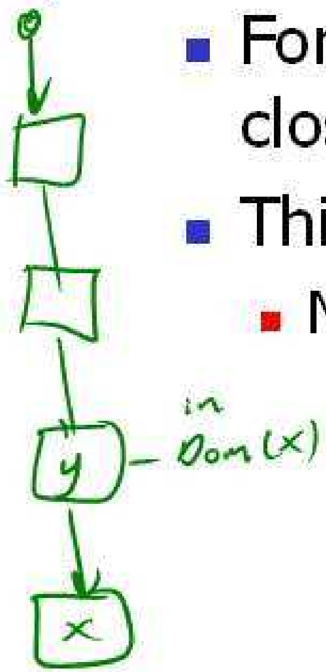


Dominators



- Definition
  - x *dominates* y iff every path from the entry of the control-flow graph to y includes x
- By definition, x dominates x
- Associate a Dom set with each node
  - | Dom(x) | ≥ 1
- Many uses in analysis and transformation
  - Finding loops, building SSA form, code motion

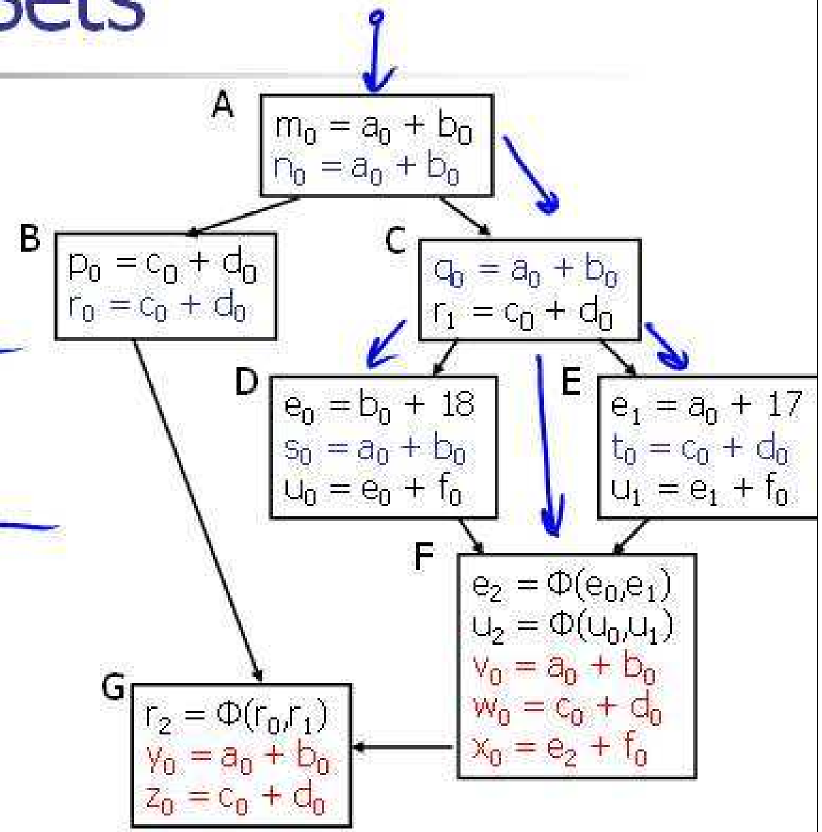
Immediate Dominators



- For any node x, there is a y in Dom(x) closest to x
- This is the *immediate dominator* of x
  - Notation: IDom(x)

