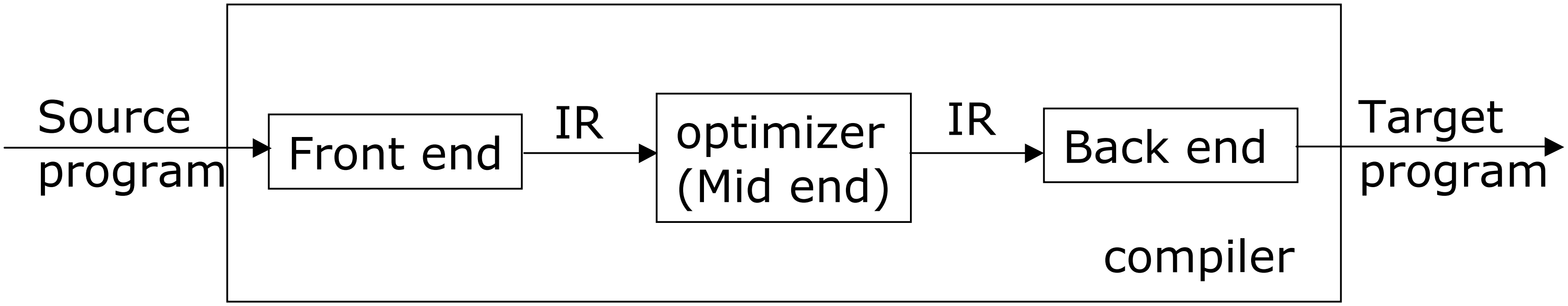
Machine Independent Code Optimizations

Useless Code and Redundant Expression Elimination

Code Optimization



- The goal of code optimization is to
  - Discover program run-time behavior at compile time
  - Use the information to improve generated code
    - Speed up runtime execution of compiled code
    - Reduce the size of compiled code
- Correctness (safety)
  - Optimizations must preserve the meaning of the input code
- Profitability
  - Optimizations must improve code quality

Applying Optimizations

- Most optimizations are separated into two phases
    - Program analysis: discover opportunity and prove safety
    - Program transformation: rewrite code to improve quality
- The input code may benefit from many optimizations
    - Every optimization acts as a filtering pass that translate one IR into another IR for further optimization
- Compilers
    - Select a set of optimizations to implement
    - Decide orders of applying implemented optimizations
        - The safety of optimizations depends on results of program analysis
        - Optimizations often interact with each other and need to be combined in specific ways
        - Some optimizations may need to applied multiple times
            - E.g., dead code elimination, redundancy elimination, copy folding
    - Implement predetermined passes of optimizations

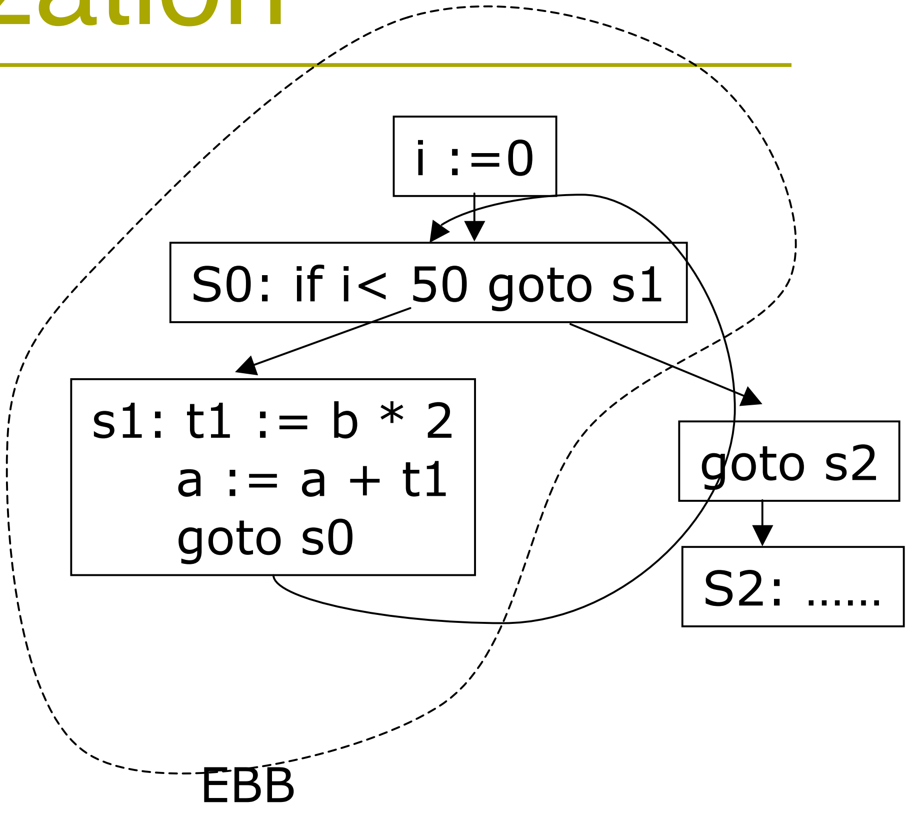
Scalar Compiler Optimizations

- Machine independent optimizations
  - Enable other transformations
    - Procedure inlining, cloning, loop unrolling
  - Eliminate redundancy
    - Redundant expression elimination
  - Eliminate useless and unreachable code
    - Dead code elimination
  - Specialization and strength reduction
    - Constant propagation, peephole optimization
  - Move operations to less-frequently executed places
    - Loop invariant code motion
- Machine dependent (scheduling) transformations
  - Take advantage of special hardware features
    - Instruction selection, prefetching
  - Manage or hide latency, introduce parallelism
    - Instruction scheduling, prefetching
  - Manage bounded machine resources
    - Register allocation

Scope Of Optimization

- Local methods
  - Applicable only to basic blocks
- Superlocal methods
  - Operate on extended basic blocks (EBB)

