Data Structures and Algorithms in Compiler Optimization

Comp314 Lecture

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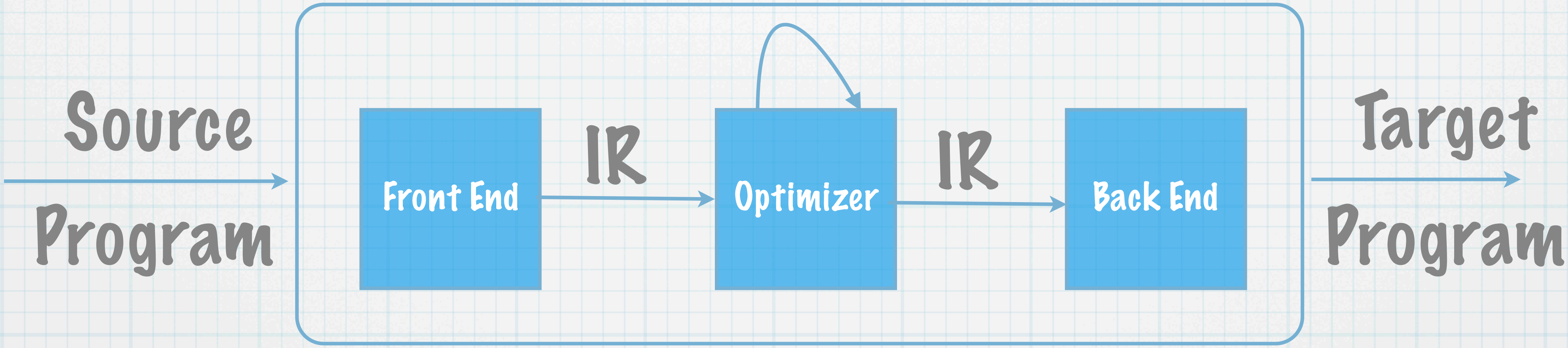
What is a compiler

* Compilers translate between program representations
* Interpreters evaluate their input to produce a result
* Writing a compiler makes large use of different data structures such as graphs, trees, and sets

High Level Organization



Data Structures

* Front End
  * Abstract Syntax Tree
  * Created during parsing and usually replaced by another IR that is better for analysis
* IR
  * Control Flow Graph
  * Usually remains throughout the life of the compiler
* Back End
  * Data flow analysis Sets
  * Created and destroyed during compiler optimization. Attached to nodes of the CFG to hold facts about the program at that point in the graph

Intermediate Representations

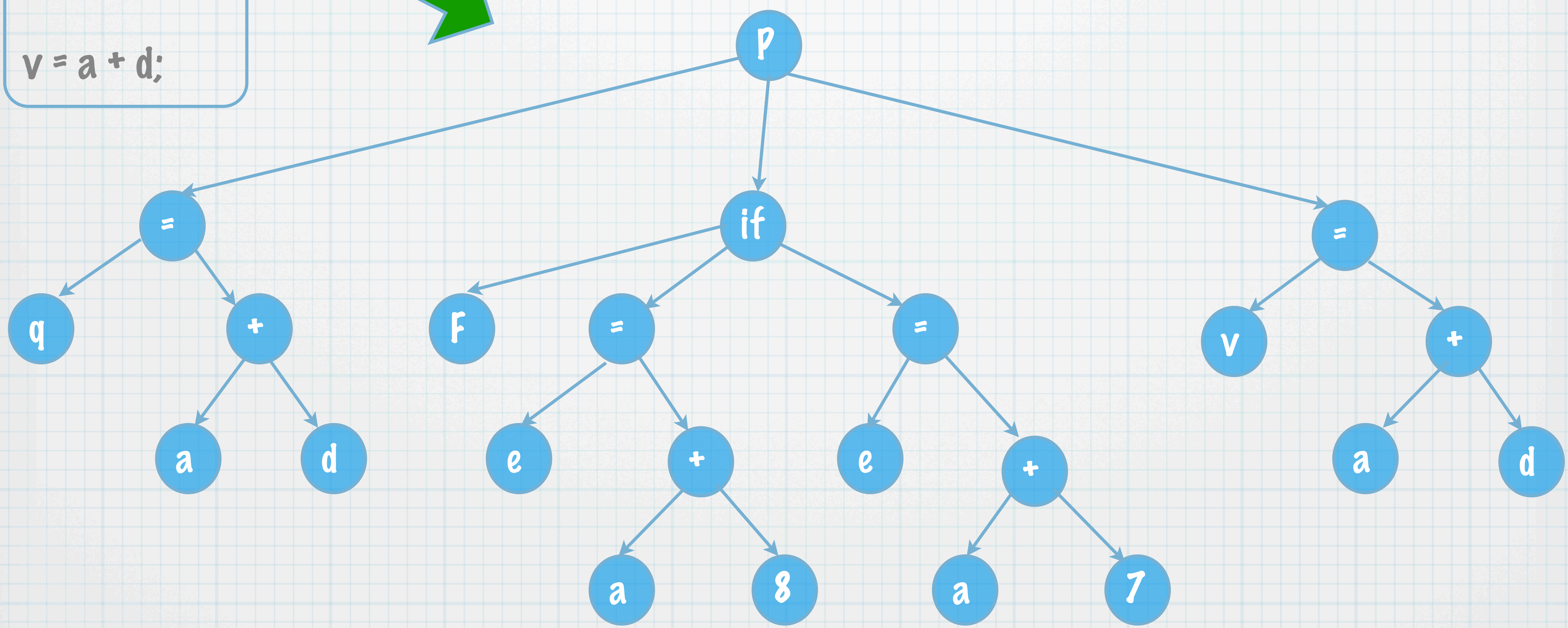
* Graph Based - the program is represented as a graph.
  * Example: AST, DAG
* Linear - the program is represented as a straight line sequence of instructions
  * Example: assembly code with jumps and branches for an abstract machine
* Hybrid - the program is represented as a combination of linear and graph structures.

AST IR

original code

```
q = a + d;

if false then
   e = b + 8;
else
   e = a + 7;

v = a + d;
```

Parsing



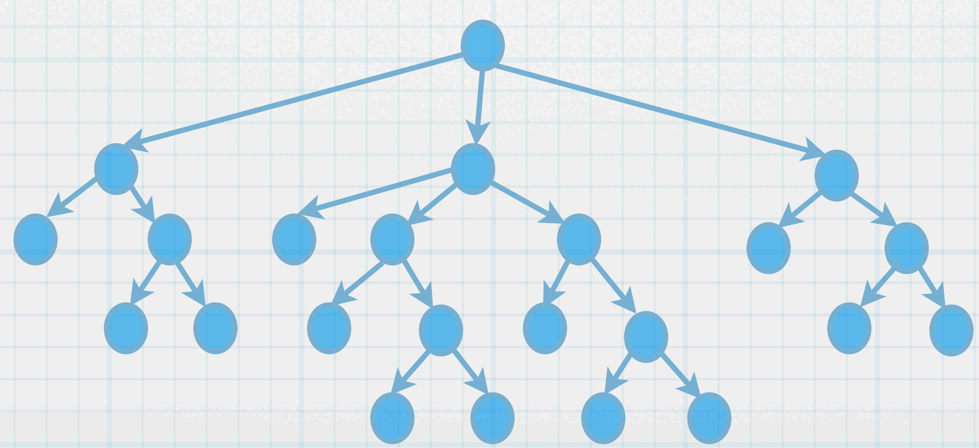
Linear IR

original code

```
q = a + d;

if false then
   e = b + 8;
else
   e = a + 7;

v = a + d;
```

