EECS 583 – Class 6
Dataflow Analysis

University of Michigan

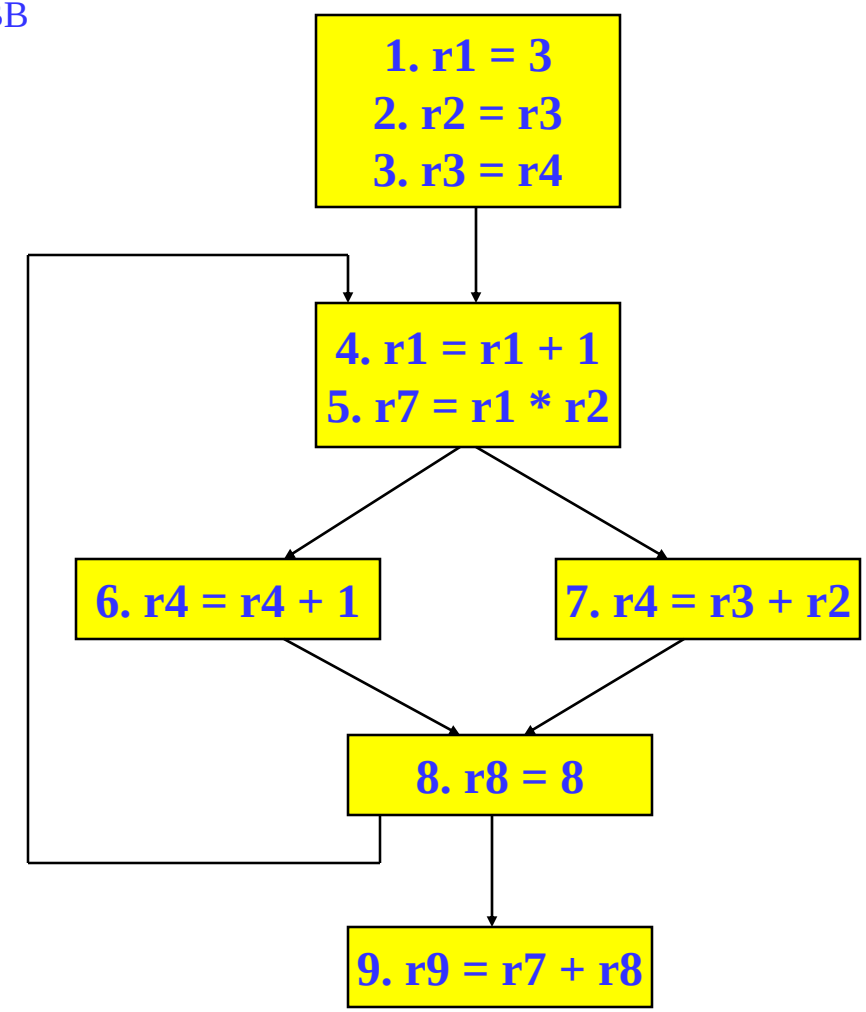
September 20, 2021

Announcements & Reading Material

- HW 2 is posted, Due Fri Oct 8, midnight
  - Please start early, significantly harder than HW 1
  - Take a look at the template code
  - Yunjie will discuss at the end of today's class
- Today's class
  - *Compilers: Principles, Techniques, and Tools*, A. Aho, R. Sethi, and J. Ullman, Addison-Wesley, 1988. (Sections: 10.5, 10.6, 10.9, 10.10 Edition 1; 9.2, 9.3 Edition 2)
- Material for Wednesday
  - "Practical Improvements to the Construction and Destruction of Static Single Assignment Form," P. Briggs, K. Cooper, T. Harvey, and L. Simpson, *Software--Practice and Experience*, 28(8), July 1998, pp. 859-891.

