RICE

COMP 412
FALL 2010

Code Optimization, Part II
Regional Techniques

Comp 412

Copyright 2010, Keith D. Cooper & Linda Torczon, all rights reserved.

Students enrolled in Comp 412 at Rice University have explicit permission to make copies of these materials for their personal use.

Faculty from other educational institutions may use these materials for nonprofit educational purposes, provided this copyright notice is preserved.

Last Lecture

Introduced concept of a redundant expression

An expression, x+y, is redundant at point p if, along each path from the procedure's entry point to p, x+y has already been evaluated and neither x nor y has been redefined.

- If *x+y* is redundant at *p*, we can save the results of those earlier evaluations and reuse them at *p*, avoiding evaluation
- In a single block, we need only consider one such path
- We developed an algorithm for redundancy elimination in a single basic block
- Two pieces to the problem
  - Proving that *x+y* is redundant
  - Rewriting the code to eliminate the redundant evaluation
- Value numbering does both for straightline code

Local Value Numbering (Recap)

The LVN Algorithm, with bells & whistles

Block is a sequence of n operations of the form

$T_i \leftarrow L_i \; Op_i \; R_i$

for $i \leftarrow 0$ to $n-1$

1. get the value numbers V_1 and V_2 for L_i and R_i

2. if L_i and R_i are both constant then — Constant folding

evaluate Li Op_i R_i, assign it to T_i, and mark T_i as a constant

3. if Li Op_i R_i matches an identity then — Algebraic identities

replace it with a copy operation or an assignment

4. if Op_i commutes and $V_1 > V_2$ then — Commutativity

swap V_1 and V_2

5. construct a hash key $<V_1,Op_i,V_2>$

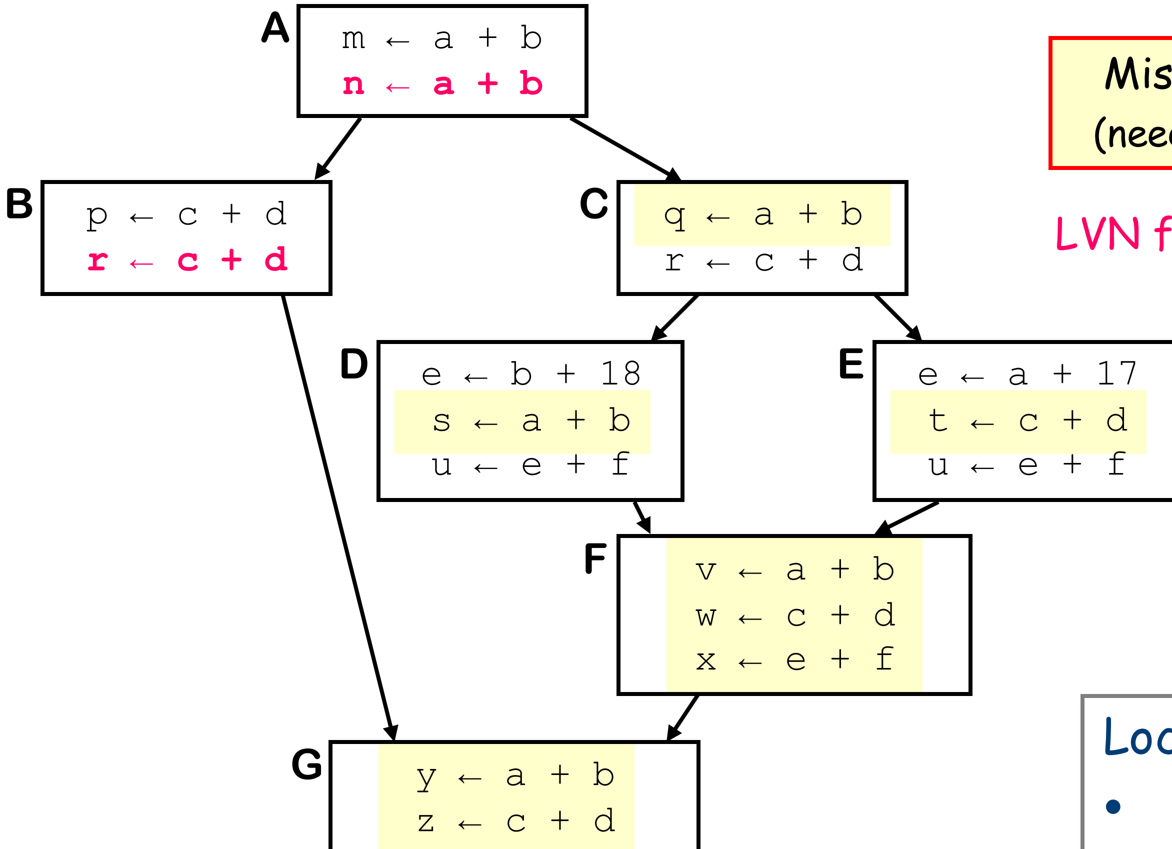
6. if the hash key is already present in the table then

