CSE P 501 – Compilers

Introduction to Optimization

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A First Running Example: Redundancy Elimination

- 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 <u>not</u> 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

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

Local Value Numbering

- Algorithm
  - 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 x^1, y^2

a = x + y

b = x + y

a = 17

c = x + y

Rewritten

Renaming

V_i^{vn}

- 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

$hash\left(\frac{+}{op}, \frac{1}{vn1}, \frac{2}{vn2}\right)$

Example Revisited

Code x^1, y^2

a = x + y

b = x + y

a = 17

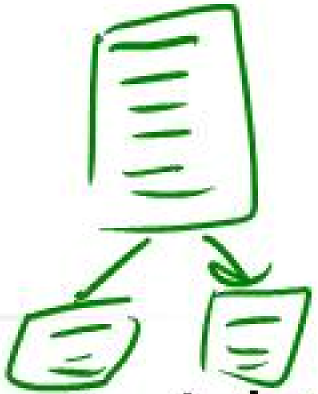
c = x + y

Rewritten

Simple Extensions to Value Numbering

- Constant folding
  - 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, ...
  - Many special cases
    - Switch on op to narrow down checks needed
    - Replace result with input VN

Larger Scopes



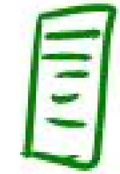
- This algorithm works on straight-line blocks of code (basic blocks)
  - Best possible results for single basic blocks
  - Loses all information when control flows to another block
- To go further we need to represent multiple blocks of code and the control flow between them

Basic Blocks

- 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

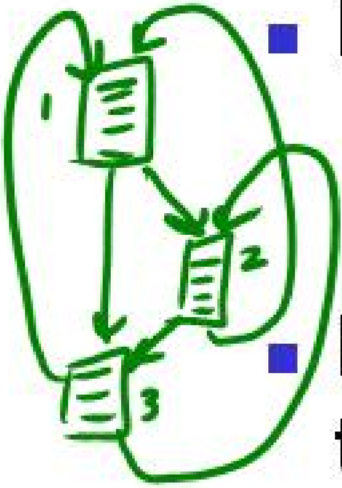
    (baring exceptions)
- In a linear IR, the first statement of a basic block is often called the *leader*
  - Procedure entry, jump targets, statements following any jump/call

r = op1 op op2


array

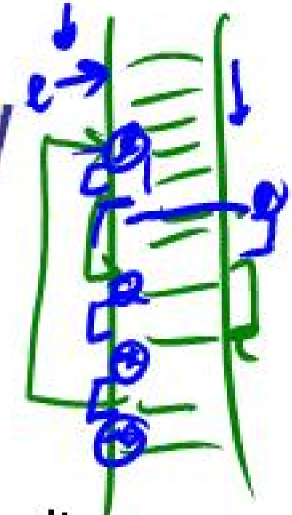
linked list

Control Flow Graph (CFG)

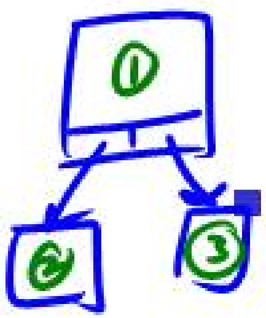


- Nodes: basic blocks
  - Possible representations: linear 3-address code, expression-level AST, DAG
- Edges: include a directed edge from n1 to n2 if there is *any* possible way for control to transfer from block n1 to n2 during execution

Constructing Control Flow Graphs from Linear IRs



- 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



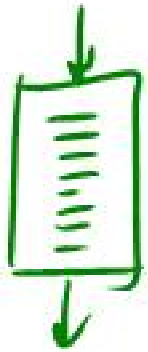
- For convenience, ensure that every block ends with conditional or unconditional jump
  - Code generator can pick the most convenient "fall-through" case later and eliminate unneeded jumps

Scope of Optimizations

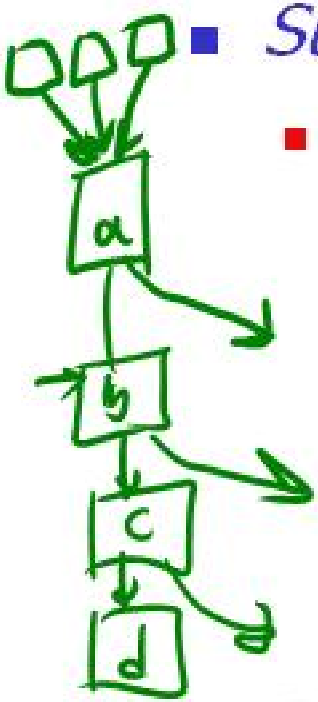
- Optimization algorithms can work on units as small as a basic block or as large as a whole program
- Local information is generally more precise and can lead to locally optimal results
- Global information is less precise (lose information at join points in the graph), but exposes opportunities for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