Parsing

Translation



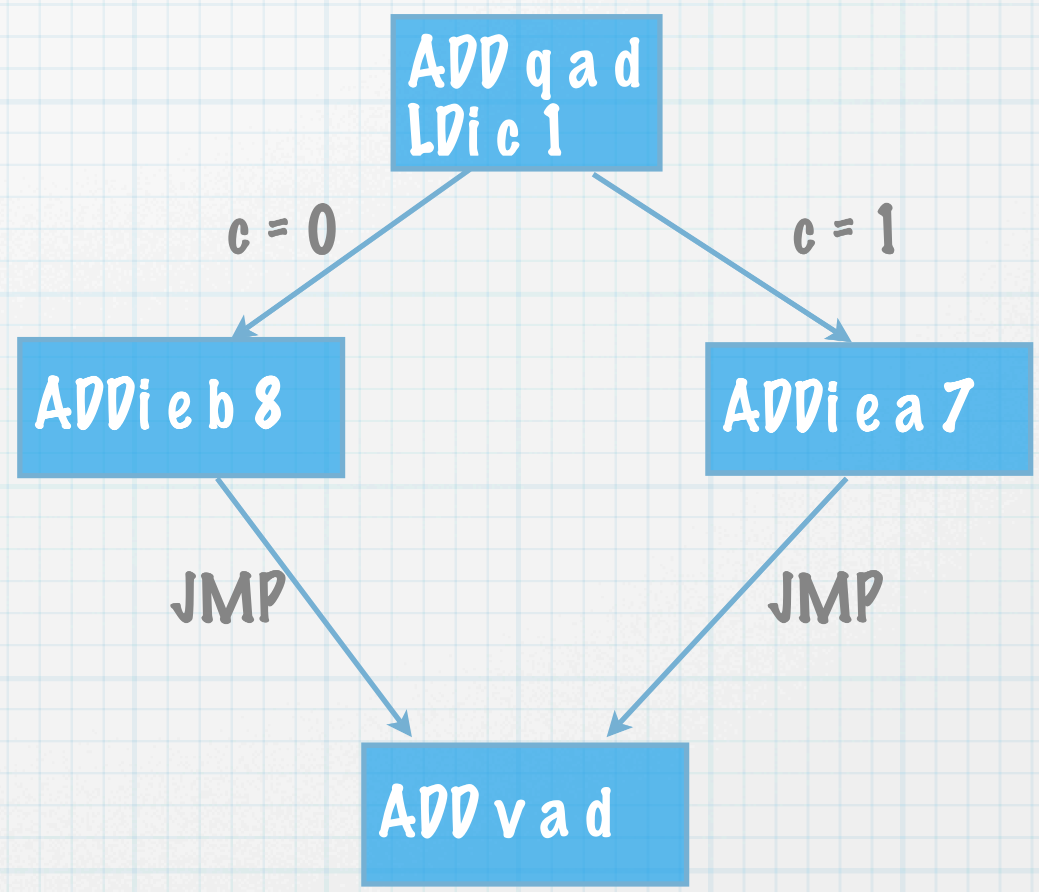
```
ADD q a d
LDi c 1
BReq A B c

A:
ADDi e b 8
JMP C

B:
ADDi e a 7
JMP C

C:
ADD v a d
```

Hybrid IR
(Control Flow Graph)

original code

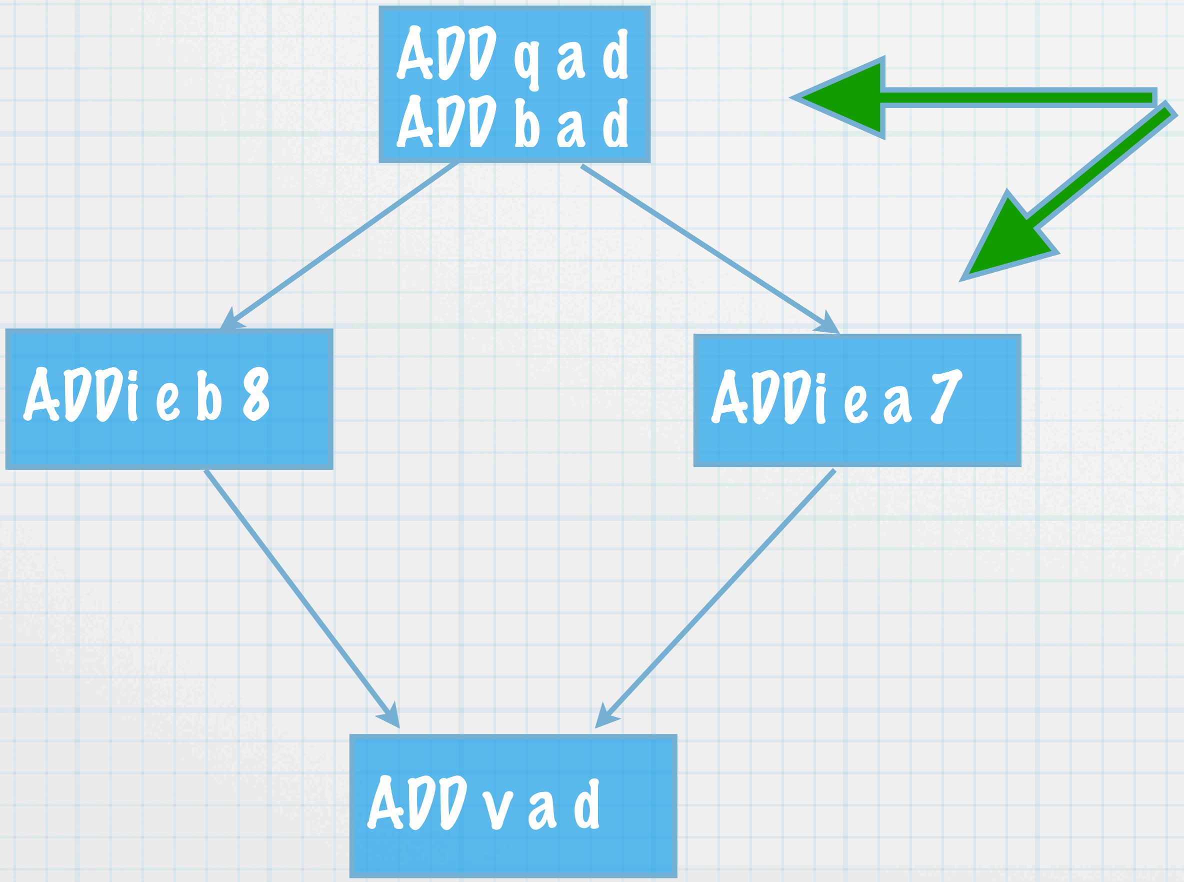
```
q = a + d

if false then
   e = b + 8
else
   e = a + 7

v = a + d
```