From Last Time: Liveness Homework Problem

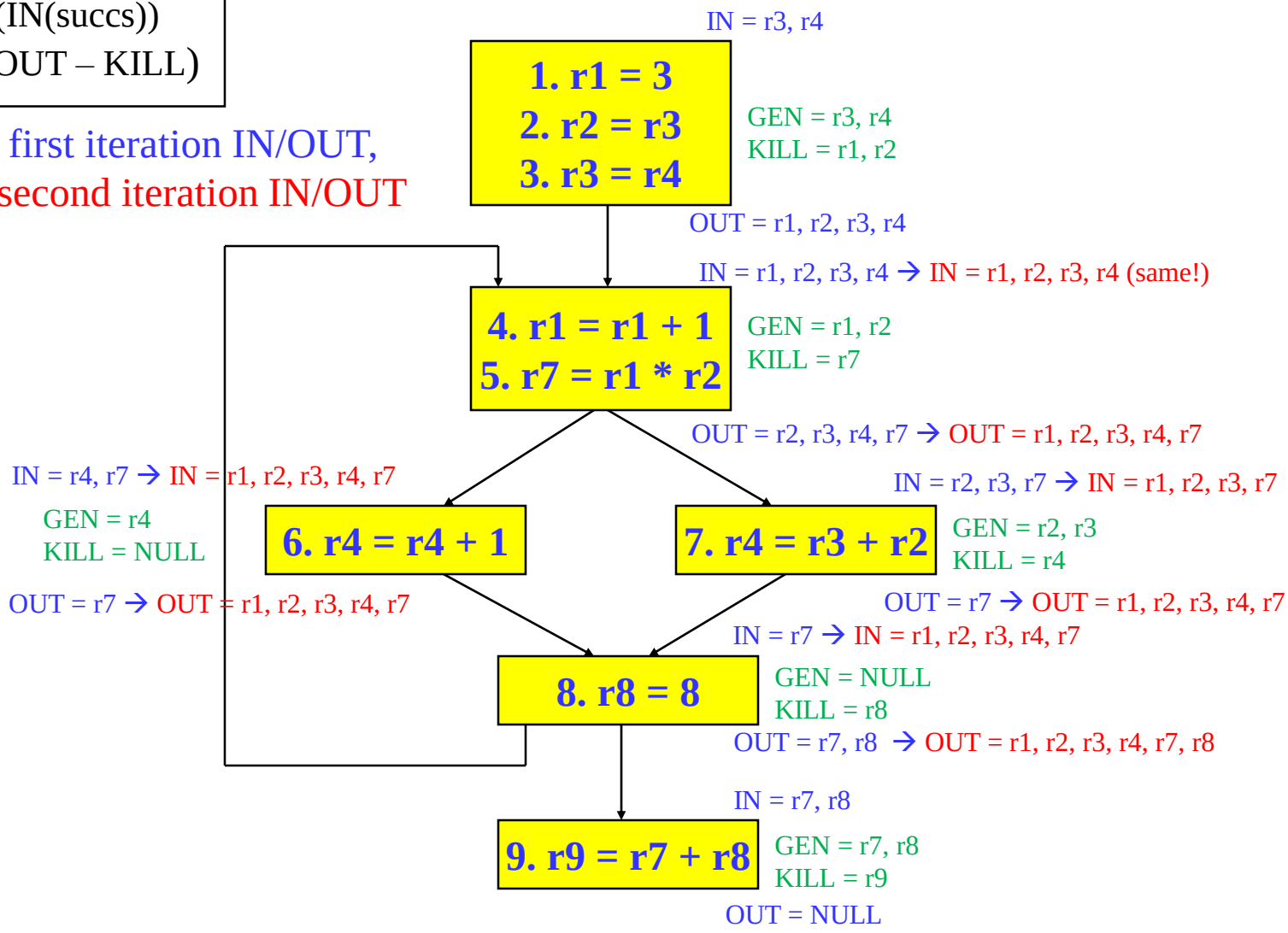
Compute liveness
- Calculate GEN/KILL for each BB
- Calculate IN/OUT for each BB



Liveness Homework Problem Answer

OUT = Union(IN(succs))
IN = GEN + (OUT – KILL)

Blue sets are the first iteration IN/OUT,
Red sets are the second iteration IN/OUT



Reaching Definition Analysis (rdefs)

- A definition of a variable x is an operation that assigns, or may assign, a value to x
- A definition d reaches a point p if there is a path from the point immediately following d to p such that d is not "killed" along that path
- A definition of a variable is killed between 2 points when there is another definition of that variable along the path
  - r1 = r2 + r3 kills previous definitions of r1
- Liveness vs Reaching defs
  - Liveness → variables (e.g., virtual registers), don't care about specific users
  - Reaching defs → operations, each def is different
  - Forward dataflow analysis as propagation occurs from defs downwards (liveness was backward analysis)

