



COMP 412
FALL 2010

Code Optimization, Part II

Regional Techniques

Comp 412

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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

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
evaluate $L_i \text{ Op}_i R_i$, assign it to T_i , and mark T_i as a constant
3. if $L_i \text{ Op}_i R_i$ matches an identity then
replace it with a copy operation or an assignment
4. if Op_i commutes and $V_1 > V_2$ then
swap V_1 and V_2
5. construct a hash key $\langle V_1, \text{Op}_i, V_2 \rangle$
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

Block is a sequence of n operations of the form

$$T_i \leftarrow L_i \text{ Op}_i R_i$$

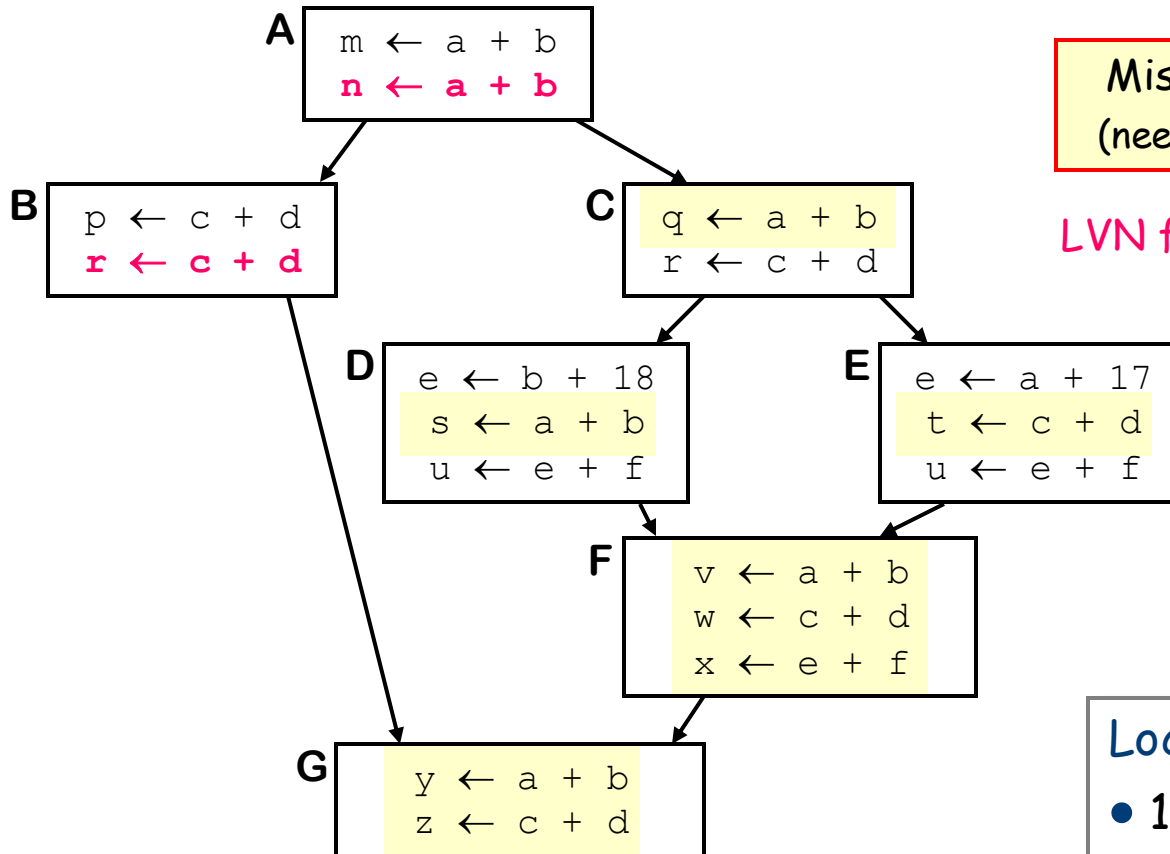
Constant folding

Algebraic identities

Commutativity



Local Value Numbering



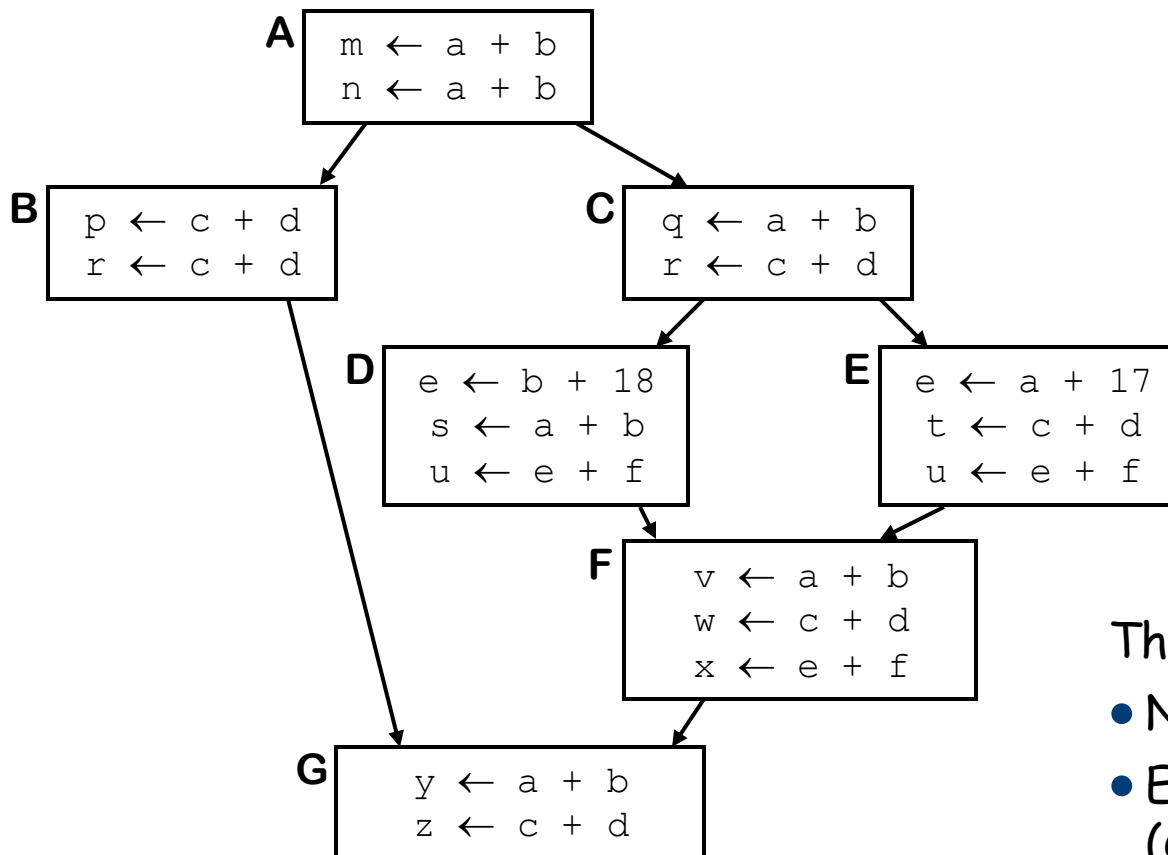
Missed opportunities
(need stronger methods)