Parsing
+
Translation



Control Flow Graph Terminology

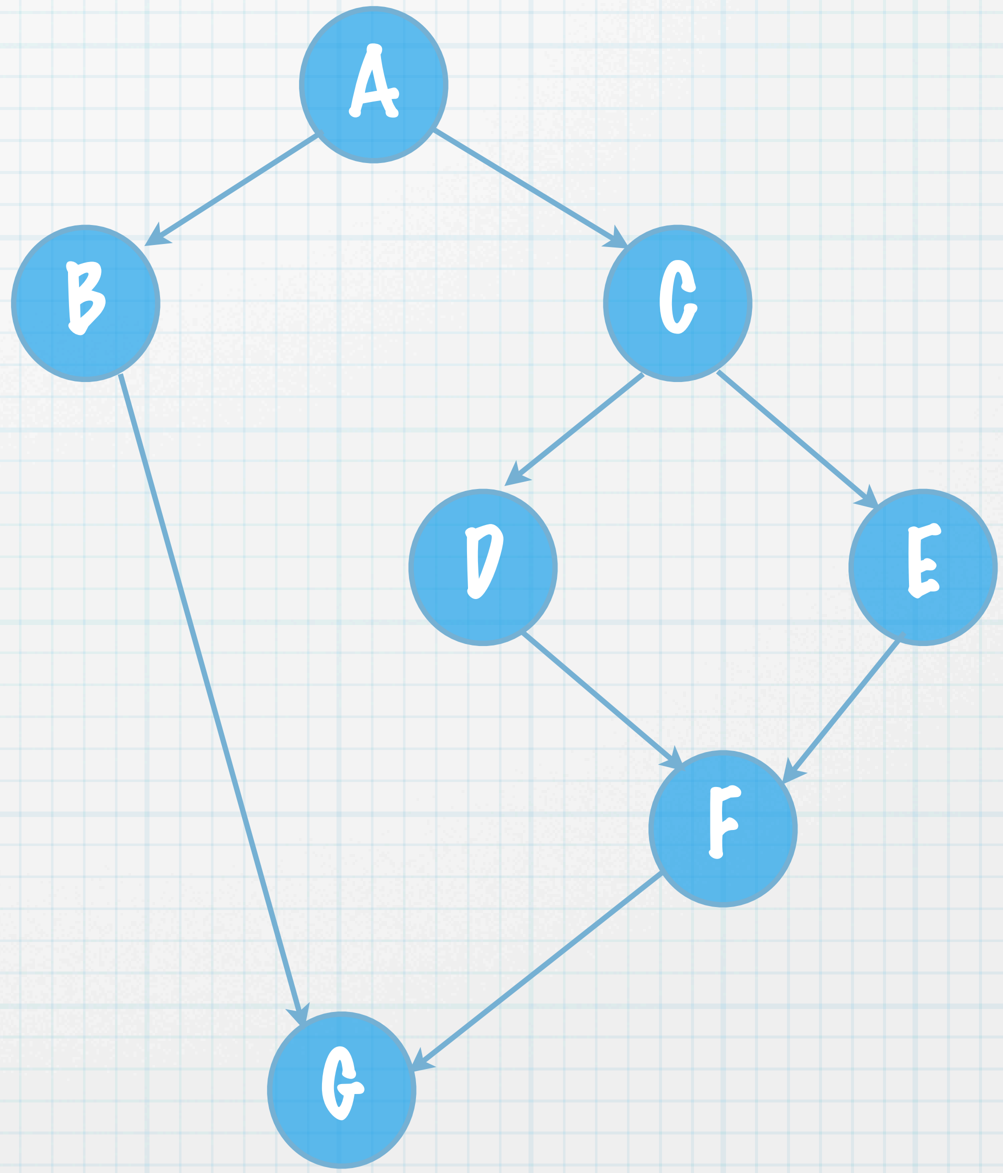
* Nodes are basic blocks
* Edges represent control flow instructions



* Basic block - maximal sequence of straight line instructions
* If one instruction in the basic block executes they all execute