replace operation I with a copy into T_i and mark T_i with the VN

else

insert a new VN into table for hash key & mark T_i with the VN

Local Value Numbering



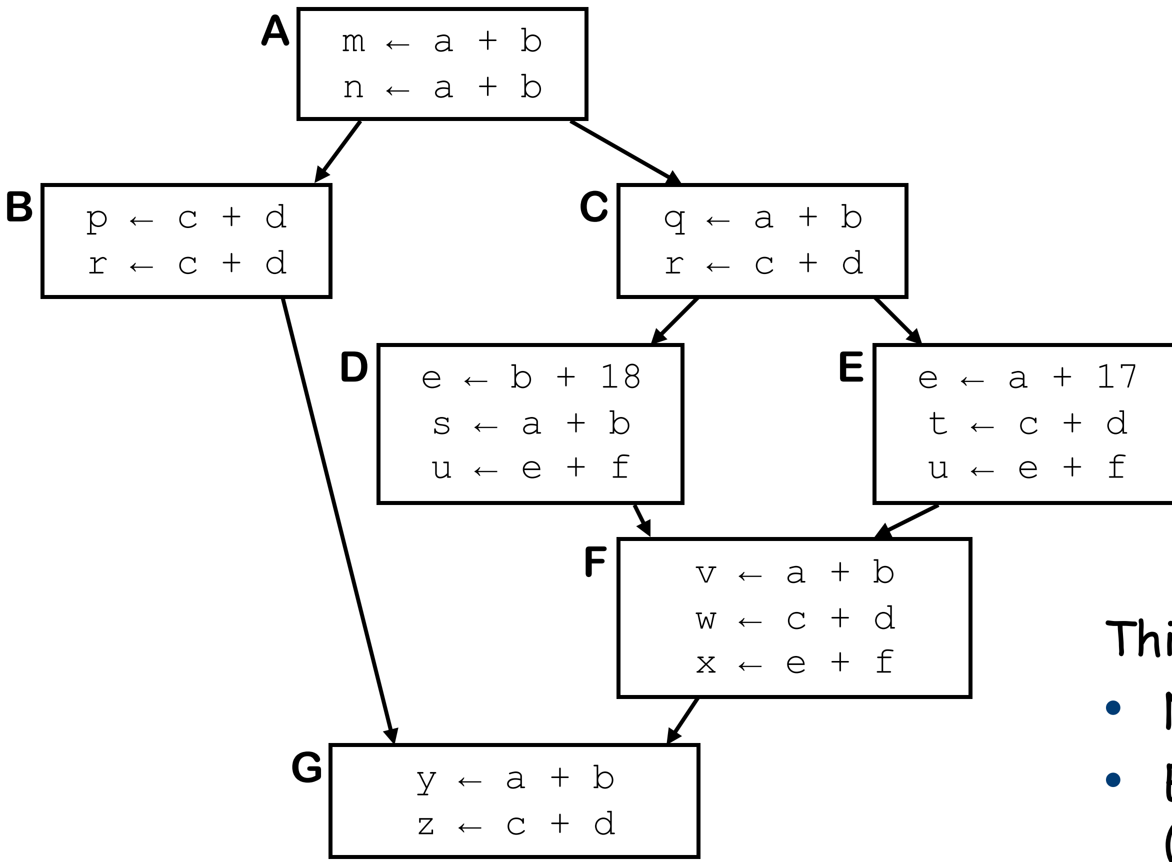
Missed opportunities (need stronger methods)

LVN finds these redundant ops

Local Value Numbering

- 1 block at a time
- Strong local results
- No cross-block effects

Terminology



Control-flow graph (CFG)

- Nodes for basic blocks
- Edges for branches
- Basis for much of program analysis & transformation

This CFG, G = (N,E)

- N = {A,B,C,D,E,F,G}
- E = {(A,B),(A,C),(B,G),(C,D),(C,E),(D,F),(E,F),(F,E)}
- |N| = 7, |E| = 8

Scope of Optimization

In scanning and parsing, "scope" refers to a region of the code that corresponds to a distinct name space.