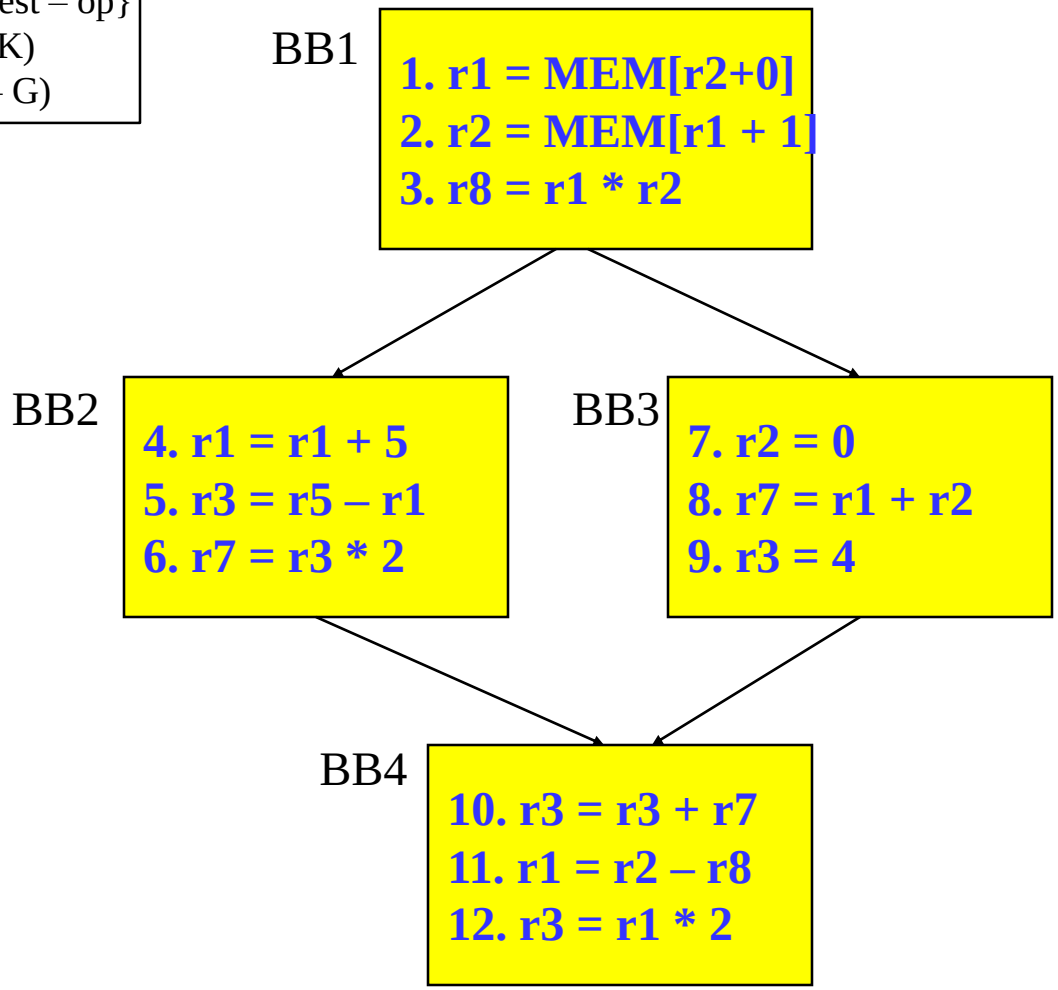
Compute Rdef GEN/KILL Sets for each BB

GEN = set of definitions created by an operation
KILL = set of definitions destroyed by an operation
- Assume each operation only has 1 destination for simplicity
  so just keep track of "ops"..

```
for each basic block in the procedure, X, do
    GEN(X) = 0
    KILL(X) = 0
    for each operation in sequential order in X, op, do
        for each destination operand of op, dest, do
            G = op
            K = {all ops which define dest – op}
            GEN(X) = G + (GEN(X) – K)
            KILL(X) = K + (KILL(X) – G)
        endfor
    endfor
endwhile
```

Example GEN/KILL Rdef Calculation

G = op
K = {all ops which define dest – op}
GEN(X) = G + (GEN(X) – K)
KILL(X) = K + (KILL(X) – G)