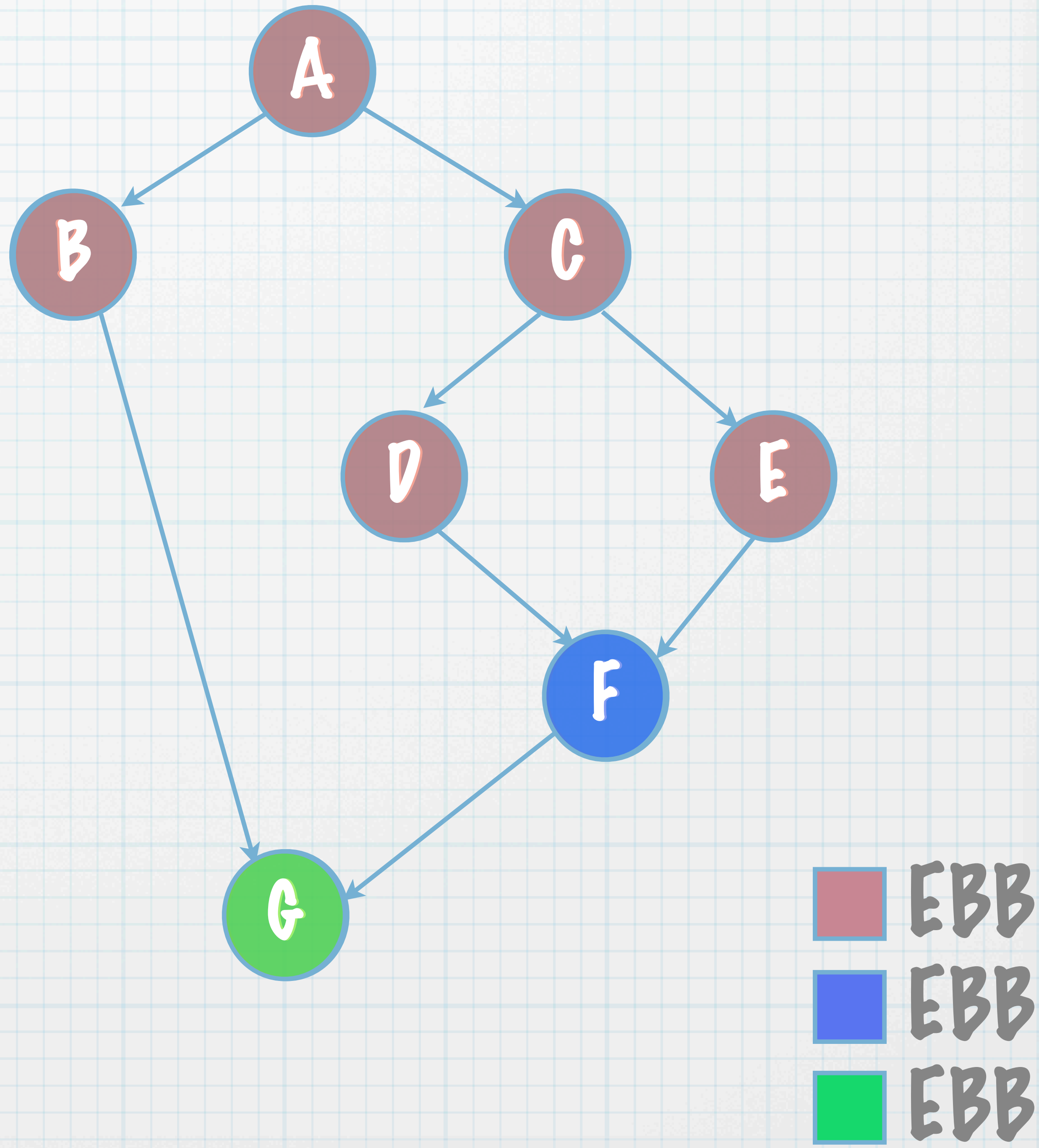
CFG Cont.
Extended Basic Blocks

- Sequence of basic blocks such that each block (except the first) has a single predecessor
- Forms a tree rooted at the entry to the EBB



CFG Cont.
Extended Basic Blocks

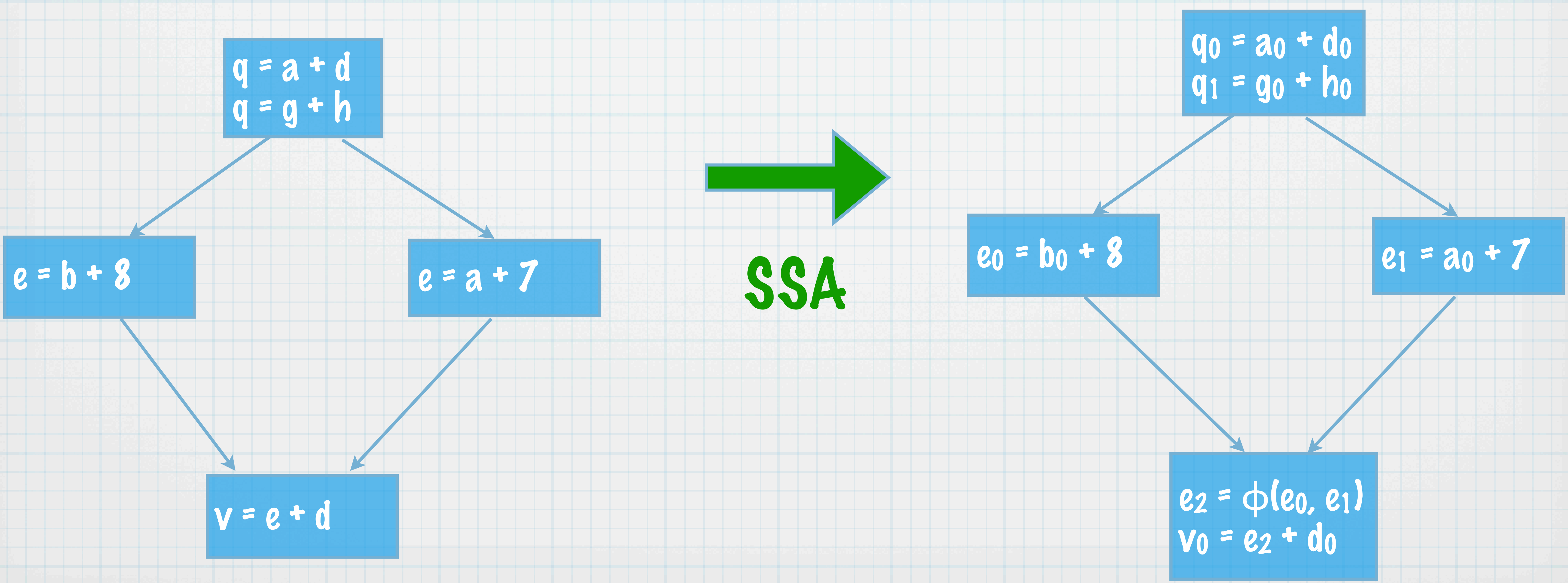
* Sequence of basic blocks such that each block (except the first) has a single predecessor
* Forms a tree rooted at the entry to the EBB



SSA Form

(Static Single Assignment)

A particular way of choosing variable names in the intermediate representation



SSA Form

* Two invariants that characterize SSA
  * Each variable is defined (assigned a value) exactly once
  * Every use refers to exactly one definition
* Encodes information about control flow and data flow into the variable names in the program
  * Phi-Nodes indicate join points in the CFG
  * Variable names show where a particular definition is used

Why Use SSA?

* Simplifies compiler optimizations by providing strong links between definitions and uses
* Single transformation can be used for analysis in many data flow problems
* Makes detecting certain errors trivial (e.g. variable used before it is initialized)

Compiler Optimization

* Optimization is a misused word, we are really talking about transformations of the IR
* Scope
    * Local - within a single basic block
    * Superlocal - within an extended block
    * Global - within an entire procedure
    * Interprocedural - between procedures

Example Optimization: Value Numbering

* This optimization finds and eliminates redundant computations (common subexpression elimination)
* Instead of recomputing an answer we save the value and reuse it in a later computation
* This is a standard optimization performed by many compilers

Local Value Numbering

Original Code

a := b + c
b := a - d
d := a - d

→ Value Number

Value Numbered

$a^3 := b^1 + c^2$
$b^5 := a^3 - d^4$
$d^5 := a^3 - d^4$

↙ Rewrite

Transformed Code

a := b + c
b := a - d
d := b

Value Numbering

* Technique originally designed for linear IRs, graphical IRs would use a DAG for this optimization instead
* Each expression is assigned a value number
* Value number is computed as a hash of value numbers in the expression and the operands
* Hashtable maps expressions to value

Value Numbering Algorithm

```
for each  instruction
(assume instruction is of the form x := y op z)
  look up the value numbers of y and z
  build the hash key "y_vn op z_vn"
   lookup key in the hash
   if key in hash
      replace the instruction with a copy operation
      record value number for x
   else
      add key to hash with a new value number
```

Local Value Numbering

(a problem)

Original Code

a := b + c
b := a - d
b := d + a
d := a - d

Value Number

Value Numbered

$a^3 := b^1 + c^2$
$b^5 := a^3 - d^4$
$b^6 := a^3 + d^4$
$d^5 := a^3 - d^4$

Rewrite

Transformed Code

a := b + c
b := a - d
b := a + d
d := ???