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, $G = (N, E)$

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



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

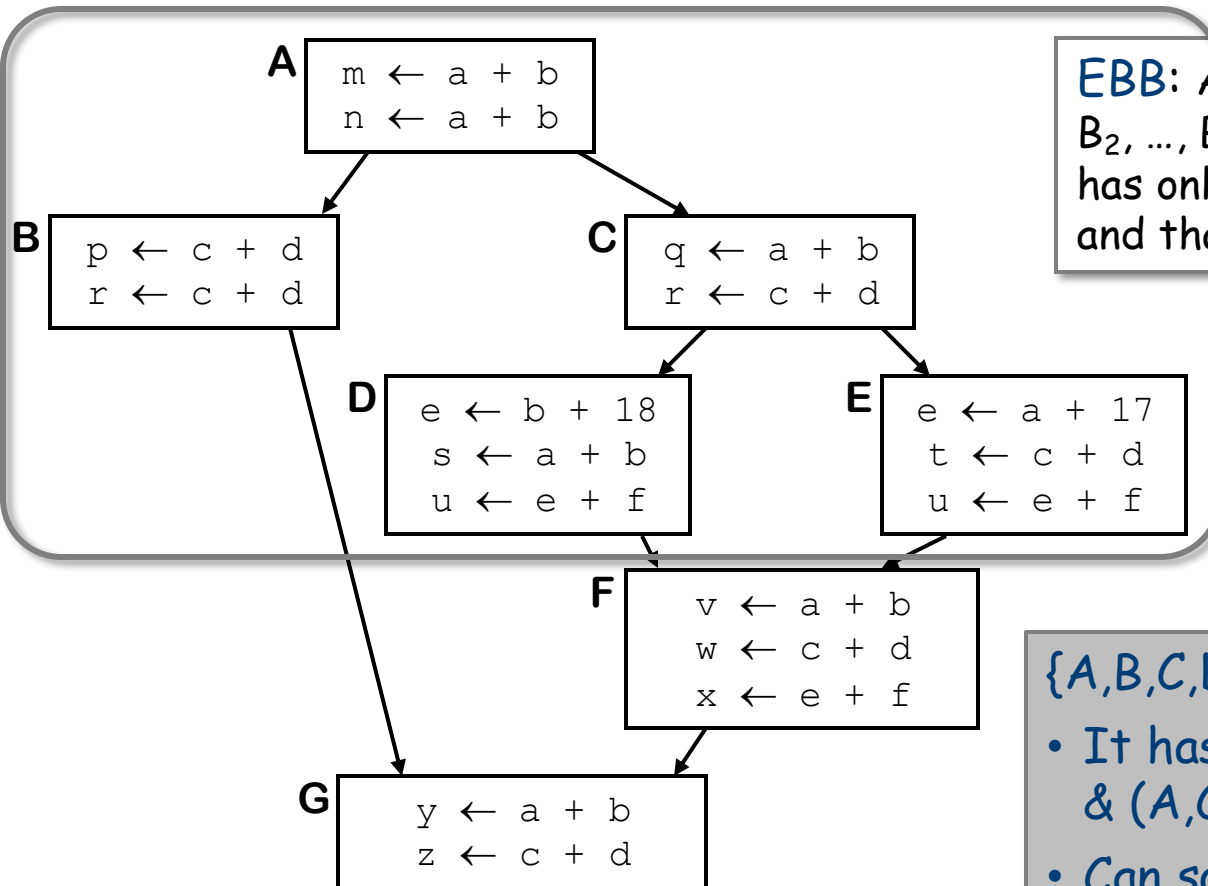
- Local methods led to regional methods
- Regional methods led to global methods
- Global methods led to interprocedural methods

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.



Superlocal Value Numbering



EBB: A maximal set of blocks B_1, B_2, \dots, 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