Optimization Categories (1)

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



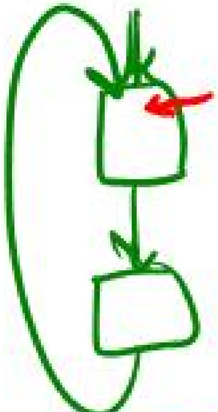
Optimization Categories (2)

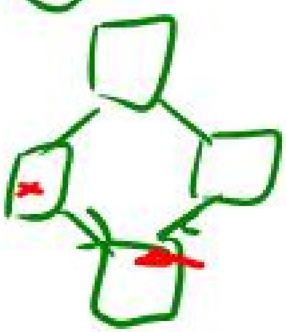


- *Superlocal methods*
  - Operate over *Extended Basic Blocks* (EBBs)
    - An EBB is a set of blocks b_1, b_2, …, b_n where b_1 has multiple predecessors and each of the remaining blocks b_i ($2 \le i \le n$) have only b_{i-1} as its unique predecessor
    - The EBB is entered only at b_1, but may 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)

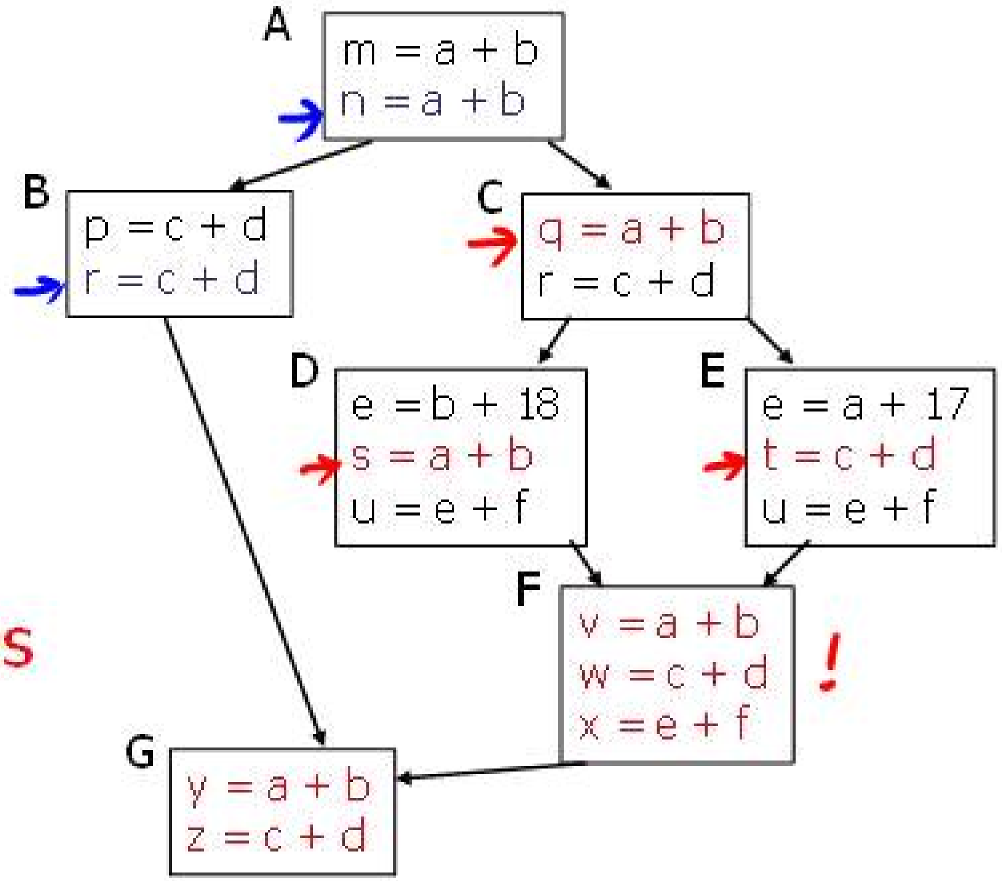
- *Global methods*
  - Operate over entire procedures
  - Sometimes called *intraprocedural* methods
  - Motivation is that local optimizations sometimes have bad consequences in larger context
  - Procedure/method/function is a natural unit for analysis, separate compilation, etc.
  - Almost always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