Local Value Numbering With SSA

Original Code

$a_0 := b_0 + c_0$
$b_1 := a_0 - d_0$
$b_2 := d_0 + a_0$
$d_1 := a_0 - d_0$

Value Number

Value Numbered

$a_0{}^3 := b_0{}^1 + c_0{}^2$
$b_1{}^5 := a_0{}^3 - d_0{}^4$
$b_2{}^6 := a_0{}^3 + d_0{}^4$
$d_1{}^5 := a_0{}^3 - d_0{}^4$

Rewrite

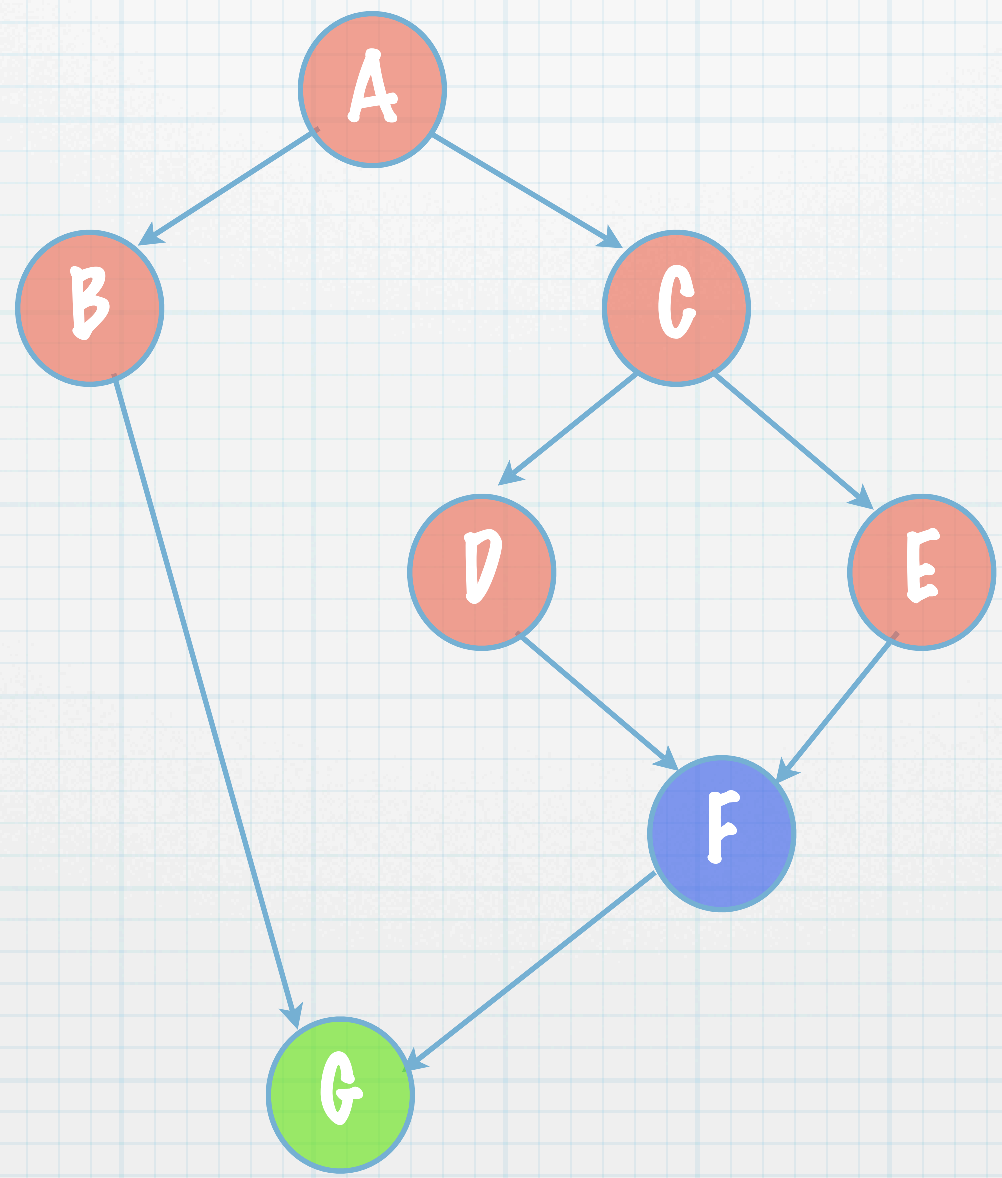
Transformed Code

$a_0 := b_0 + c_0$
$b_1 := a_0 - d_0$
$b_2 := d_0 + a_0$
$d_1 := b_1$

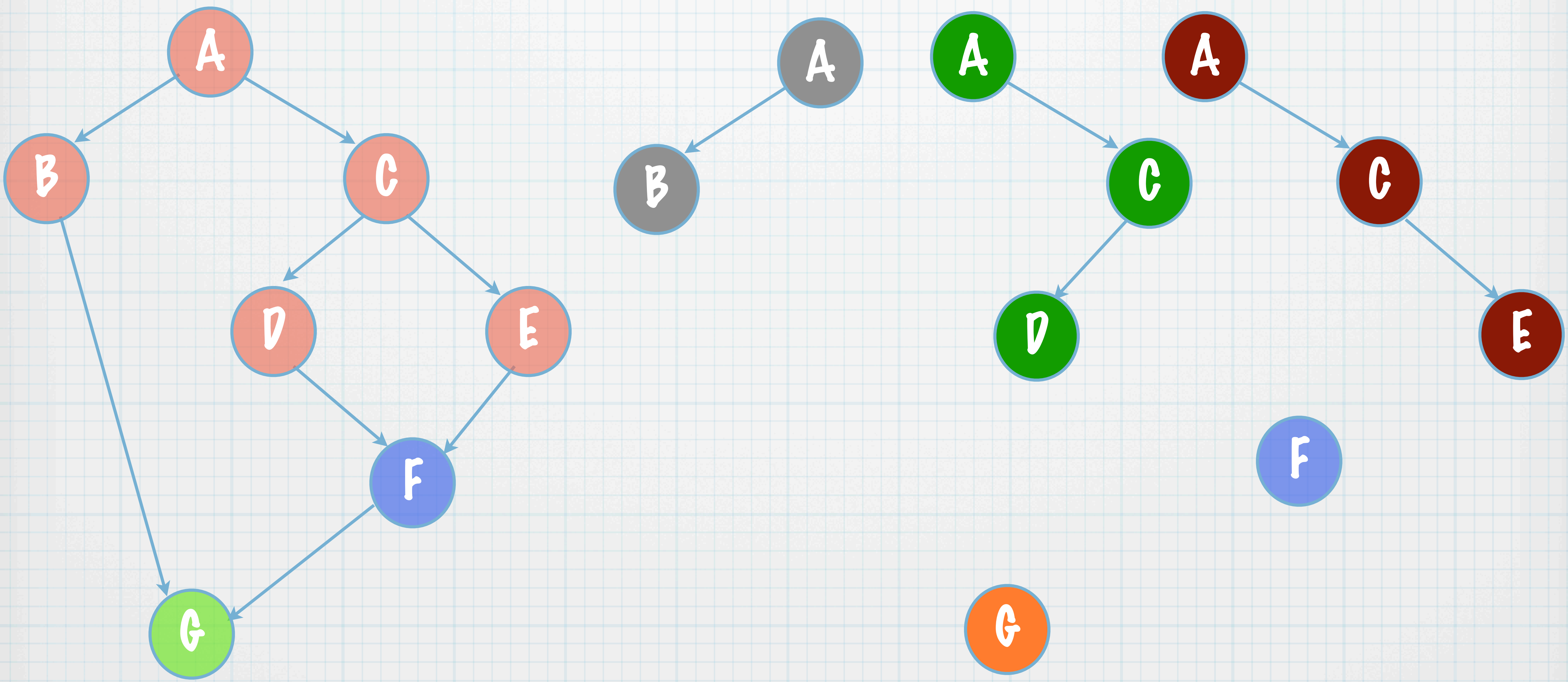
Superlocal Value Numbering

* Operates over extended basic blocks (EBBs)
* Allows us to capture more redundant computations
* Treat individual paths through an EBB as if it were a single basic block