    B1,B2,B3,…,Bm, where Bi is the single predecessor of B(i+1)
- Regional methods
  - Operate beyond EBBs, e.g. loops, conditionals
- Global (intraprocedural) methods
  - Operate on entire procedure (subroutine)
- Whole-program (interprocedural) methods
  - Operate on entire program



Loop Unrolling

- An enabling transformation to expose opportunities for other optimizations
  - Reduce the number of branches by a factor 4
  - Provide a bigger basic block (loop body) for local optimization
    - Better instruction scheduling and register allocation

```
do i = 1 to n by 1
   a(i) = a(i) + b(i)
end
```

Original loop

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

Unrolled by 4, n = 100

Loop Unrolling --- arbitrary n

```
do i = 1 to n-3 by 4
   a(i) = a(i) + b(i)
   a(i+1) = a(i+1) + b(i+1)
   a(i+2) = a(i+2) + b(i+2)
   a(i+3) = a(i+3) + b(i+3)
End
do while (i <= n)
    a(i) = a(i) + b(i)
     i=i+1
end
```

Unrolled by 4, arbitrary n

```
i = 1
if (mod(n,2) > 0) then
   a(i) = a(i) + b(i)
   j=j+1
if (mod(n,4) > 1) then
   a(i) = a(i)+b(i)
   a(i+1)=a(i+1)+b(i+1)
    i=i+2
do i = i to n by 4
   a(i) = a(i) + b(i)
   a(i+1) = a(i+1) + b(i+1)
   a(i+2) = a(i+2) + b(i+2)
   a(i+3) = a(i+3) + b(i+3)
end
```

Unrolled by 4, arbitrary n

Eliminating Redundant Expressions

Original code

```
m := 2 * y * z
n := 3 * y * z
o := 2 * y - z
```

Rewritten code

```
t0:=2 * y
m := t0 * z
n := 3 * y * z
o := t0 - z
```

- The second 2*y computation is redundant
- What about y*z?
  - 2*y*z ➔ (2*y) * z   not 2*(y*z)
  - 3*y*z➔ (3*y) * z   not 3*(y*z)
  - Change associativity may change evaluation result
    - For integer operations, optimization is sensitive to ordering of operands
- Typically applied only to integer expressions due to precision concerns

The Role Of Naming

```
a := x + y
b := x + y
a := 17
c := x + y
```

(1)

```
m := 2 * y * z
y := 3 * y * z
o := 2 * y - z
```

(2)

```
m := 2 * y * z
*p := 3 * y * z
o := 2 * y - z
```

(3)

(1) The expression `x+y’ is redundant, but no longer available in ‘a’ when being assigned to `c’

- Keep track of available variables for each value number
- Create new temporary variables for value numbers if necessary

(2) The expression 2*y is not redundant

- the two 2*y evaluation have different values

(3) Pointer Variables could point to anywhere

- If p points to y, then 2*y is no longer redundant
- All variables (memory locations) may be modified from modifying *p
- Pointer analysis ---reduce the set of variables associated with p

Eliminate Redundancy In Basic Blocks
Value numbering (1)

- Simulate the runtime evaluation of expressions
  - For every distinct runtime value, create a unique integer number as compile-time handle
- Use a hash table to map every expression e to a integer value number VN(e)
  - Represent the runtime value of expression

  VN (e1 op e2) =

  unique_map(op,VN(e1),VN(e2))
- If an expression has a already-defined value number
  - It is redundantly evaluated and can be removed

```
a<3> := b<1> + c<2>;
b<5> := a<3> – d<4>;
c<6> := b<5> + c<2>;
d<5> := a<3> – d<4>;
```

```
a := b + c;
b := a – d ;
c := b + c ;
d := b;
```

Eliminate Redundancy In Basic Blocks Value numbering (2)

for each expression e of the form result := opd1 op opd2

```
1.  Find value numbers for opd1 and opd2
     if  VN(opd1) or VN(opd2) is a constant or has a replacement variable
         replace opd1/opd2 with the value
2. Construct a hash key for expression e from op, VN(opd1) and VN(opd2)
3. if  the hash key is already defined in hash table with a value number
        if (result is a temporary) then remove e
        else   replace e with a copy
        record the value number for result
    else
        insert e into hash table with new value number
        record value number for result (set replacement variable of value number
```

Extensions:

```
  When valuating a hash key k for expression e
      if  operation can be simplified, simplify the expression
      if op is commutative, sort operands by their value numbers
```

Example: Value Numbering

```
ADDR_LOADI @c → r9
INT_LOADA @i → r10
INT_LOADI 4 → r11
INT_MULT r10 r11 → r12
INT_PLUS r9 r12 → r13
FLOAT_LOADI 0.0 → r14
FLOAT_STORE r14 → r13
```

```
ADDR_LOADI c → r9
INT_LOADA i → r10
INT_MULTI r10 4 → r12
INT_PLUS r9 r12 → r13
FLOAT_STOREI 0.0 → r13
```