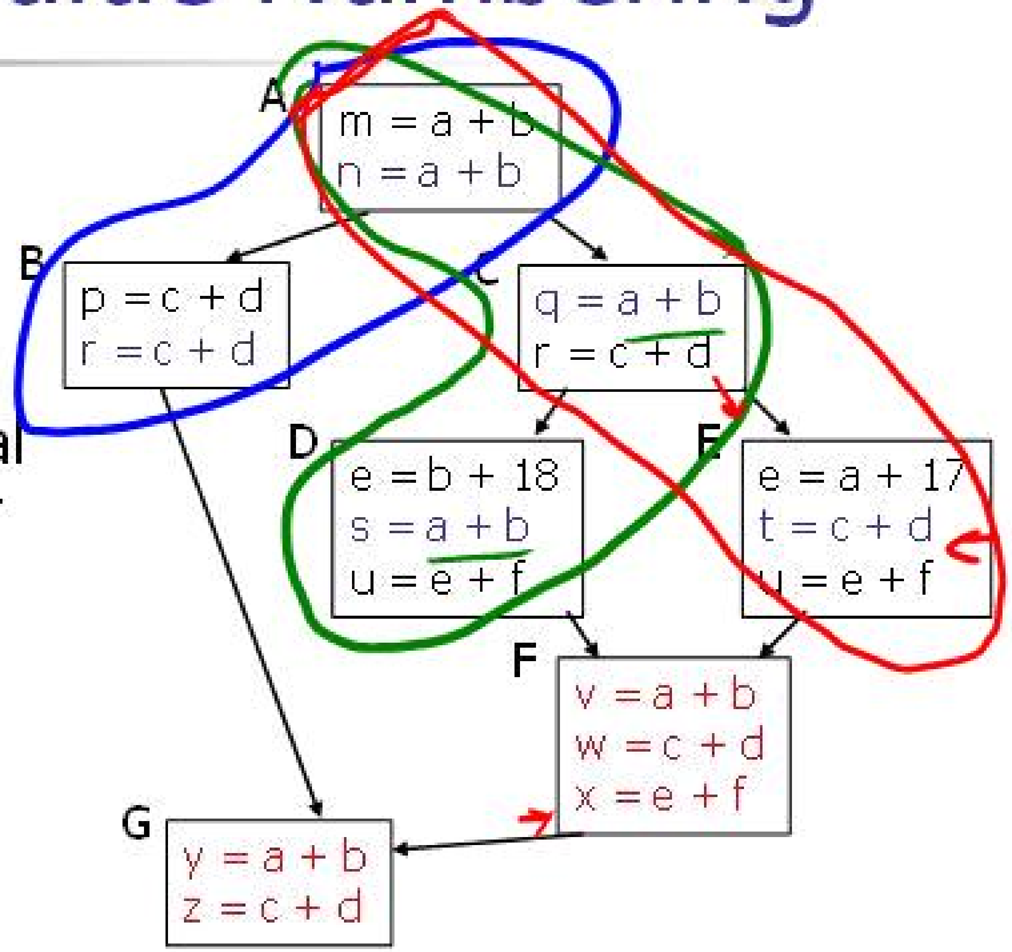
Value Numbering Revisited

- 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



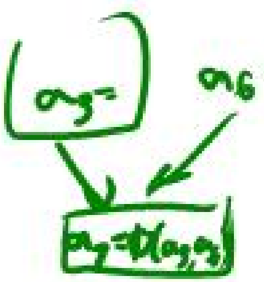
SSA Name Space (from before)

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 ⇔ VN
- a_0^3 is available to assign to c_0^3