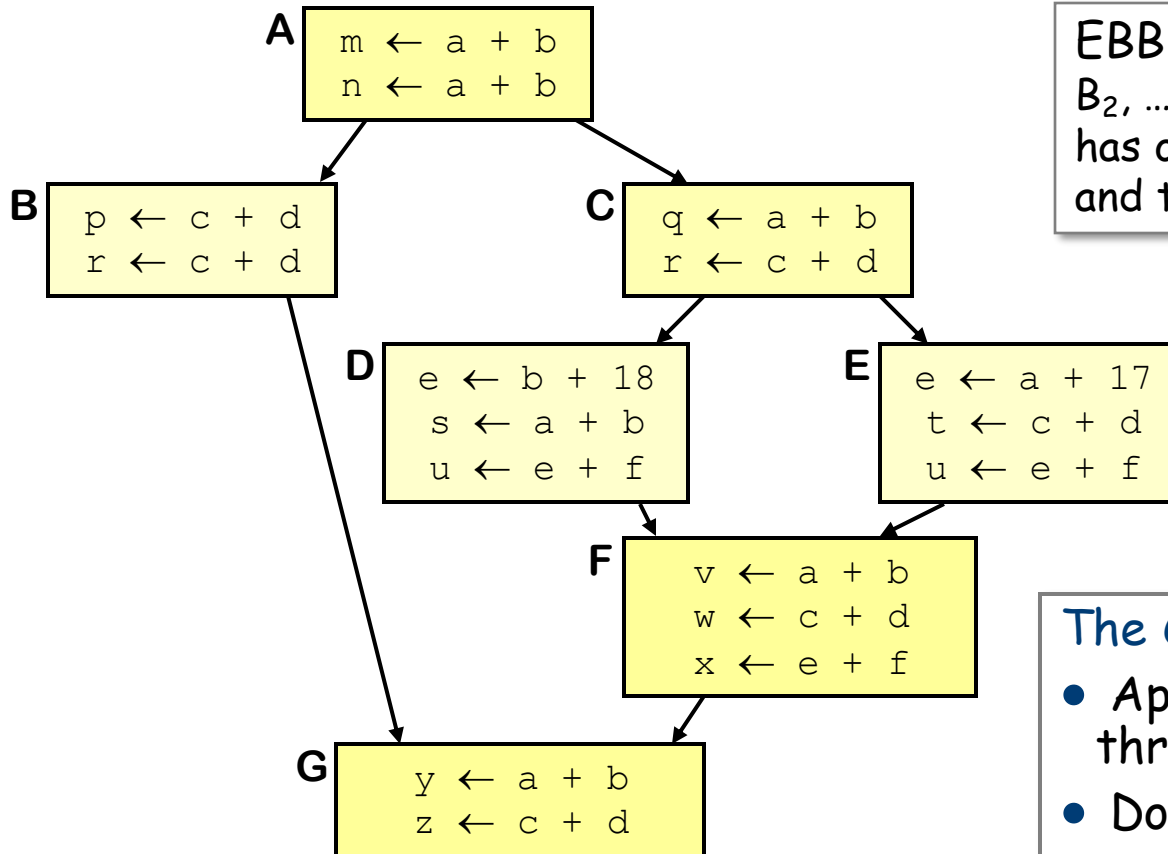
- It has 3 paths: (A, B) , (A, C, D) , & (A, C, E)
- Can sometimes treat each path as if it were a block

$\{F\}$ & $\{G\}$ are degenerate EBBs

Superlocal: "applied to an EBB"



Superlocal Value Numbering



EBB: A maximal set of blocks B_1, B_2, \dots, 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