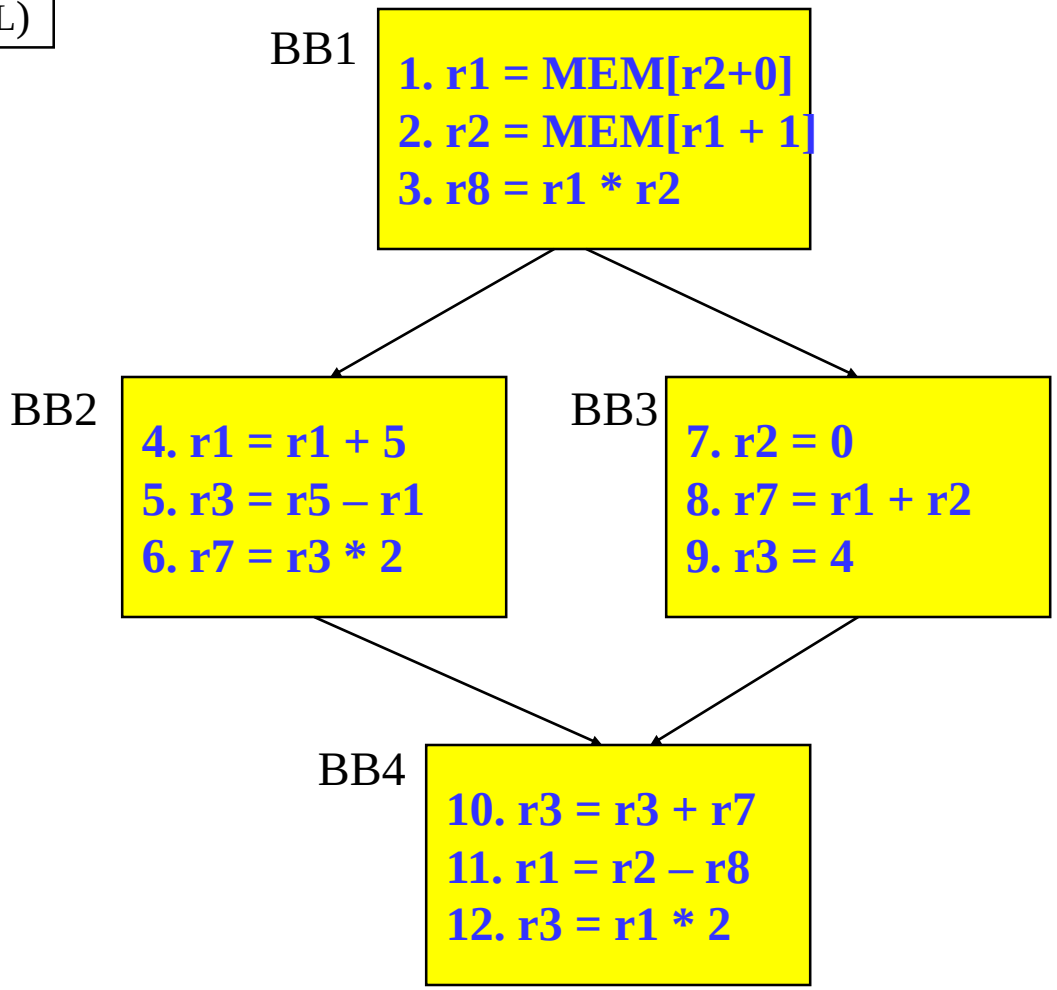
Compute Rdef IN/OUT Sets for all BBs

IN = set of definitions reaching the entry of BB
OUT = set of definitions leaving BB

```
initialize IN(X) = 0 for all basic blocks X
initialize OUT(X) = GEN(X) for all basic blocks X
change = 1
while (change) do
    change = 0
    for each basic block in procedure, X, do
        old_OUT = OUT(X)
        IN(X) = Union(OUT(Y)) for all predecessors Y of X
        OUT(X) = GEN(X) + (IN(X) – KILL(X))
        if (old_OUT != OUT(X)) then
            change = 1
        endif
    endfor
endwhile
```