SSA Name Space

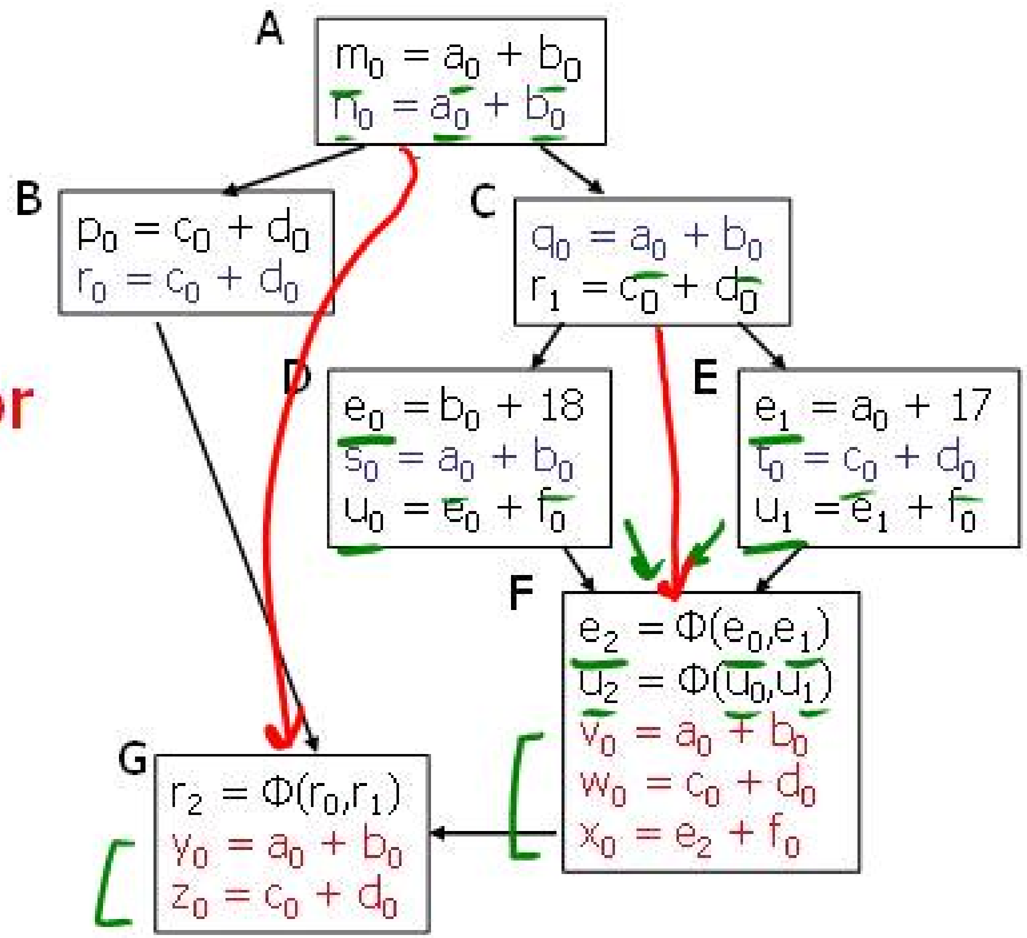
- Two Principles
  - ✓ Each name is defined by exactly one operation
  - ✓ Each operand refers to exactly one definition



- Need to deal with merge points
  - Add Φ functions at merge points to reconcile names
  - Use subscripts on variable names for uniqueness