Treat each path through the EBB as a basic block



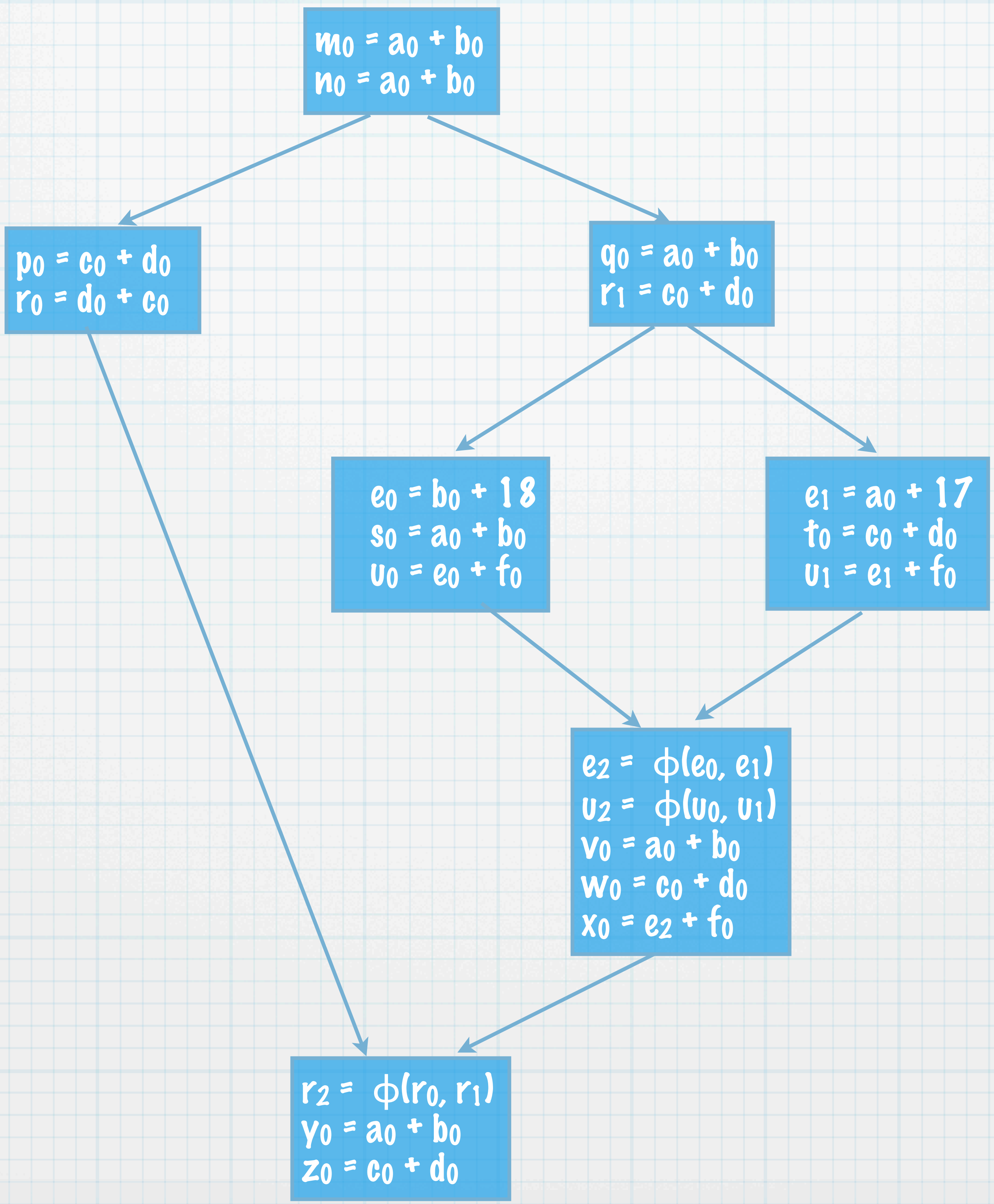
Treat each path through the EBB as a basic block