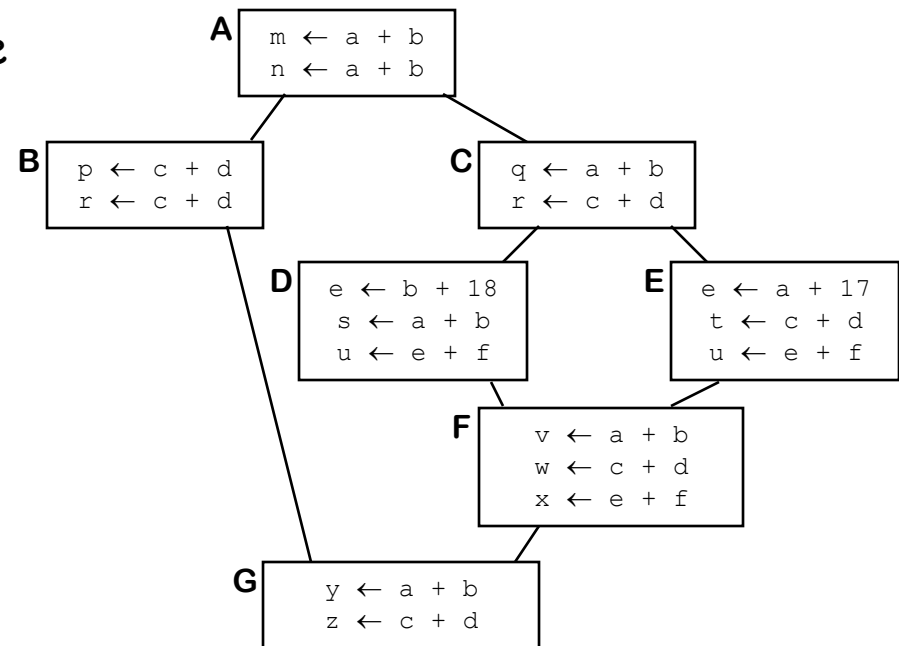


Superlocal Value Numbering

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 $VN \rightarrow \text{name}$ mapping to handle kills
 - Must restore map with scope
 - Adds complication, not cost

"kill" is a re-definition of some name



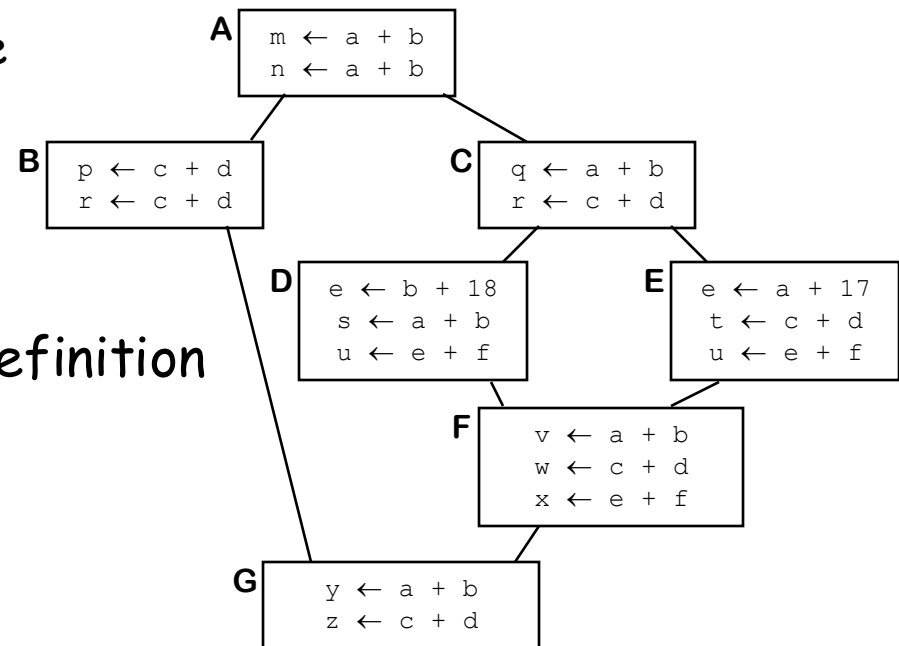


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To simplify matters

- Need *unique name* for each definition
- Makes $\text{name} \Leftrightarrow \text{VN}$
- 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

$a_0 \leftarrow x_0 + y_0$
* $b_0 \leftarrow x_0 + y_0$
 $a_1 \leftarrow 17$
* $c_0 \leftarrow x_0 + y_0$

With VNs

$a_0^3 \leftarrow x_0^1 + y_0^2$
* $b_0^3 \leftarrow x_0^1 + y_0^2$
 $a_1^4 \leftarrow 17$
* $c_0^3 \leftarrow x_0^1 + y_0^2$

Rewritten

$a_0^3 \leftarrow x_0^1 + y_0^2$
* $b_0^3 \leftarrow a_0^3$
 $a_1^4 \leftarrow 17$
* $c_0^3 \leftarrow a_0^3$