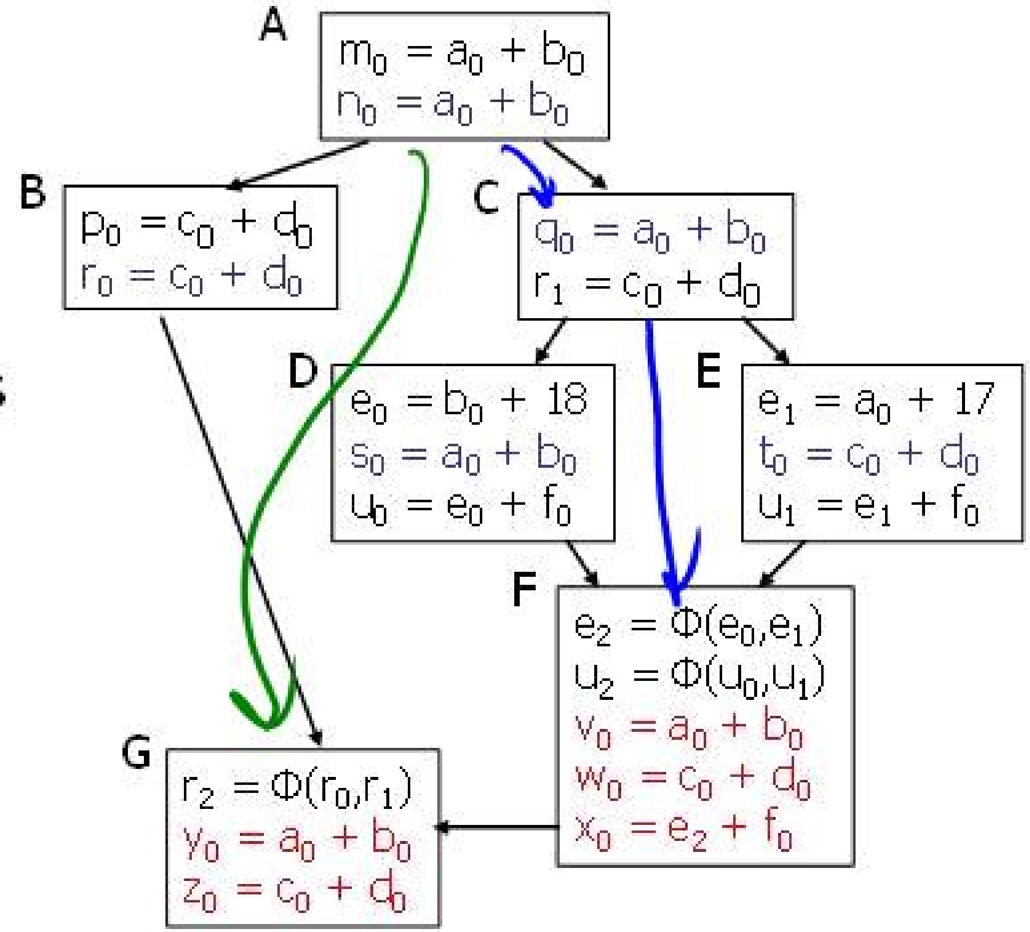
Superlocal Value Numbering with All Bells & Whistles