In optimization "scope" refers to a region of the code that is subject to analysis and transformation.

- Notions are somewhat related
- Connection is not necessarily intuitive

Different scopes introduces different challenges & different opportunities

Historically, optimization has been performed at several distinct scopes.

Scope of Optimization

A basic block is a maximal length sequence of straightline code.

Local optimization

- Operates entirely within a single basic block
- Properties of block lead to strong optimizations

Regional optimization

- Operate on a region in the CFG that contains multiple blocks
- Loops, trees, paths, extended basic blocks

Whole procedure optimization (*intraprocedural*)

- Operate on entire CFG for a procedure
- Presence of cyclic paths forces analysis then transformation

Whole program optimization (*interprocedural*)

- Operate on some or all of the call graph (*multiple procedures*)
- Must contend with call/return & parameter binding

A Comp 412 Fairy Tale

We would like to believe optimization developed in an orderly fashion

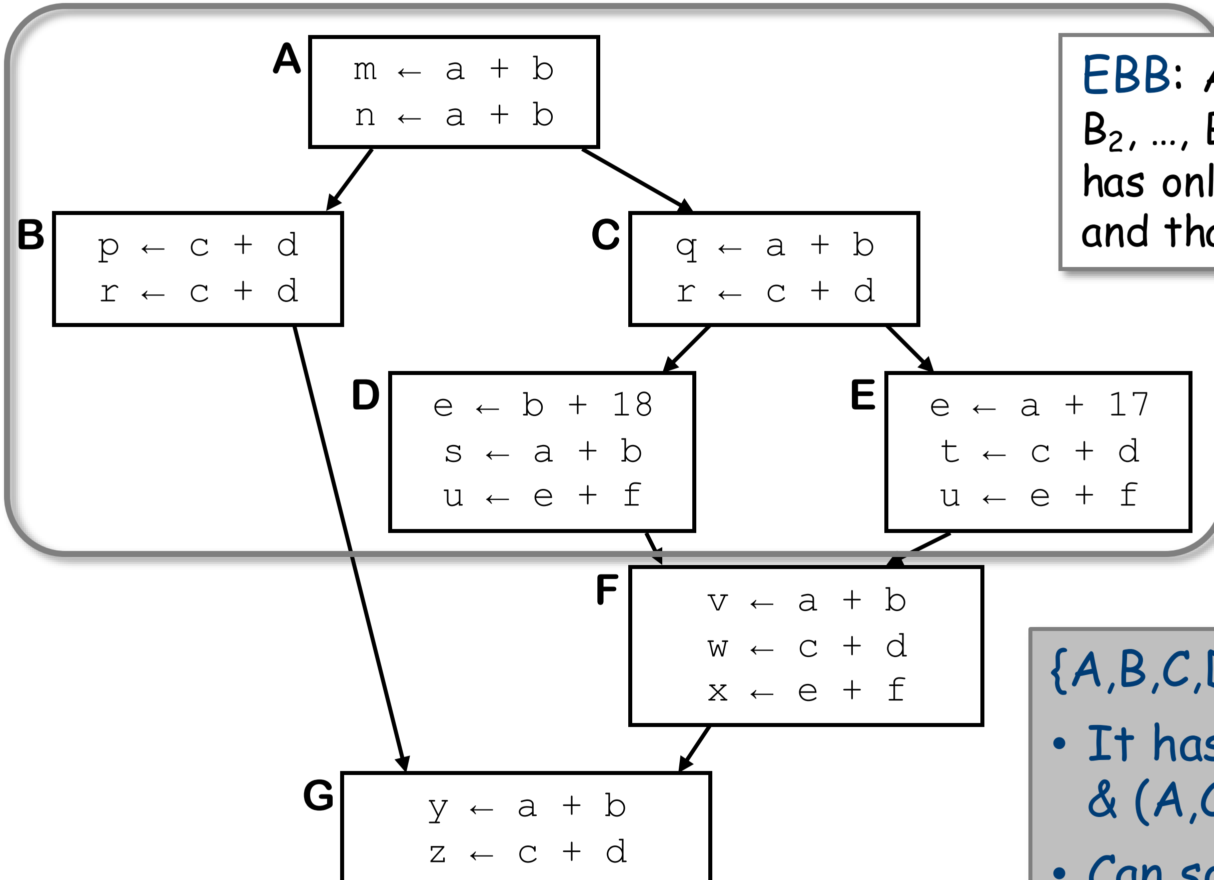
- Local methods led to regional methods
- Regional methods led to global methods
- Global methods led to interprocedural methods

It did not happen that way

- First compiler, FORTRAN, used both local & global methods
- Development has been scattershot & concurrent
- Scope appears to relate to the inefficiency being attacked, rather than the refinement of the inventor.