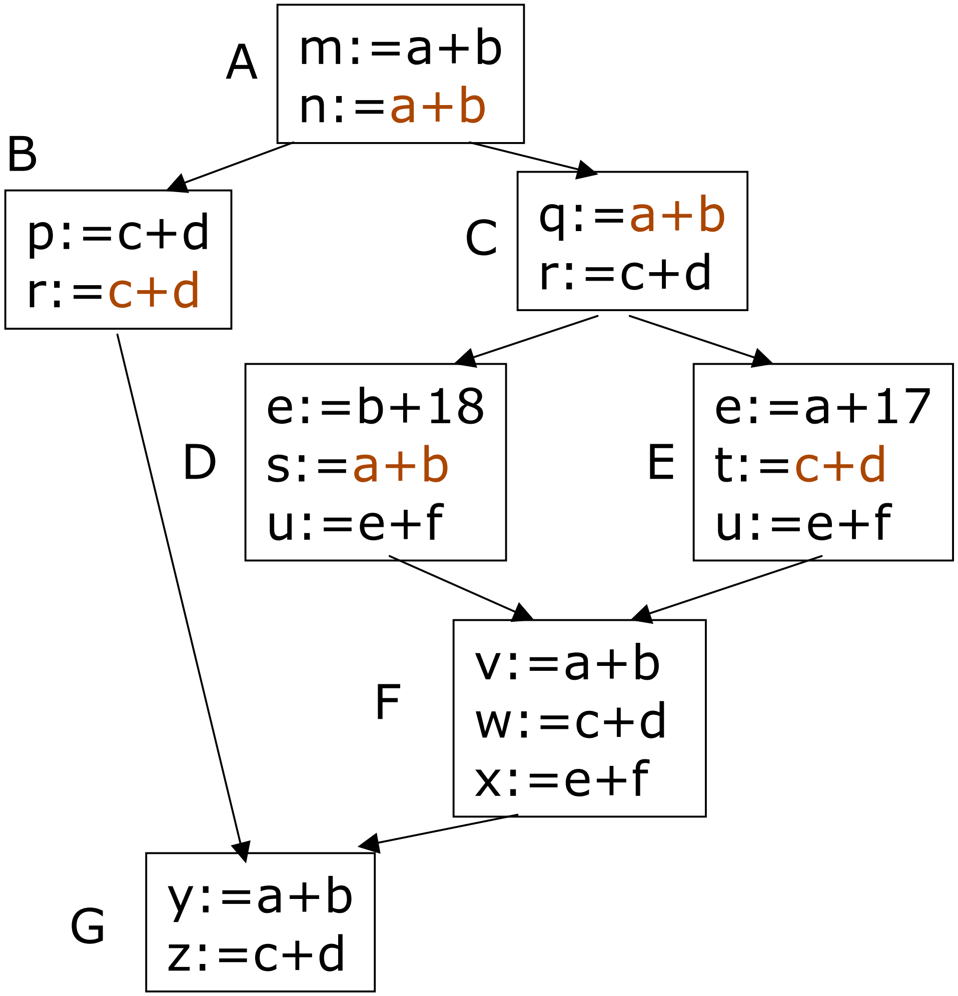
OP	opd1	opd2	Value-number
	@c		v1
ALOADI	@c		v2
	r9		v2
	@i		v3
ILOADA	@i		v4
	r10		v4
	r11		INT_4
……			

Value-number	variable
v1	
v2	r9
v3	
v4	r10
v5	r12
v6	r13

Implementing Value Numbering

- Implementing value numbers
  - Two types of value numbers
    - Compile-time integer constants
    - Integers representing unknown runtime values
  - Use a tag (bit) to tell which type of value number
- Implementing hash table
  - Must uniquely map each expression to a value number
    - variable name ➔ value number
    - (op, VN1, VN2) ➔ value number
  - Evaluating hash key
    - int hash(const char* name);
    - int hash(int op, int vn1, int vn2);
  - Need to resolve hash conflicts if necessary
- Keeping track of variables for value numbers
  - Every runtime value number resides in one or more variables
  - Replace redundant evaluations with saved variables