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

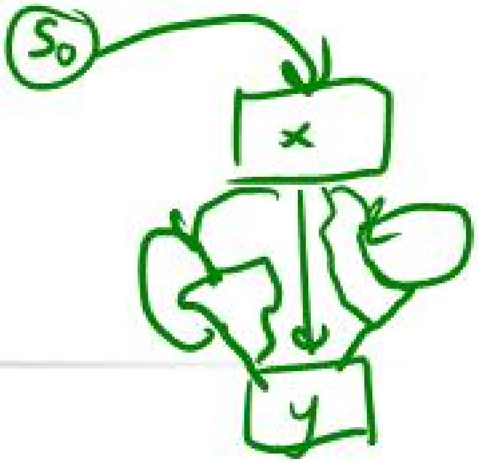


Larger Scopes

- 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



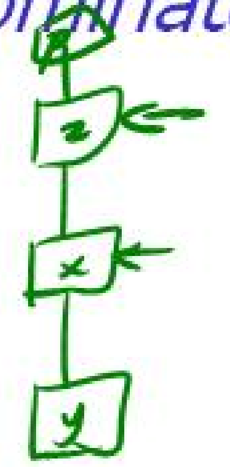
Dominators



- 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

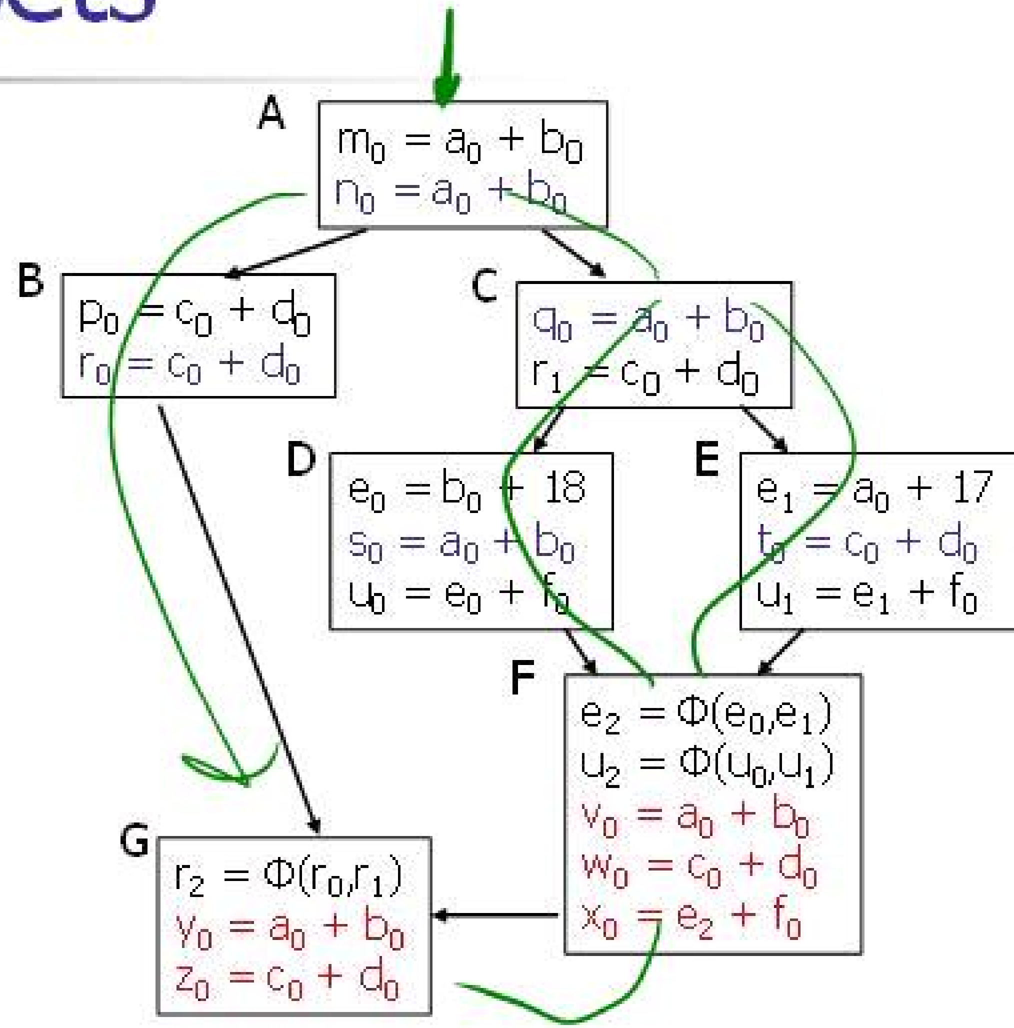
Immediate Dominators

- For any node x, there is a y in Dom(x) closest to x , not = x (strictly dominates)
- This is the *immediate dominator* of x
  - Notation: IDom(x)