A Regional Technique

Superlocal Value Numbering



EBB: A maximal set of blocks B_1, B_2, …, B_n where each B_i, except B_1, has only exactly one predecessor and that block is in the EBB.

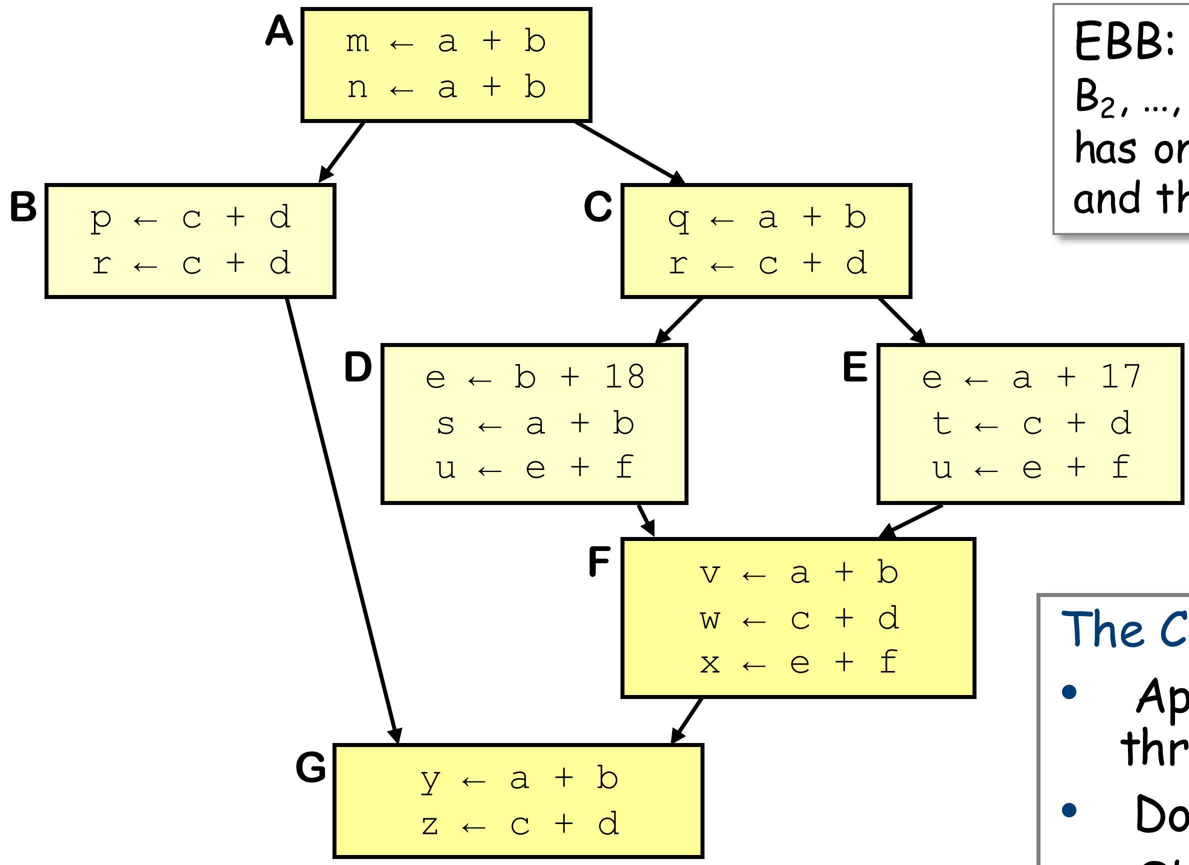
{A,B,C,D,E} is an EBB

- It has 3 paths: (A,B), (A,C,D), & (A,C,E)
- Can sometimes treat each path as if it were a block

{F} & {G} are degenerate EBBs

Superlocal: "applied to an EBB"

Superlocal Value Numbering



EBB: A maximal set of blocks B_1, B_2, …, B_n where each B_i, except B_1, has only exactly one predecessor and that block is in the EBB.