Superlocal Value Numbering



A
m:=a+b
n:=a+b

B
p:=c+d
r:=c+d

C
q:=a+b
r:=c+d

D
e:=b+18
s:=a+b
u:=e+f

E
e:=a+17
t:=c+d
u:=e+f

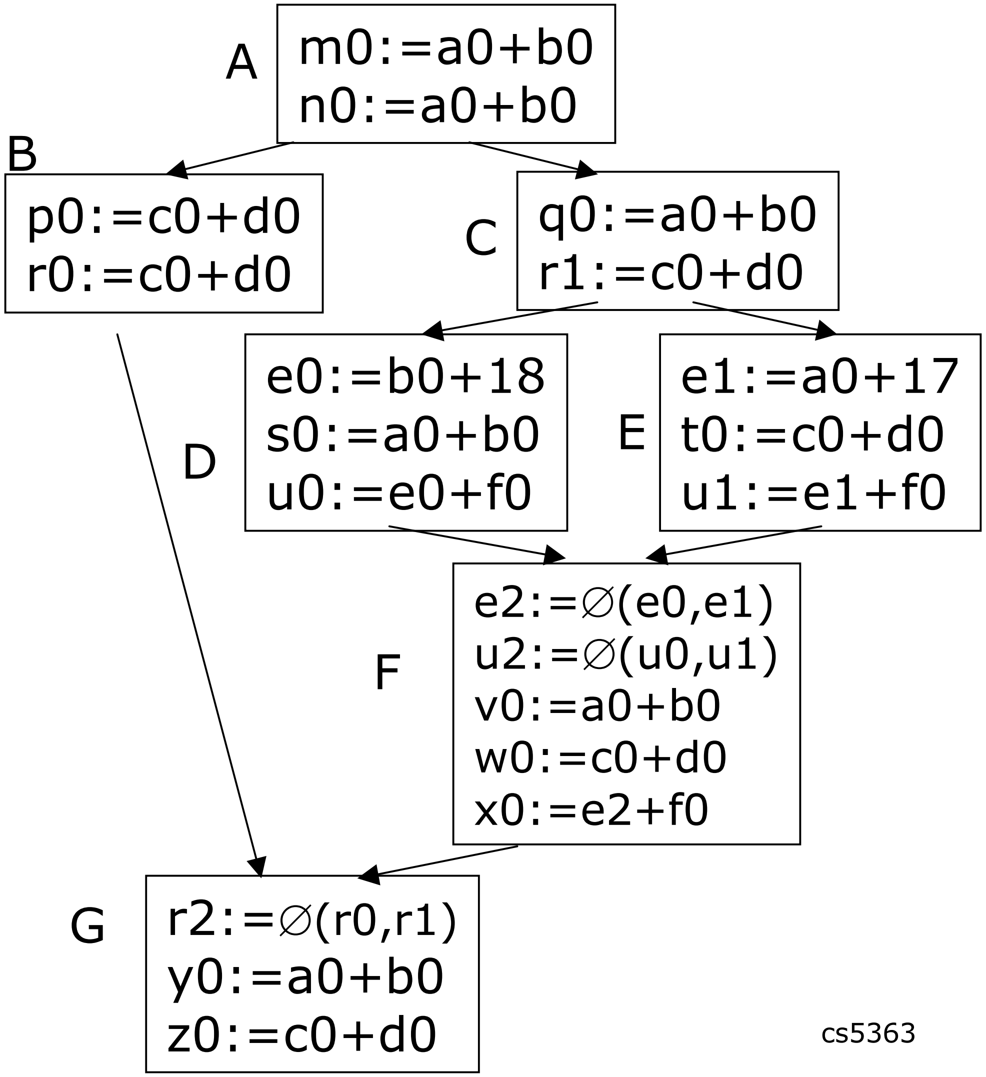
F
v:=a+b
w:=c+d
x:=e+f

G
y:=a+b
z:=c+d

- Finding EBBs in control-flow graph
  - AB, ACD, ACE, F, G
  - Expressions can be in multiple EBBs
- Need to restore state of hash table at each block boundary
  - Record and restore
  - Use scoped value table
- Weakness: does not catch redundancy at node F
- Algorithm

```
ValueNumberEBB(b,tbl,VN)
  PushBlock(tbl, VN)
  ValueNumbering(b,tbl,VN)
  for each child bi of b
    if b is the only parent of bi
      ValueNumberEBB(bi,tbl,VN)
  PopBlock(tbl,VN)
```

Dominator-Based Value Numbering



A
m0:=a0+b0
n0:=a0+b0

B
p0:=c0+d0
r0:=c0+d0

C
q0:=a0+b0
r1:=c0+d0

D
e0:=b0+18
s0:=a0+b0
u0:=e0+f0

E
e1:=a0+17
t0:=c0+d0
u1:=e1+f0

F
e2:=∅(e0,e1)
u2:=∅(u0,u1)
v0:=a0+b0
w0:=c0+d0
x0:=e2+f0

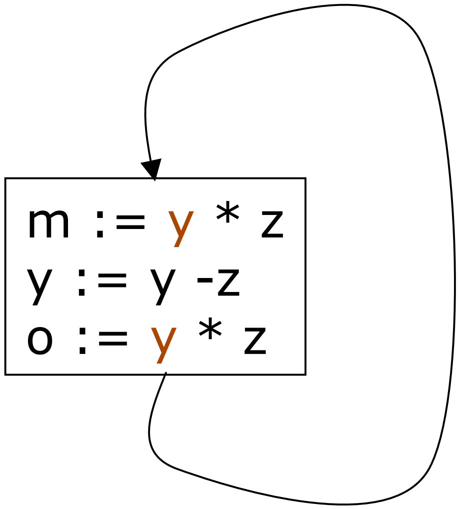
G
r2:=∅(r0,r1)
y0:=a0+b0
z0:=c0+d0

- The execution of C always precedes F
  - Can we use value table of C for F?
- Problem: variables in C may be redefined in D or E
- Solution: rename variables so that each variable is defined once
  - SSA: static single assignment
- Similarly, can use table of A for optimizing G

Exercise: Value Numbering

```
int A[100];
void fee(int x, int y)
{
int I = 0, j = i;
int z = x + y, h =0;
while (I < 100) {
   I = I + 1;
   if (y < x) j = z + y;
   h = x + y;
   A[I] = x + y;
}
return;
}
```

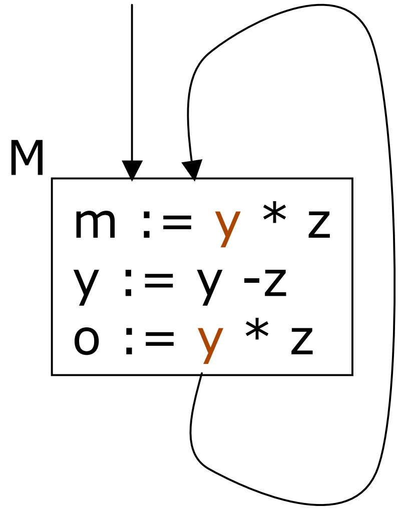
Global Redundancy Elimination



```
m := y * z
y := y -z
o := y * z
```

- Value numbering cannot handle cycles in CFG
  - Makes a single pass over all basic blocks in predetermined order
- Global redundancy elimination
  - Intra-procedural methods
    - Handles arbitrarily shaped CFG
  - Based on expression syntax, not value
    - The first and second y*z considered identical expression despite different values
    - Different from value number approach

Global redundancy elimination



m := y * z
y := y -z
o := y * z

(1) Collect all expressions in the code, each expression given a unique temporary name

- Expressions in M:

  y*z, y – z

(2) At each CFG point p, determine the set of available expressions

- An expression e is available at p if every CFG path leading to p contains a definition of e, and no operand of e is modified after the definition

(3)At each CFG point, replace redundant evaluation of available expressions with a copy of the temporary variables

Computing Available Expressions

- For each basic block n, let
  - DEExpr(n)=expressions evaluated by n and available at exit of n
  - ExprKill(n)=expressions whose operands are modified by n (killed by n)

Goal: evaluate expressions available on entry to n

- $\text{Avail}(n) = \bigcap_{m \in \text{pred}(n)} (\text{DEExpr}(m) \cup (\text{Avail}(m) - \text{ExprKill}(m)))$

```
for each basic block bi
    compute DEExpr(bi) and ExprKill(bi)
    if (bi is entry) Avail(bi)=∅ else Avail(bi)=domain;
for (changed := true; changed; )
    changed = false
    for each basic block bi
        oldAvail = Avail(bi)
        Avail(bi)= ∩ (DEExpr(m) ∪ (Avail(m) - ExprKill(m))
                 m∈pred(bi)
        if (Avail(bi) != oldAvail) changed := true
```

Exercise: Global Redundancy Elimination

```
int A[100];
void fee(int x, int y)
{
int I = 0, j = i;
int z = x + y, h =0;
while (I < 100) {
   I = I + 1;
   if (y < x) j = z + y;
   h = x + y;
   A[I] = x + y;
}
return;
}
```