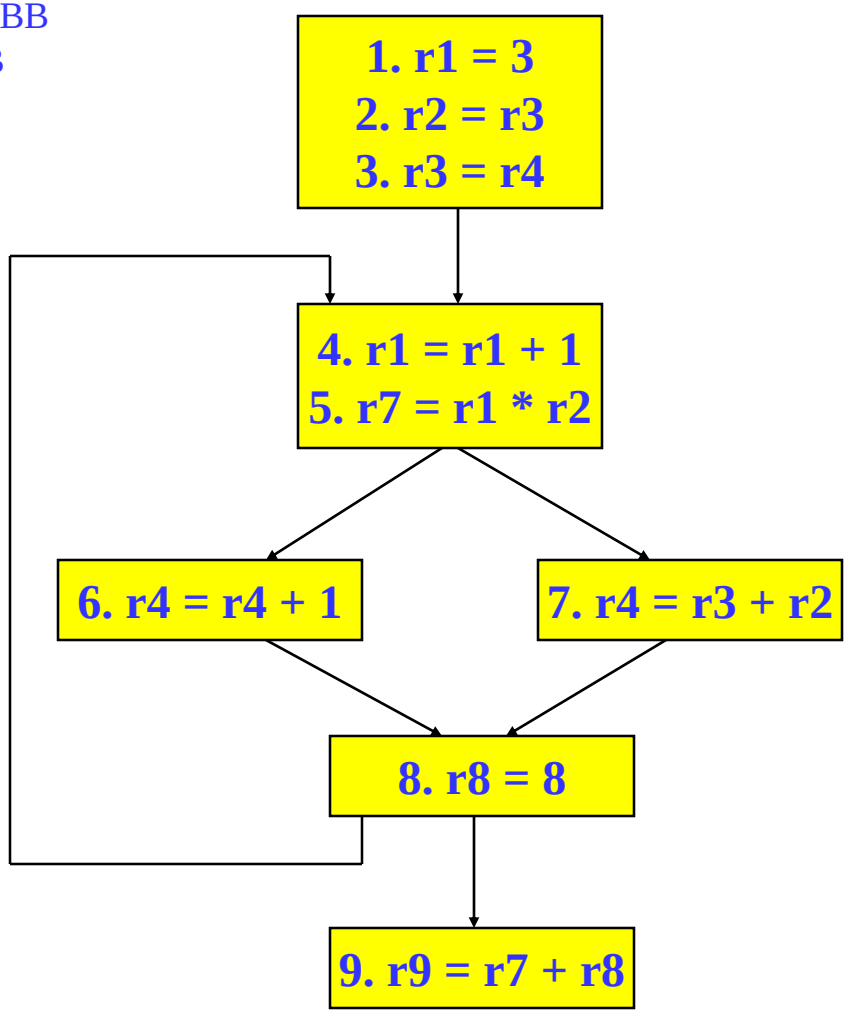
Example Rdef Calculation

IN = Union(OUT(preds))
OUT = GEN + (IN – KILL)