The Concept

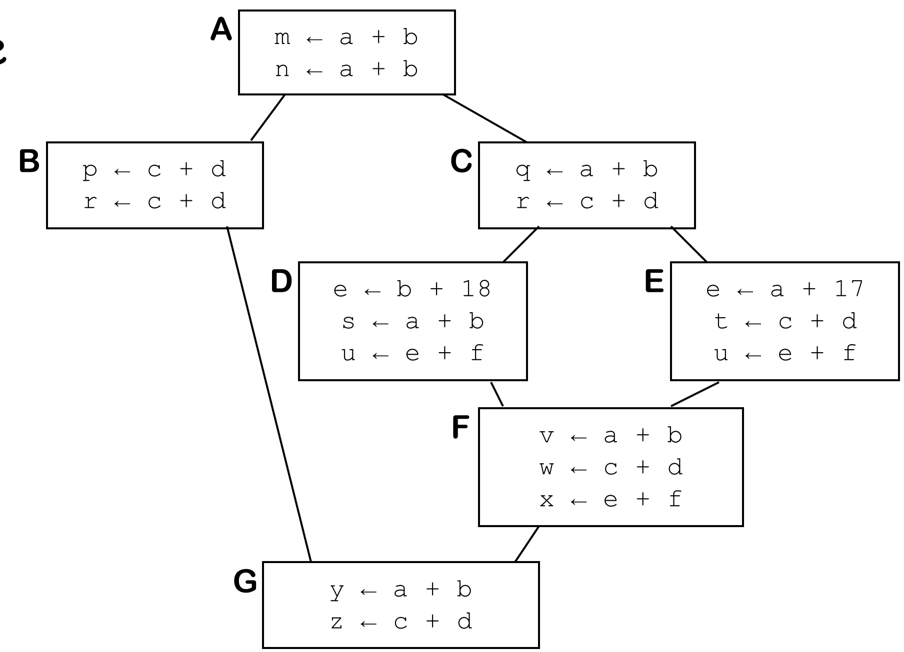
- Apply local method to paths through the EBBs
- Do {A,B}, {A,C,D}, & {A,C,E}
- Obtain reuse from ancestors
- Avoid re-analyzing A & C
- Does not help with F or G

Superlocal Value Numbering

Efficiency

- Use A's table to initialize tables for B & C
- To avoid duplication, use a scoped hash table
  - A, AB, A, AC, ACD, AC, ACE, F, G
- Need a VN → name mapping to handle kills
  - Must restore map with scope
  - Adds complication, not cost

"kill" is a re-definition of some name

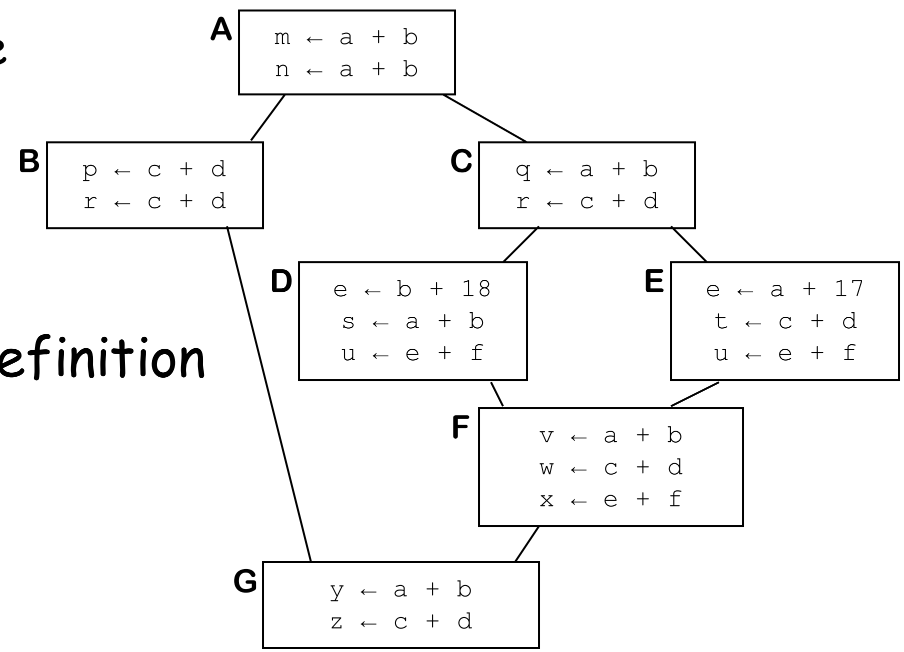


Superlocal Value Numbering

Efficiency

- Use A's table to initialize tables for B & C
- To avoid duplication, use a scoped hash table
  - A, AB, A, AC, ACD, AC, ACE, F, G
- Need a VN → name mapping to handle kills
  - Must restore map with scope
  - Adds complication, not cost

"kill" is a re-definition of some name



To simplify matters

- Need *unique name* for each definition
- Makes name → VN
- Use the SSA name space

The subscripted names from the earlier example are an instance of the SSA name space.