Useless/Dead Code Elimination

- Eliminate instructions whose results are never used
  (1) mark all critical instructions as useful
    - Instructions that return values, perform input/output, or modify externally visible storage

  (2) Mark all instructions that affect already-marked instruction i
    - Instructions that define operands of i or control the execution of i

```
void foo(int b, int c) {
  int a, d, e, f;
  a := b + c;
  d := b – c;
  e := b * c;
  f := b / c;
  return e;
}
```

Useless code:

```
  a := b + c;
  d := b – c;
  f := b / c;
```

Useless/Dead Code Elimination Algorithm

Main:

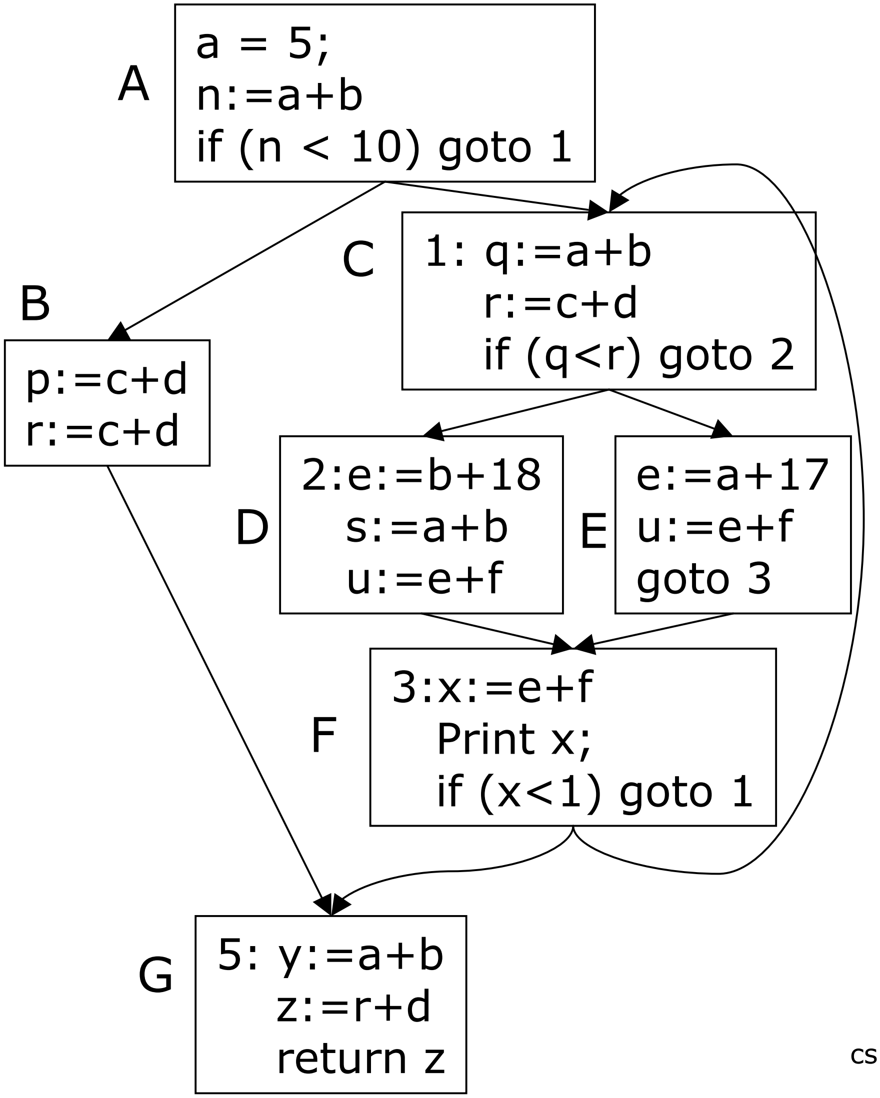
```
    MarkPass()
    SweepPass()
```

```
SweepPass()
  for each operation i
    if i is unmarked then
      if i is a branch then
         rewrite i with a jump
           to i’s nearest marked
           postdominator
      if i is not a jump then
         delete i
```

Compute def(var): data-flow analysis or SSA.
Compute control(i): reverse dominance frontier analysis

```
MarkPass()
  WorkList := ∅
  for each operation i
    if i is critical then
      mark i; WorkList ∪ = {i}
  while WorkList ≠ ∅
    remove i from WorkList
    let i be x := y op z
    if def(y) is not marked then
      mark def(y); WorkList∪={def(y)}
    if def(z) is not marked then
      mark def(z); WorkList∪={def(z)}
    for each branch j that
               controls execution of i
       if j is not marked then
          mark j; WorkList ∪= {j}
```