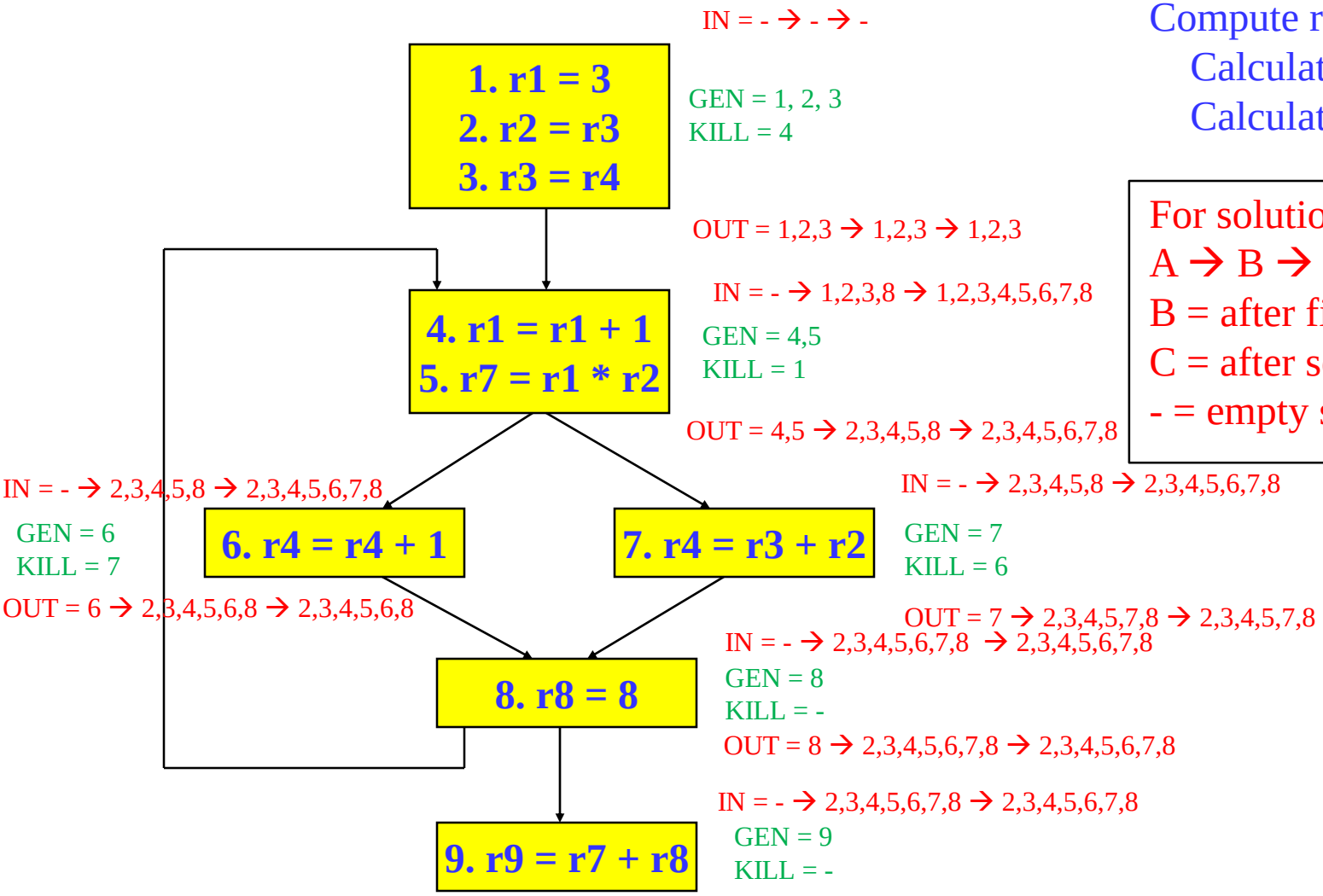


Homework Problem – Answer on Next Slide
Don't look before trying on your own!

Compute reaching defs
- Calculate GEN/KILL for each BB
- Calculate IN/OUT for each BB



Rdefs Homework Problem –**Answer**



Compute reaching defs

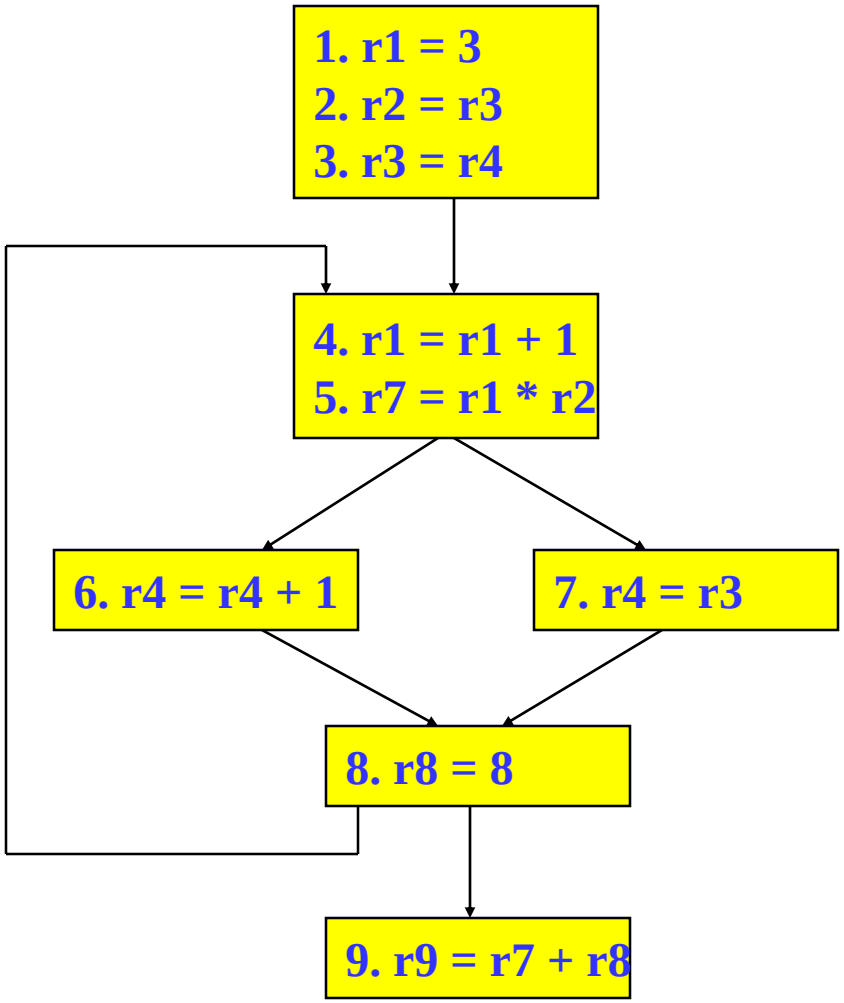
- Calculate GEN/KILL for each BB
- Calculate IN/OUT for each BB