SSA Name Space (locally)

Example (from earlier):

Original Code	**With VNs**	**Rewritten**
$a_0 \leftarrow x_0 + y_0$	$a_0^3 \leftarrow x_0^1 + y_0^2$	$a_0^3 \leftarrow x_0^1 + y_0^2$
✶ $b_0 \leftarrow x_0 + y_0$	✶ $b_0^3 \leftarrow x_0^1 + y_0^2$	✶ $b_0^3 \leftarrow a_0^3$
$a_1 \leftarrow 17$	$a_1^4 \leftarrow 17$	$a_1^4 \leftarrow 17$
✶ $c_0 \leftarrow x_0 + y_0$	✶ $c_0^3 \leftarrow x_0^1 + y_0^2$	✶ $c_0^3 \leftarrow a_0^3$

Renaming:
- Give each value a unique name
- Makes it clear

Notation:
- While complex, the meaning is clear

Result:
- a_0^3 is available
- Rewriting just works

SSA Name Space (in general)

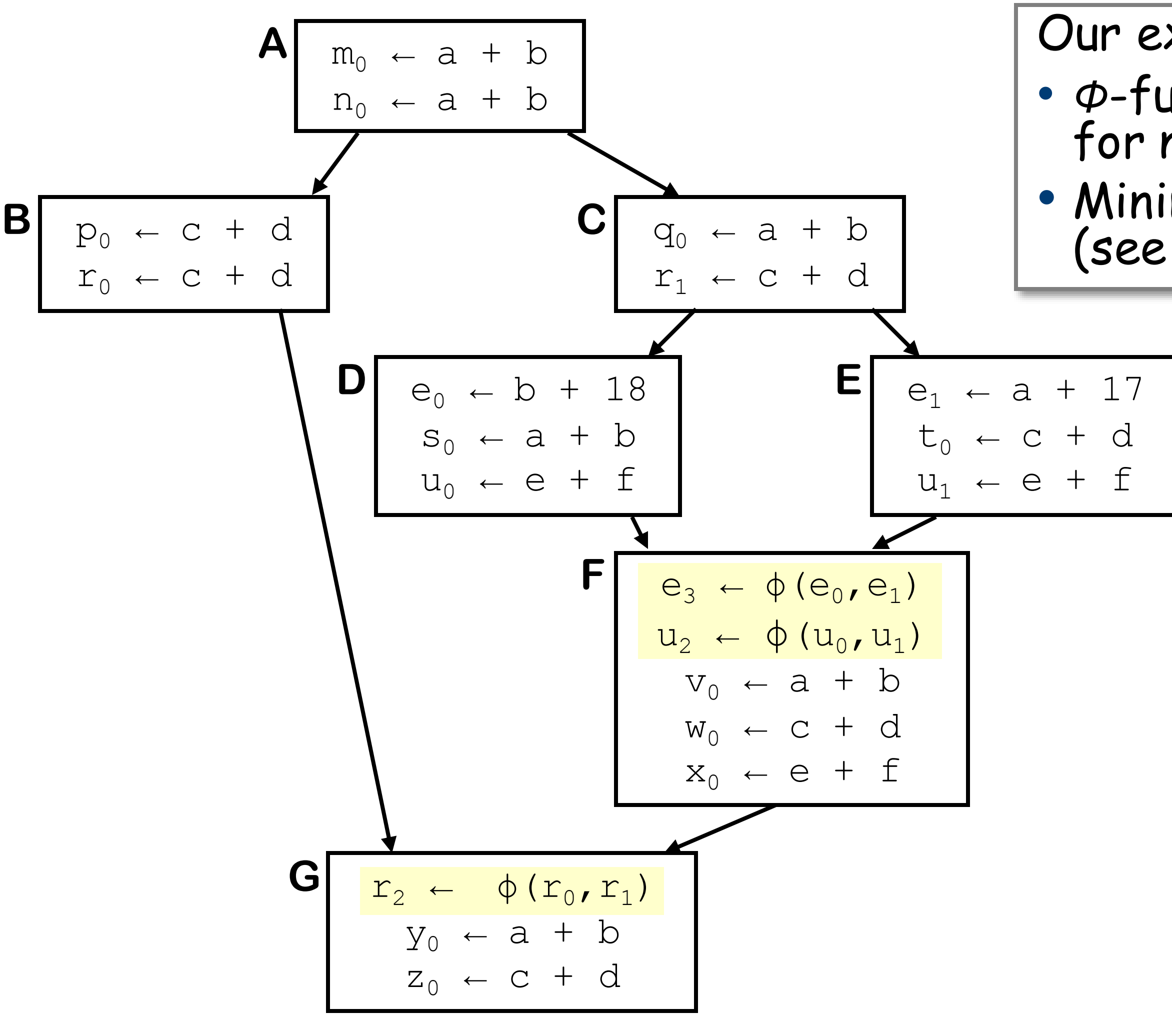
Two principles

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

To reconcile these principles with real code

- Insert ϕ-functions at merge points to reconcile name space
- Add subscripts to variable names for uniqueness

Superlocal Value Numbering



Our example in SSA form

- ϕ-functions at join points for names that need them
- Minimal set of ϕ-functions (see Chapter 9 in EaC)