Useless Code Elimination Example



A
a = 5;
n:=a+b
if (n < 10) goto 1

B
p:=c+d
r:=c+d

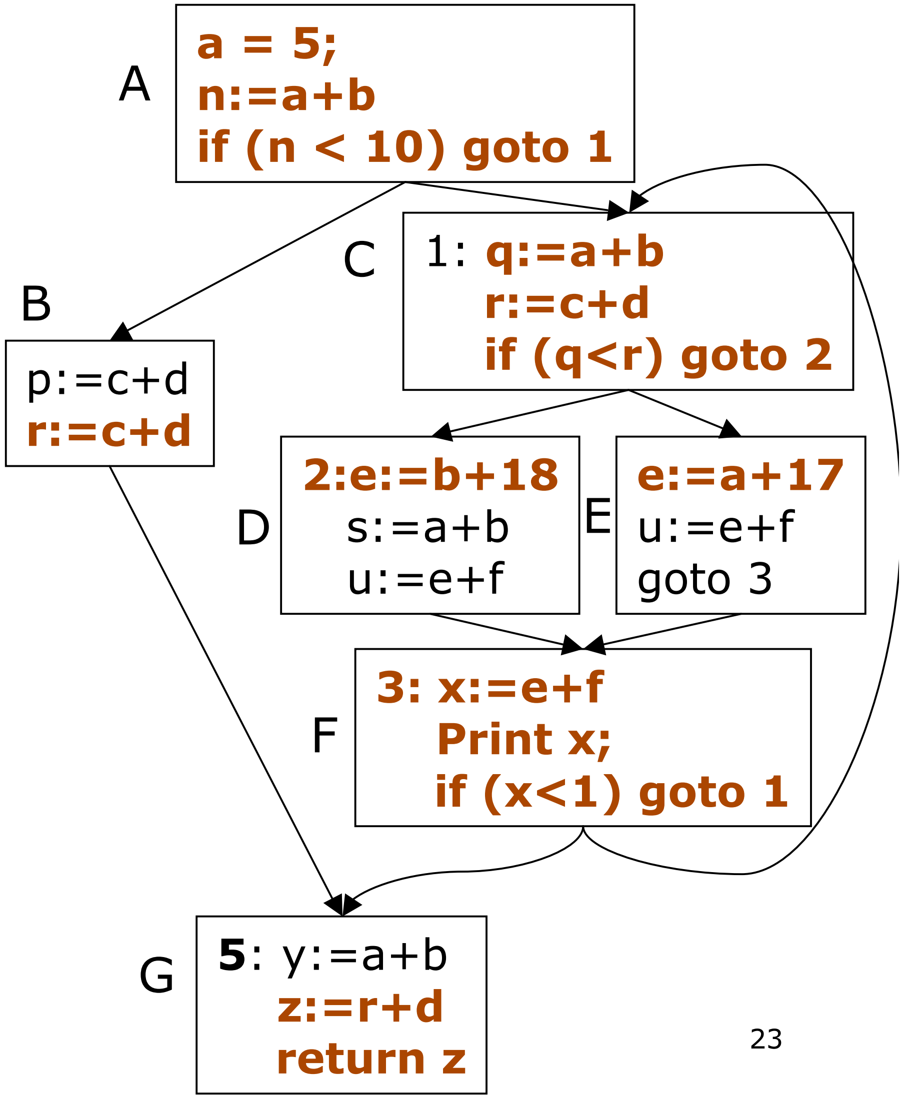
C
1: q:=a+b
r:=c+d
if (q<r) goto 2

D
2:e:=b+18
s:=a+b
u:=e+f

E
e:=a+17
u:=e+f
goto 3

F
3:x:=e+f
Print x;
if (x<1) goto 1

G
5: y:=a+b
z:=r+d
return z



A
a = 5;
n:=a+b
if (n < 10) goto 1

B
p:=c+d
r:=c+d

C
1: **q:=a+b**
r:=c+d
if (q<r) goto 2

D
2:e:=b+18
s:=a+b
u:=e+f

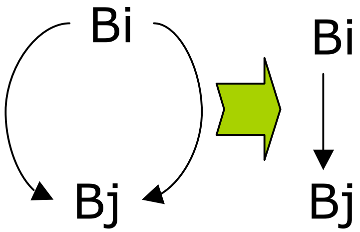
E
e:=a+17
u:=e+f
goto 3

F
3: x:=e+f
Print x;
if (x<1) goto 1

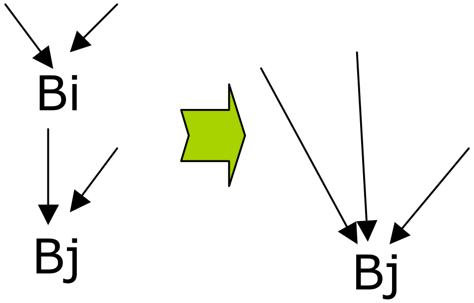
G
5: y:=a+b
z:=r+d
return z

Eliminating useless control flow

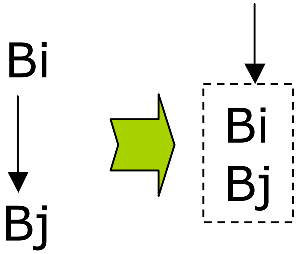
- Optimizations may introduction superfluous control flow
  - Eg., SSA conversion that breaks CFG edges



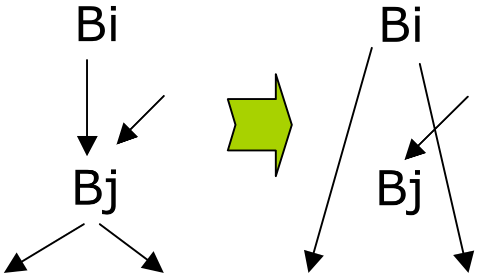
(1) Folding redundant branch



(2) Removing an empty block



(3) Combining blocks



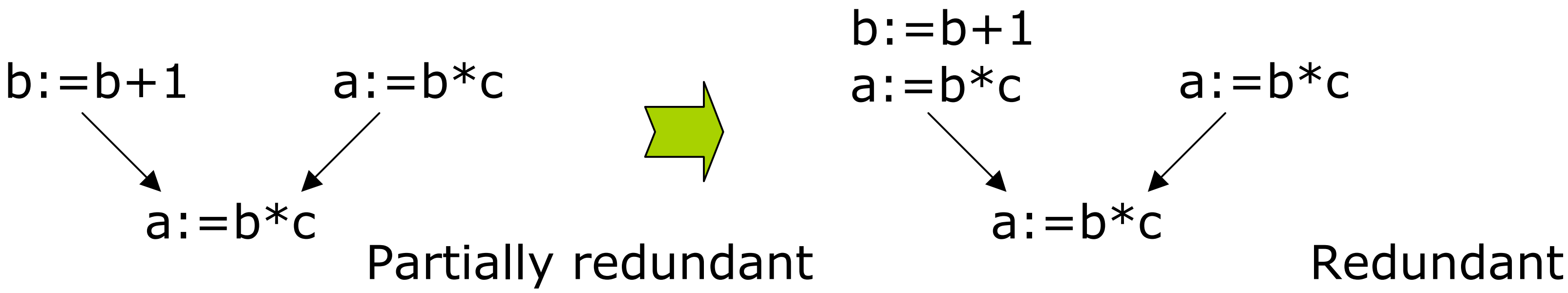
(4) Hoisting a branch

Exercise:
Useless Code Elimination

```
int A[100];
void fee(int x, int y)
{
int I = 0, j = i;
int z = x + y, h =0;
while (I < 100) {
   I = I + 1;
   if (y < x) j = z + y;
   h = x + y;
   A[I] = x + y;
}
return;
}
```