For solution IN/OUT sets specified as A → B → C, A = initial state of sets, B = after first iteration of analysis, C = after second iteration of analysis, - = empty set

DU/UD Chains

- Convenient way to access/use reaching defs info
- Def-Use chains
  - Given a def, what are all the possible consumers of the operand produced
  - Maybe consumer
- Use-Def chains
  - Given a use, what are all the possible producers of the operand consumed
  - Maybe producer

Example – DU/UD Chains



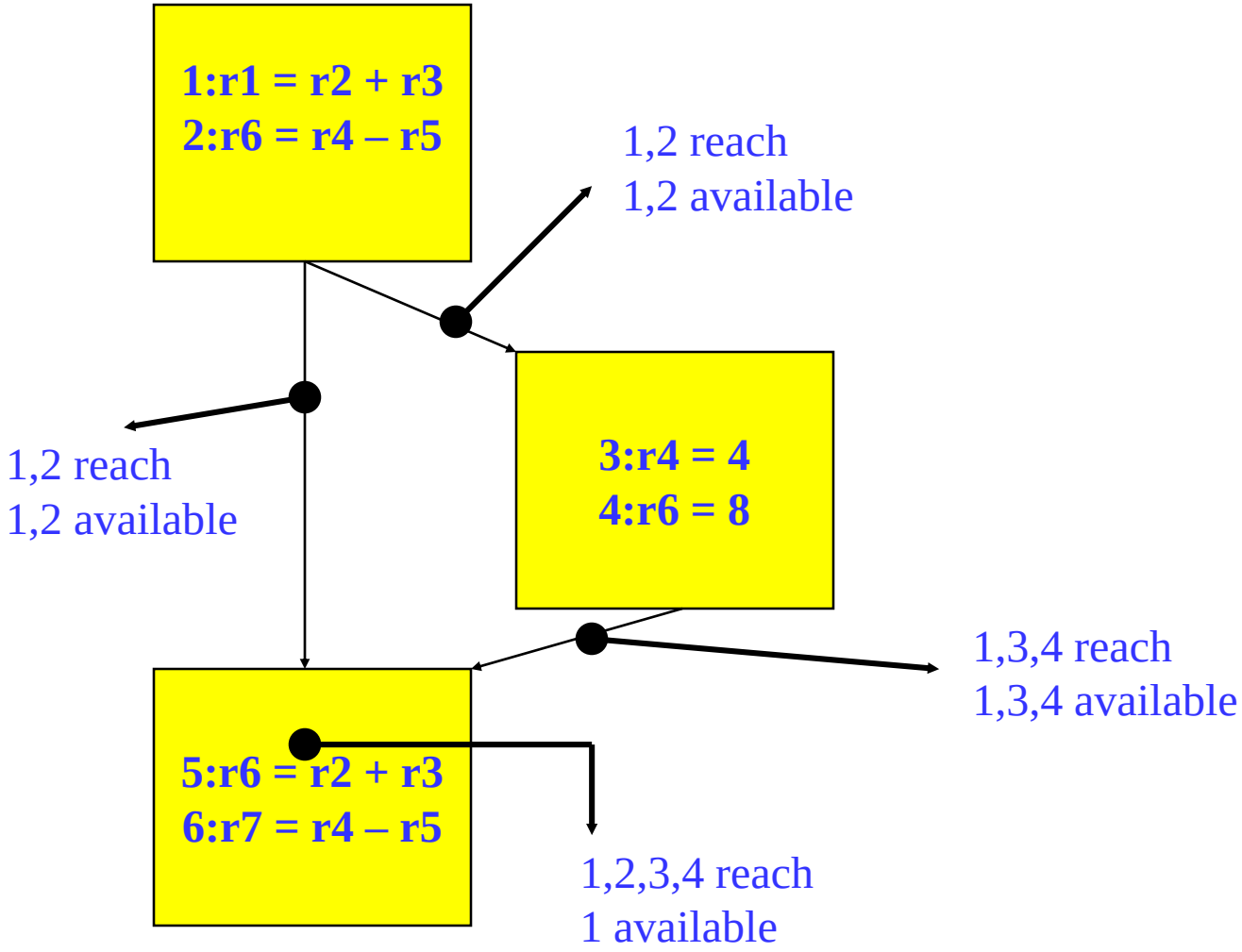
Generalizing Dataflow Analysis

- Transfer function
  - How information is changed by "something" (BB)
  - OUT = GEN + (IN – KILL) /* forward analysis */
  - IN = GEN + (OUT – KILL) /* backward analysis */
- Meet function
  - How information from multiple paths is combined
  - IN = Union(OUT(predecessors)) /* forward analysis */
  - OUT = Union(IN(successors)) /* backward analysis */
- Generalized dataflow algorithm
  - while (change)
    - change = false
    - for each BB
      - apply meet function
      - apply transfer functions
      - if any changes → change = true

What About All Path Problems?

- Up to this point
  - Any path problems (maybe relations)
    - Definition reaches along some path
    - Some sequence of branches in which def reaches
    - Lots of defs of the same variable may reach a point
  - Use of Union operator in meet function
- All-path: Definition guaranteed to reach
  - Regardless of sequence of branches taken, def reaches
  - Can always count on this
  - Only 1 def can be guaranteed to reach
  - Availability (as opposed to reaching)
    - Available definitions