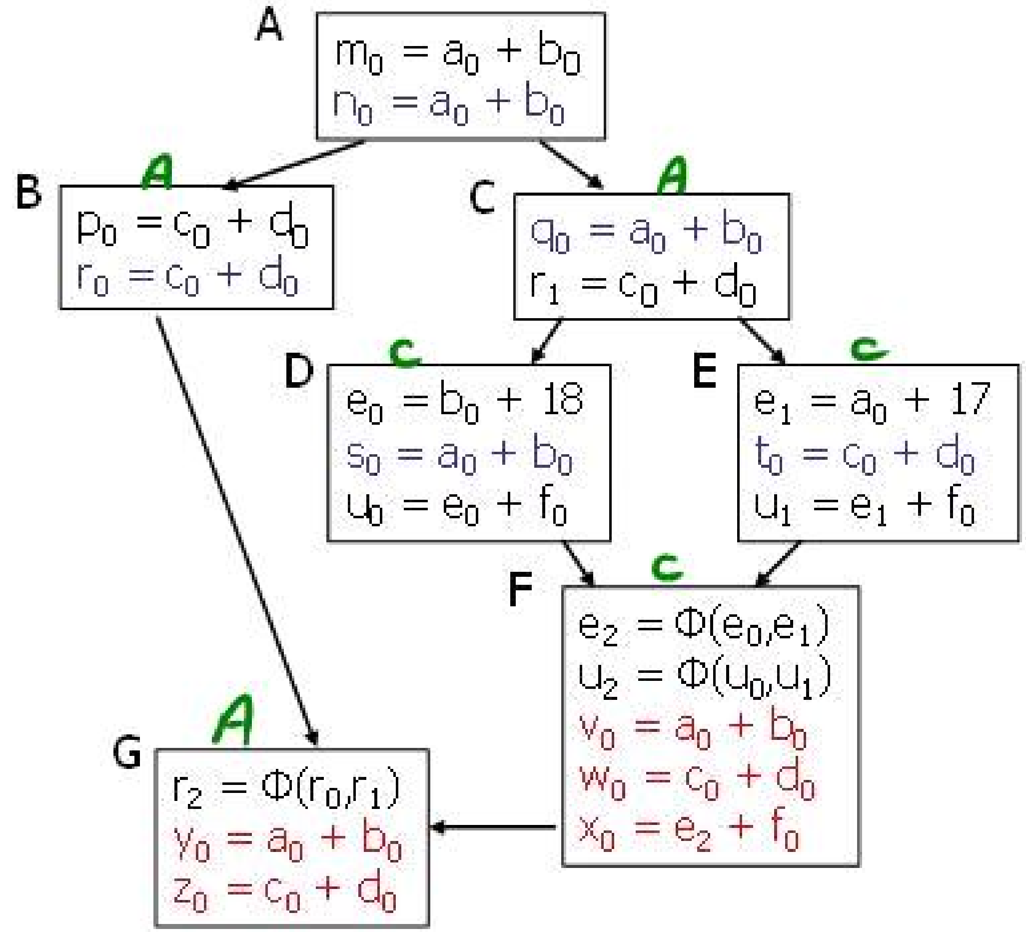
Dominator Sets

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)

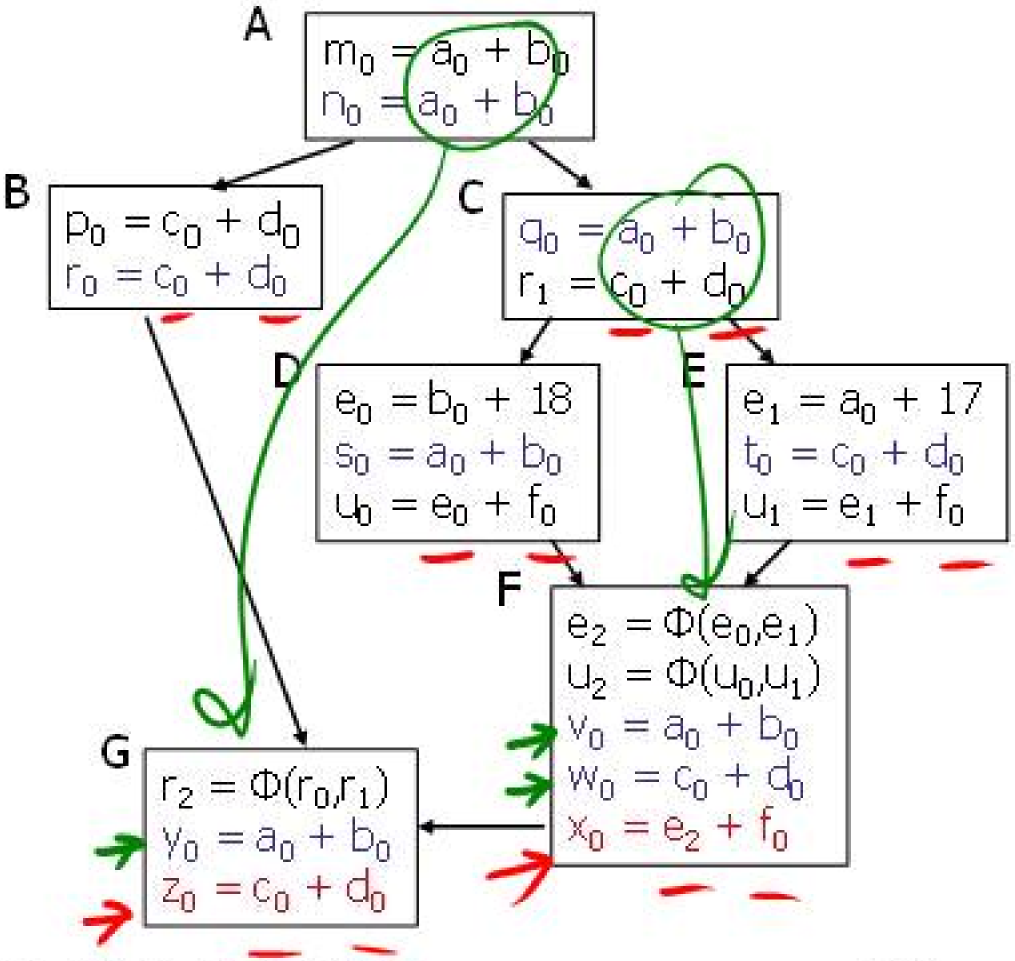


DVNT algorithm

- 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