Lazy code motion

- Move partially redundant code to less-frequently executed regions
  - Eg., move loop invariant code outside of loops



b:=b+1

a:=b*c

a:=b*c

Partially redundant

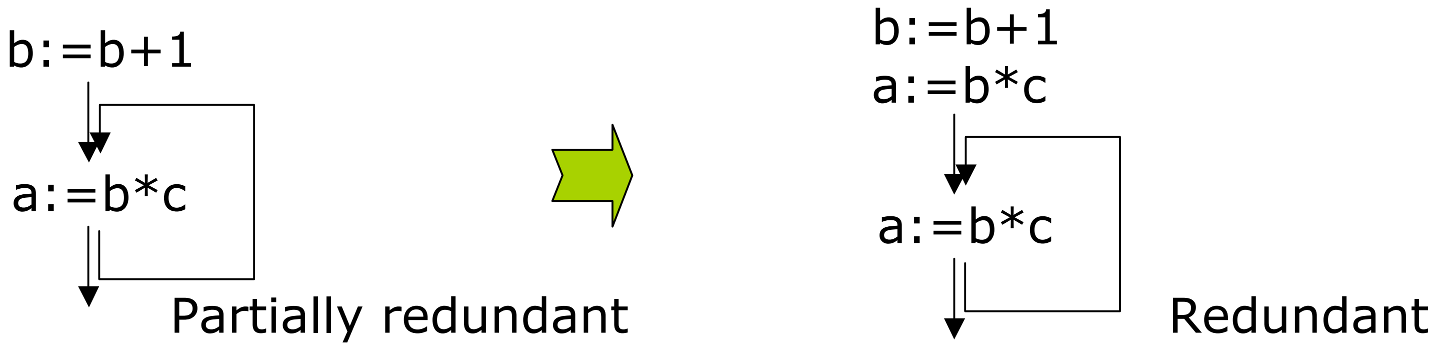
b:=b+1

a:=b*c

a:=b*c

a:=b*c

Redundant



b:=b+1

a:=b*c

Partially redundant

b:=b+1

a:=b*c

a:=b*c

Redundant

Lazy code motion --- algorithm

- Compute available expressions at the entry and exit of each basic block n
  - Expressions that can be safely moved forward along edges to n
  - Forward data flow analysis
- Compute anticipatable expressions at the entry and exit of each basic block
  - Expressions that can be safely moved backward along CFG edges to n
  - Backward dataflow analysis
- Compute the placement of expressions
  - Each CFG edge is annotated as the earliest location for placing a set of expressions (to be inserted into the edge)
  - Some expressions may be moved to later nodes (to be removed)
- Compute insertion and deletion sets
  - Insert expressions to CFG edges and remove expressions from CFG nodes

Availability and anticipatability analysis

Availability analysis: for each basic block n, let

- DEExpr(n)=expressions evaluated by n and available at exit of n
- ExprKill(n)=expressions whose operands are modified by n

expressions available on entry to n and on exit from n

- $\mathrm{AvailIn}(n) = \bigcap_{m \in \mathrm{preds}(n)} \mathrm{AvailOut}(m)$

  $\mathrm{AvailOut}(m) = \mathrm{DEExpr}(m) \cup (\mathrm{AvailIn}(m) - \mathrm{ExprKill}(m))$

Anticipatability analysis: for each basic block n, let

- UEExpr(n)=expressions used in n without redefinition to operands
- ExprKill(n)=expressions whose operands are modified by n

expressions available on entry to n and on exit from n

- $\mathrm{AntOut}(n) = \bigcap_{m \in \mathrm{succ}(n)} \mathrm{AntIn}(m)$

  $\mathrm{AntIn}(m) = \mathrm{UEExpr}(m) \cup (\mathrm{AntOut}(m) - \mathrm{ExprKill}(m))$

Placement of expressions

Earliest placement

- For an edge <bi,bj> in the CFG, an expression e ∈ Earliest(bi,bj) iff the computation can legally move to <bi,bj> and cannot move to any earlier edge

Earliest(bi,bj)=AntIn(bj)-AvailOut(bi)- (AntOut(bi) - ExprKill(bi))

later placement

- Can the earliest placement of an expression be moved forward in CFG without changing expression result?

$$\text{LaterIn}(bj) = \bigcap_{bi \in \text{pred}(bj)} \text{Later}(bi,bj)$$

$$\text{Later}(bi,bj) = \text{Earliest}(bi,bj) \cup (\text{LaterIn}(bi) - \text{UEExpr}(bi))$$

Rewrite the code

Compute insert set

- At each edge (bi,bj), the set of expressions to insert evaluation

  Insert(bi,bj) = Later(bi,bj) – LaterIn(bj)

  - If bi has a single successor, insert at the end of bi
  - If bj has a single predecessor, insert at the entry of bj
  - Otherse, split (bi,bj) and insert a new block

Compute delete set

- At each basic block bi, the set of expressions to delete from bi

  Delete(bi) = UEExpr(bi) – LaterIn(bi)

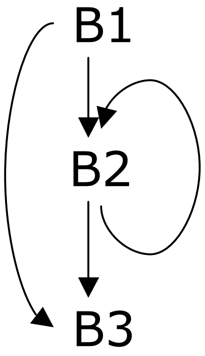
  - If e $\in$ Delete(bi), then the upward-exposed evaluation of e is redundant in bi after all the insertions have been made. Remove all such evaluations with a reference to results of earlier evaluation

Example for lazy code motion

```
B1: loadI 1          => r1
    i2i    r1        => r2
    loadAI r0,@m  => r3
    i2i    r3        =>r4
    cmp_LT r2,r4 => r5
    cbr    r5        => B2,B3
B2: mult r17,r18   => r20
    add  r19, r20 => r21
    i2i    r21       => r8
    addI  r2, 1     => r6
    i2i    r6        => r2
    cmp_GT  r2, r4 => r7
    cbr  r7     => B3,B2
B3: ……
```