Superlocal Value Numbering

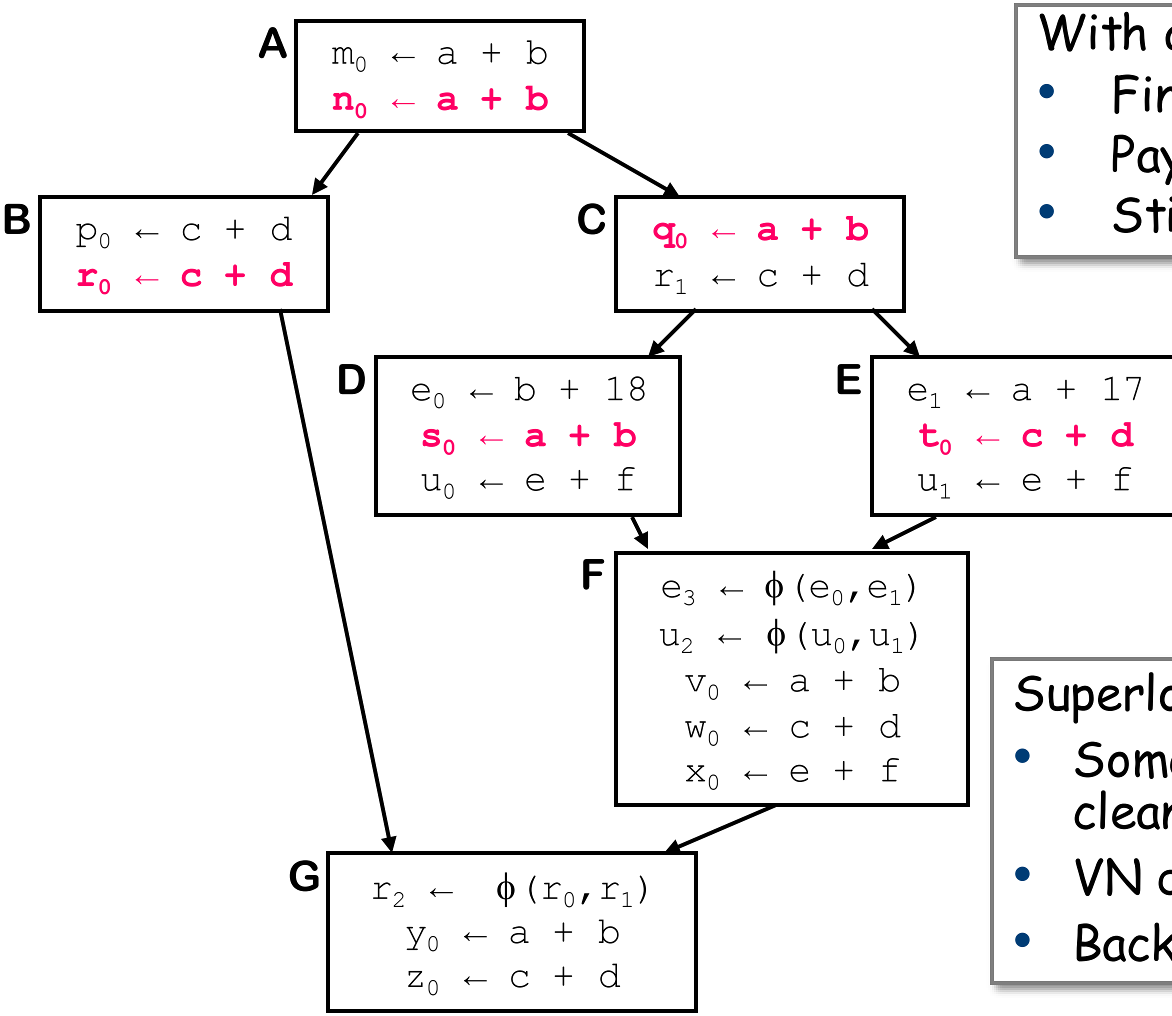
The SVN Algorithm

WorkList ← { *entry block* }   Blocks to process
Empty ← *new table*   Table for base case
while (WorkList is not empty)
    remove a block b from WorkList
    SVN(b, Empty)

SVN(Block, Table)
    t ← *new table for Block, with Table linked as surrounding scope*
    LVN(Block, t)   Use LVN for the work
    for each successor s of Block
        if s has just 1 predecessor   In the same EBB
            then SVN(s, t)
        else if s has not been processed   Starts a new EBB
            then add s to WorkList
    deallocate t

Assumes LVN has been parameterized around block and table

Superlocal Value Numbering



With all the bells & whistles

- Find more redundancy
- Pay minimal extra cost
- Still does nothing for F & G

Superlocal techniques

- Some local methods extend cleanly to superlocal scopes
- VN does not back up
- Backward motion causes probs

Loop Unrolling

Applications spend a lot of time in loops

- We can reduce loop overhead by unrolling the loop

do i = 1 to 100 by 1
*a(i) ← b(i) * c(i)*
end

Complete unrolling

*a(1) ← b(1) * c(1)*
*a(2) ← b(2) * c(2)*
*a(2) ← b(3) * c(3)*
...
*a(100) ← b(100) * c(100)*

- Eliminated additions, tests, and branches
  - *Can subject resulting code to strong local optimization!*
- Only works with fixed loop bounds & few iterations
- The principle, however, is sound
- Unrolling is always safe, as long as we get the bounds right

Loop Unrolling

Unrolling by smaller factors can achieve much of the benefit

Example: unroll by 4

```
do i = 1 to 100 by 1
        a(i) ← b(i) * c(i)
        end