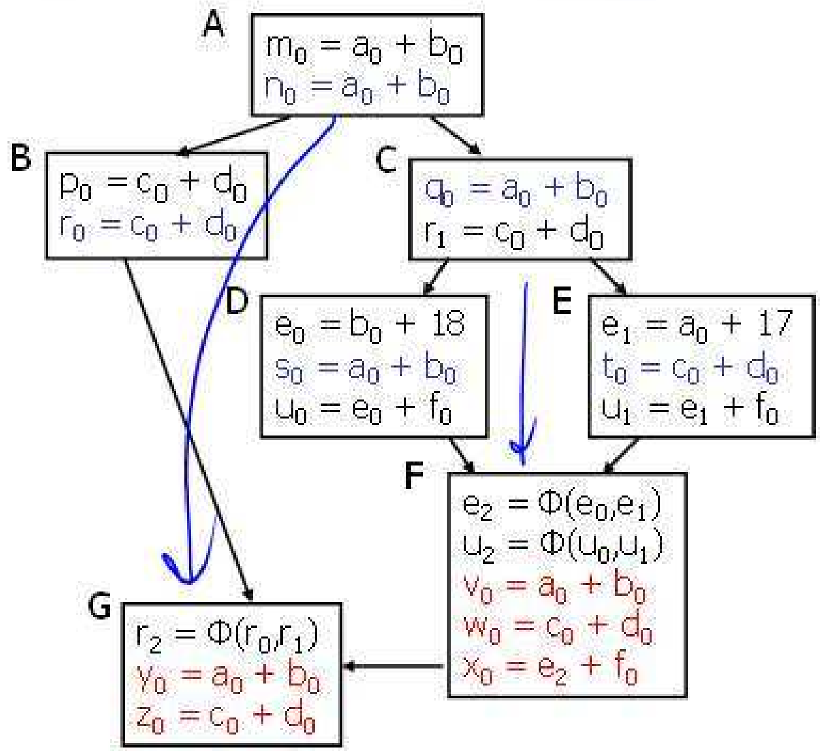
Dominator Sets

Block	Dom	IDom
A	A	–
B	A, B	A
C	A, C	A
D	A, C, D	C
E	A, C, E	C
F	A, C, F	C
G	A, G	A



Dominator Value Numbering

- Still looking for a way to handle F and G
- Idea: Use info from IDom(x) to start analysis of x
  - Use C for F and A for G
- Dominator VN Technique (DVNT)

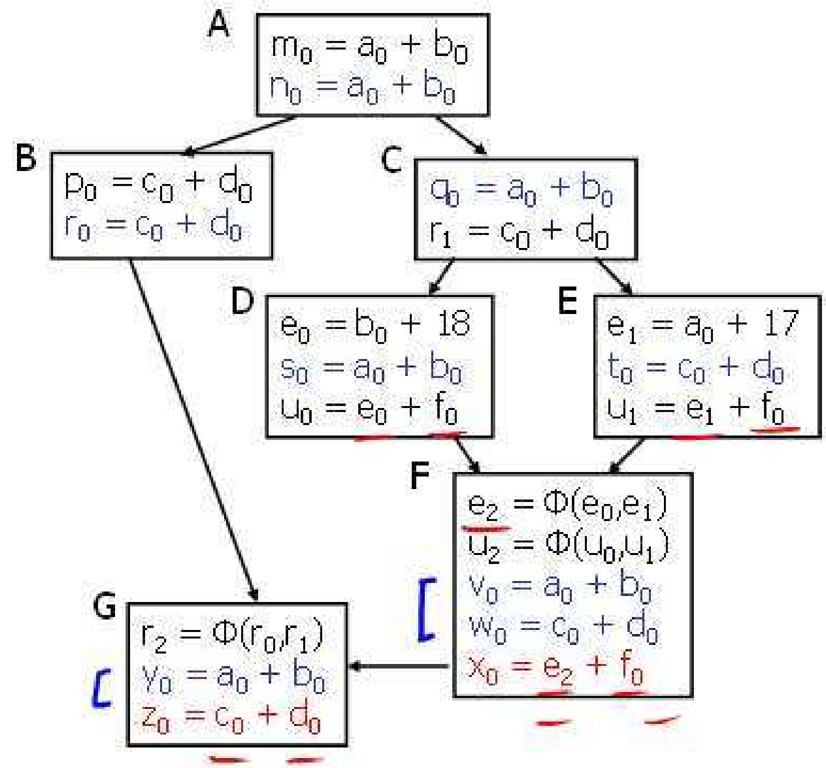


DVNT algorithm

- Use superlocal algorithm on extended basic blocks
  - Use scoped hash tables & SSA name space as before
- Start each node with table from its IDOM
- No values flow along back edges (i.e., loops)
- Constant folding, algebraic identities as before

Dominator Value Numbering

- Advantages
  - Finds more redundancy
  - Little extra cost
- Shortcomings
  - Misses some opportunities (common calculations in ancestors that are not IDOMs)
  - Doesn't handle loops or other back edges



The Story So Far…

- Local algorithm
- Superlocal extension
  - Some local methods extend cleanly to superlocal scopes
- Dominator VN Technique (DVNT)
- All of these propagate along forward edges
- None are global

Coming Attractions

- Data-flow analysis
  - Provides global solution to redundant expression analysis
    - Catches some things missed by DVNT, but misses some others
  - Generalizes to many other analysis problems, both forward and backward
- Transformations
  - A catalog of some of the things a compiler can do with the analysis information