Set of expressions:
r1, r3, r5, r6, r7, r20, r21

CFG:

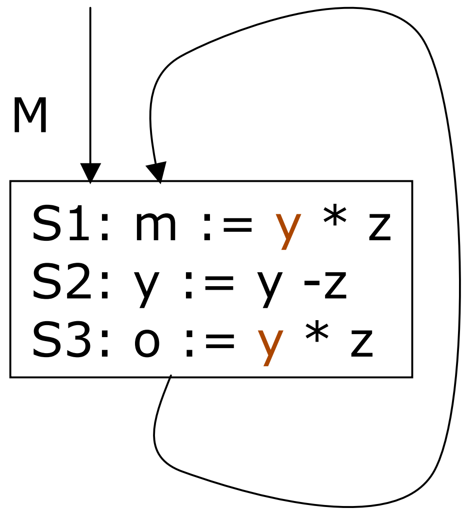


Summary
Machine independent optimizations

- Eliminate redundancy
  - redundant expression elimination
- Specialize computation
  - Constant propagation, peephole optimization
- Eliminate useless and unreachable code
  - Dead code elimination
- Move operations to less-frequently executed places
  - Loop invariant code motion
- Enable other transformations
  - Inlining, cloning, loop unrolling

Appendix: Available Expression Analysis: Compute local sets

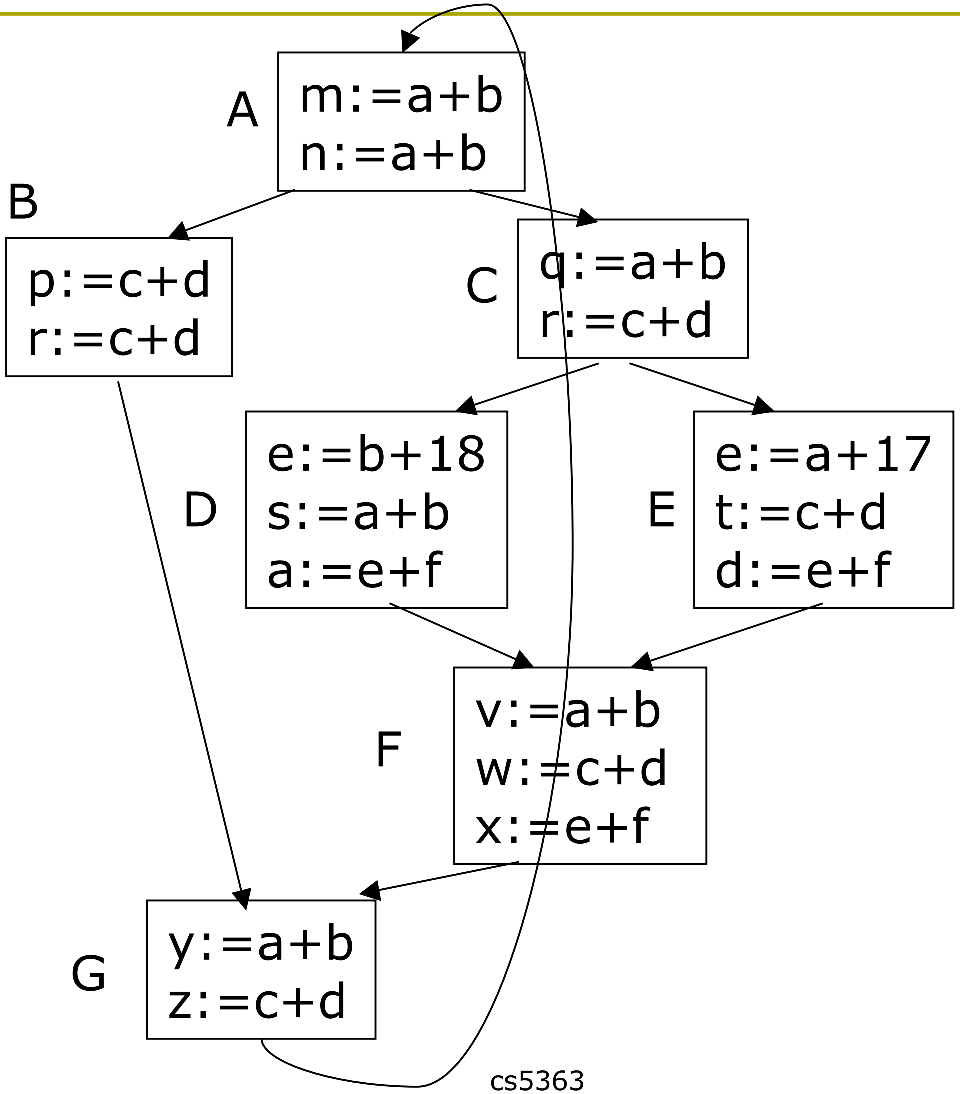
for each basic block n:S1;S2;S3;…;Sk



S1: m := y * z
S2: y := y -z
S3: o := y * z

```
VarKill := $\emptyset$
DEExpr(n) := $\emptyset$
for i = k to 1
   suppose Si is “x := y op z”
   if y $\notin$ VarKill and z $\notin$ VarKill
         DEExpr(n) = DEExpr(n) $\cup$ {y op z}
   VarKill = VarKill $\cup$ {x}
ExprKill(n) := $\emptyset$
for each expression e in the procedure
   for each variable v $\in$ e
       if v $\in$ VarKill then
             ExprKill(n) := ExprKill(n) $\cup$ {e}
```

Appendix: Example: applying GRE



A
m:=a+b
n:=a+b

B
p:=c+d
r:=c+d

C
q:=a+b
r:=c+d

D
e:=b+18
s:=a+b
a:=e+f

E
e:=a+17
t:=c+d
d:=e+f

F
v:=a+b
w:=c+d
x:=e+f

G
y:=a+b
z:=c+d