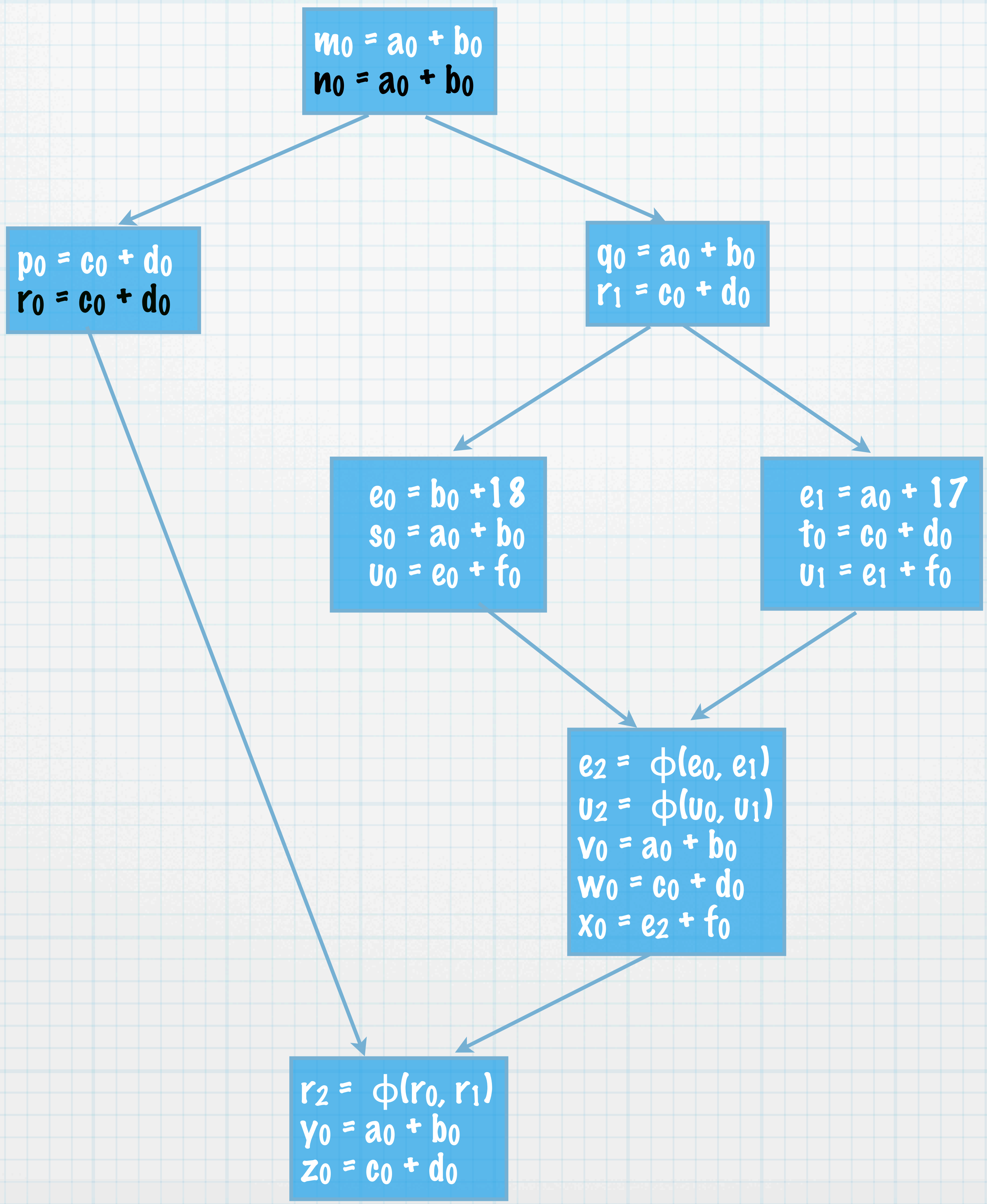
Value Numbering Over EBBs

* Treat each path through the EBB as a single basic block
* Initialize the hash table from the previous basic block in the path
* Remove the entries from hash table for the basic block when recursing up the path