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

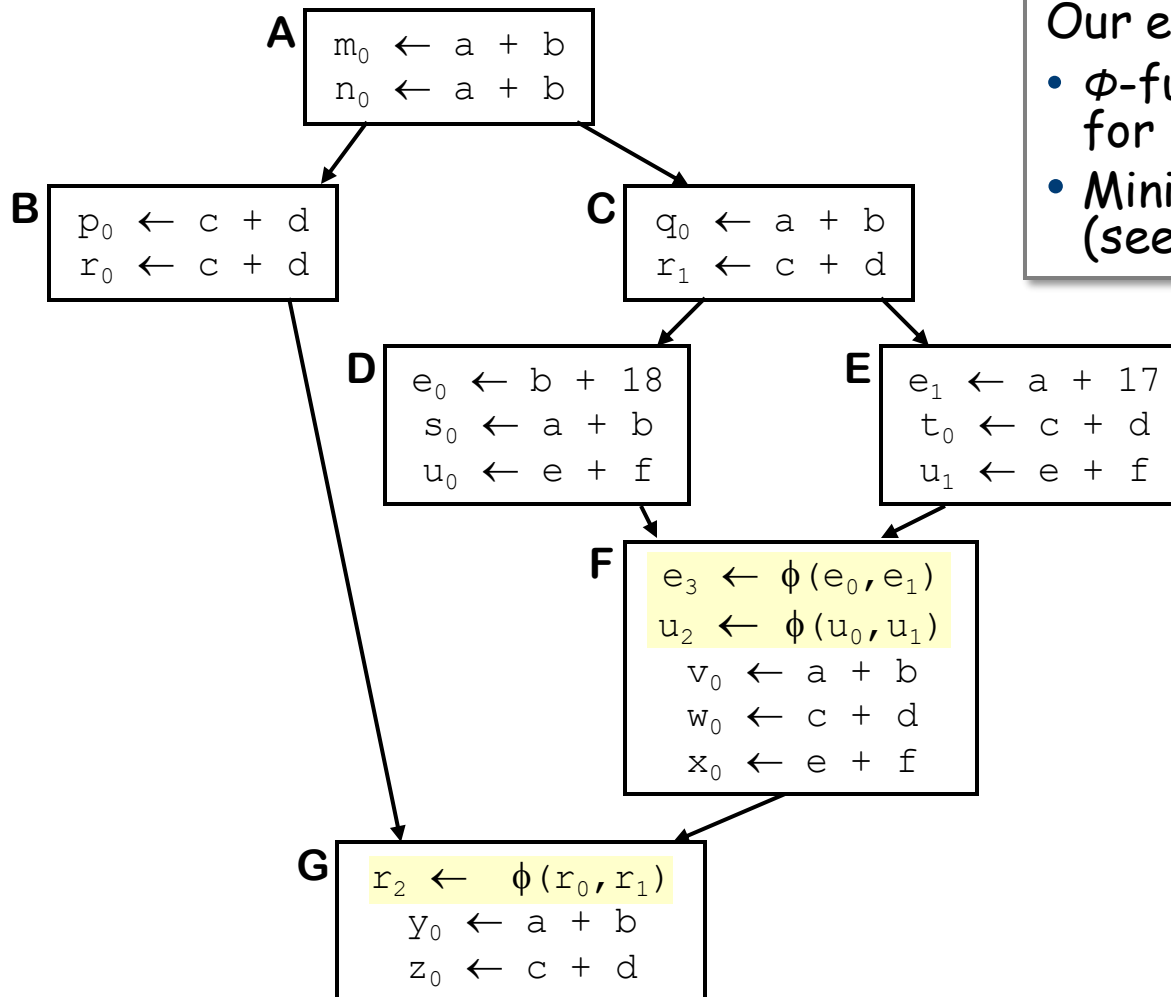
To reconcile these principles with real code

- 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 \leftarrow { entry block }

Blocks to process

Empty \leftarrow new table

Table for base case

while (*WorkList* is not empty)

remove a block b from WorkList

SVN(b, Empty)