```

Unroll by 4

```
do i = 1 to 100 by 4
    a(i)   ← b(i) * c(i)
    a(i+1) ← b(i+1) * c(i+1)
    a(i+2) ← b(i+2) * c(i+2)
    a(i+3) ← b(i+3) * c(i+3)
    end
```

Achieves much of the savings with lower code growth

- Reduces tests & branches by 25%
- LVN will eliminate duplicate adds and redundant expressions
- Less overhead per useful operation

But, it relied on knowledge of the loop bounds…

Loop Unrolling

Unrolling with unknown bounds

Need to generate guard loops

```
do i = 1 to n by 1
        a(i) ← b(i) * c(i)
        end
```

Unroll by 4

```
i ← 1
do while (i+3 < n )
    a(i)   ← b(i) * c(i)
    a(i+1) ← b(i+1) * c(i+1)
    a(i+2) ← b(i+2) * c(i+2)
    a(i+3) ← b(i+3) * c(i+3)
    i ← i + 4
    end
do while (i < n)
    a(i)   ← b(i) * c(i)
    i ← i + 1
    end
```

Achieves most of the savings

- Reduces tests & branches by 25%
- LVN still works on loop body
- Guard loop takes some space

Can generalize to arbitrary upper & lower bounds, unroll factors

Loop Unrolling

One other unrolling trick

Eliminate copies at the end of a loop

```
t1 ← b(0)
do i = 1 to 100 by 1
    t2 ← b(i)
    a(i) ← a(i) + t1 + t2
    t1 ← t2
end
```

Unroll and rename

```
t1 ← b(0)
do i = 1 to 100 by 2
    t2      ← b(i)
    a(i)    ← a(i) + t1 + t2
    t1      ← b(i+1)
    a(i+1)  ← a(i+1) + t2 + t1
end
```

Unroll by LCM of copy-cycle lengths

- Eliminates the copies, which were a naming artifact
- Achieves some of the benefits of unrolling
  - Lower overhead, longer blocks for local optimization
- Situation occurs in more cases than you might suspect

This result has been rediscovered many times. [Kennedy's thesis]