Value Numbering Example

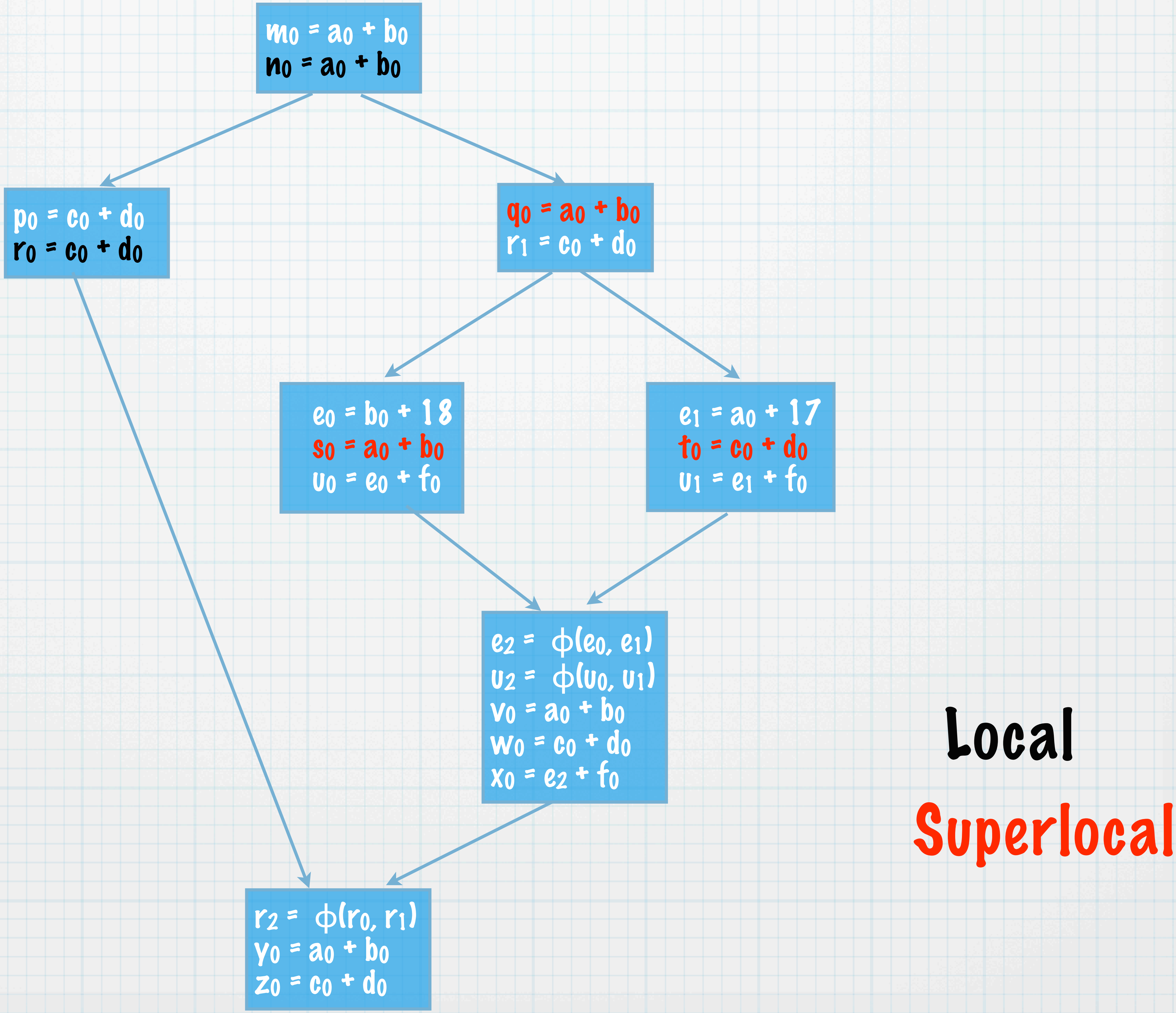


Value Numbering Example



Local

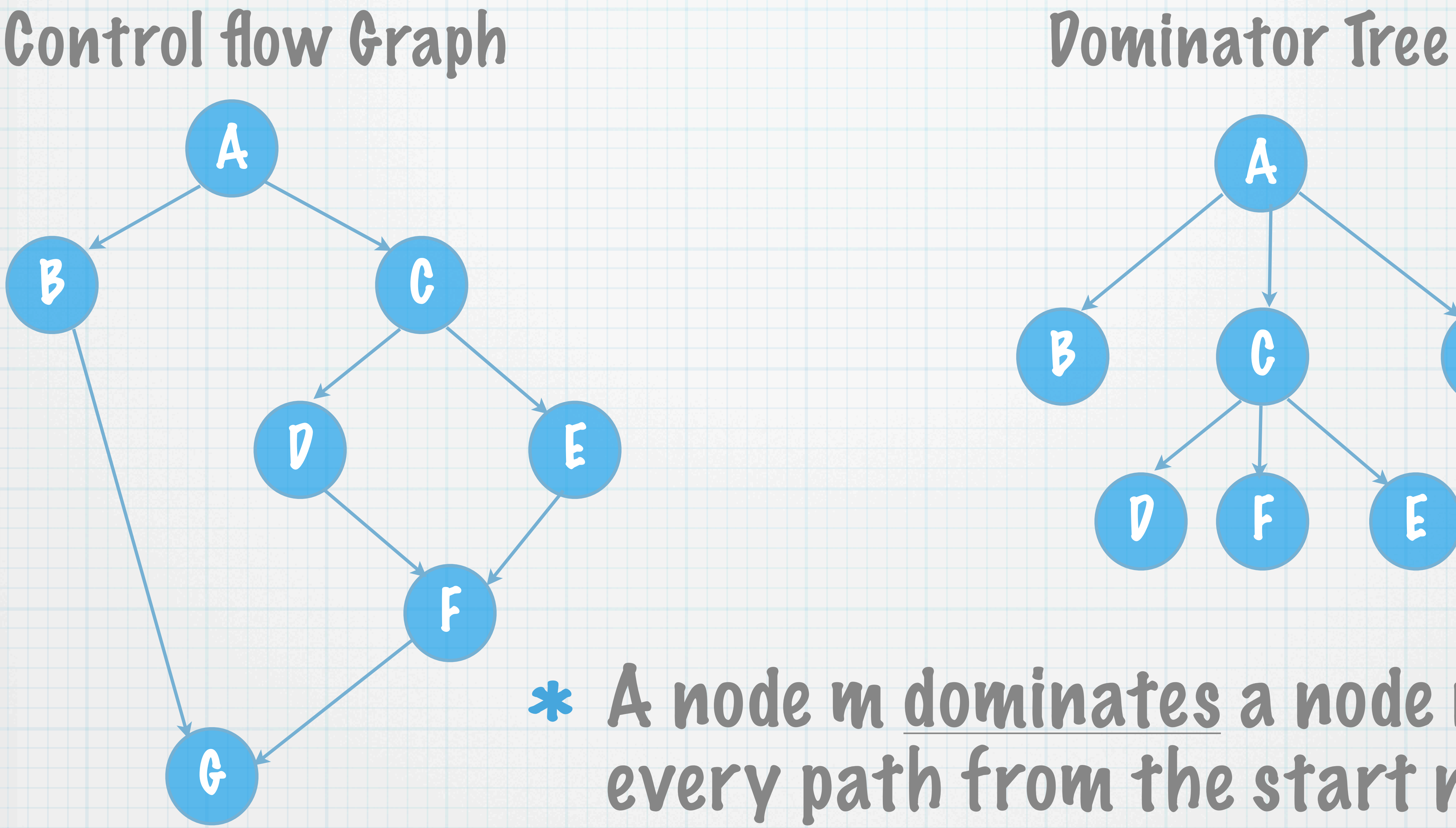
Value Numbering Example



Room for improvment

* Still miss some opportunities because we must discard the value table each time we reach a node with multiple predecessors
* Would like to keep some information about values we have already seen
* There is another technique we can use to find more opportunities for optimization

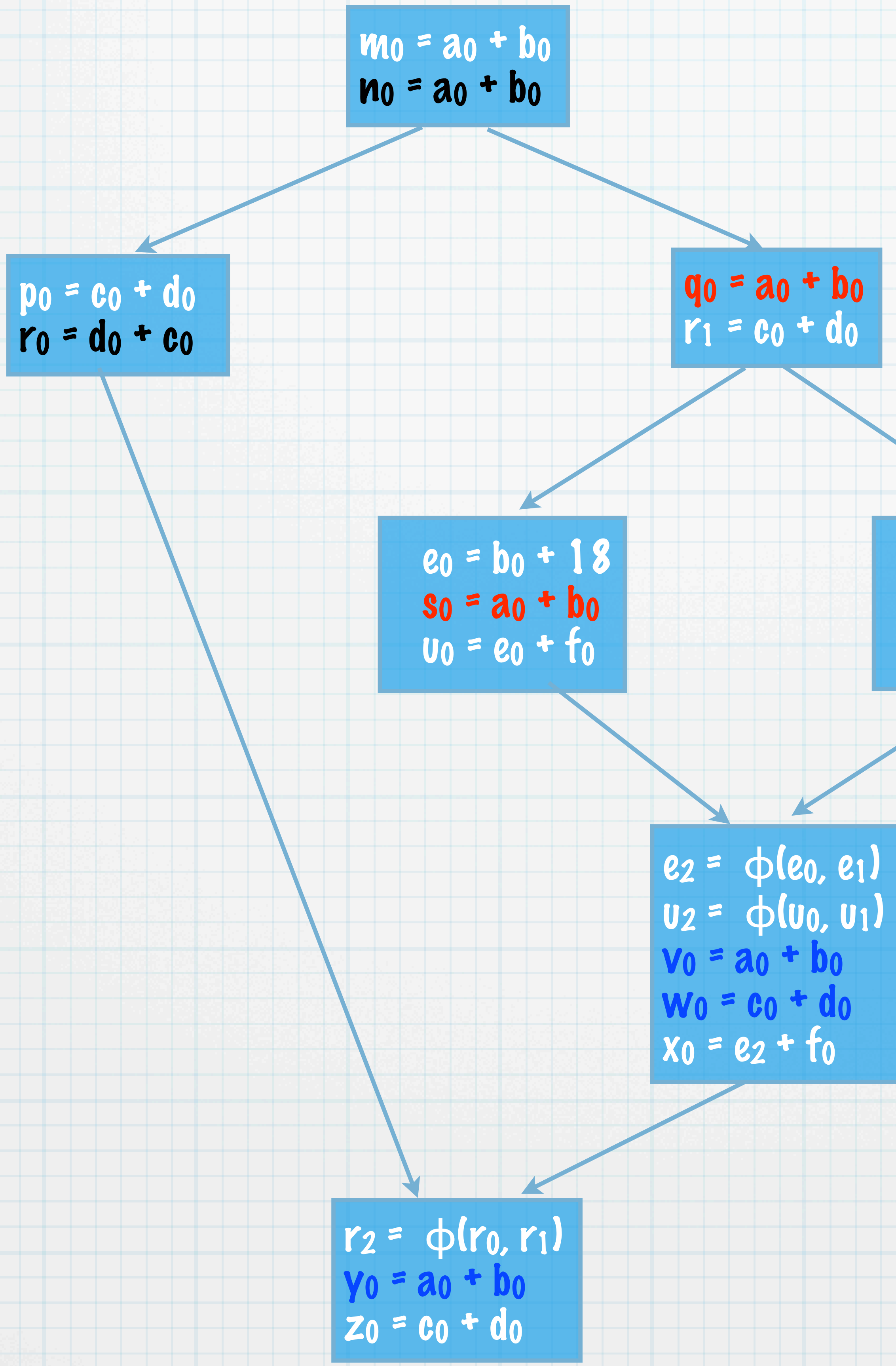
Dominators



* A node m dominates a node n if every path from the start node to n goes through m.
* By definition a node dominates itself

Dominator Based Value Numbering

* Preorder traversal of the dominator tree
* Initialize the value table with the blocks immediate dominator in the tree
* Remove the entries from the table when returning from the block



Local

Superlocal

Dominator

Can we do better?

* Yes, using global value numbering.
* Technique uses data flow analysis to compute which expressions are available at any point in the program
* Take comp 512 for all the data flow analysis you could ever want

Resources

* Engineering a Compiler
  * Cooper and Torczon
* The Dragon Book
  * Aho, Sethi and Ullman
* Comp 412