SVN(Block, Table)

t \leftarrow 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

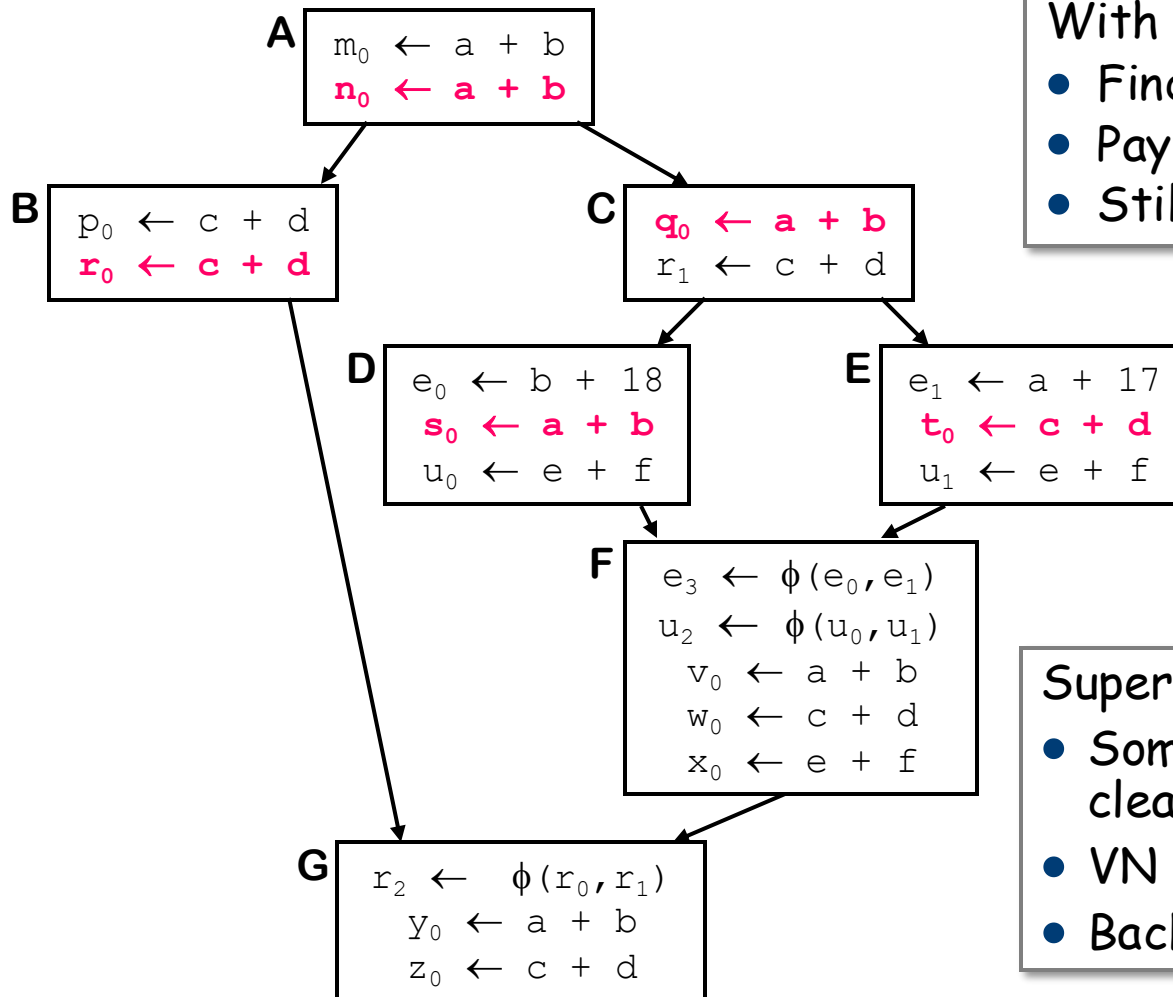
Starts a new EBB

then add s to WorkList

deallocate t



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
```



```
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

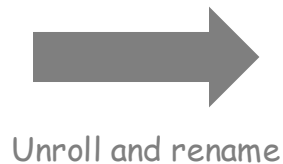


Loop Unrolling

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
```



```
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