    - Available expressions (could also have reaching expressions, but not that useful)

Reaching vs Available Definitions



Available Definition Analysis (Adefs)

- A definition d is available at a point p if along all paths from d to p, d is not killed
- Remember, a definition of a variable is killed between 2 points when there is another definition of that variable along the path
  - r1 = r2 + r3 kills previous definitions of r1
- Algorithm
  - Forward dataflow analysis as propagation occurs from defs downwards
  - Use the Intersect function as the meet operator to guarantee the all-path requirement
  - GEN/KILL/IN/OUT similar to reaching defs
    - Initialization of IN/OUT is the tricky part

Compute GEN/KILL Sets for each BB (Adefs)

Exactly the same as reaching defs !!!

```
for each basic block in the procedure, X, do
   GEN(X) = 0
   KILL(X) = 0
   for each operation in sequential order in X, op, do
      for each destination operand of op, dest, do
         G = op
         K = {all ops which define dest – op}
         GEN(X) = G + (GEN(X) – K)
         KILL(X) = K + (KILL(X) – G)
      endfor
   endfor
endwhile
```

Compute IN/OUT Sets for all BBs (Adefs)

U = universal set of all operations in the Procedure
IN(0) = 0
OUT(0) = GEN(0)
for each basic block in procedure, W, (W != 0), do
    IN(W) = 0
    OUT(W) = U – KILL(W)

change = 1
while (change) do
    change = 0
    for each basic block in procedure, X, do
        old_OUT = OUT(X)
        IN(X) = **Intersect**(OUT(Y)) for all predecessors Y of X
        OUT(X) = GEN(X) + (IN(X) – KILL(X))
        if (old_OUT != OUT(X)) then
            change = 1
        endif
    endfor
endwhile

Available Expression Analysis (Aexprs)

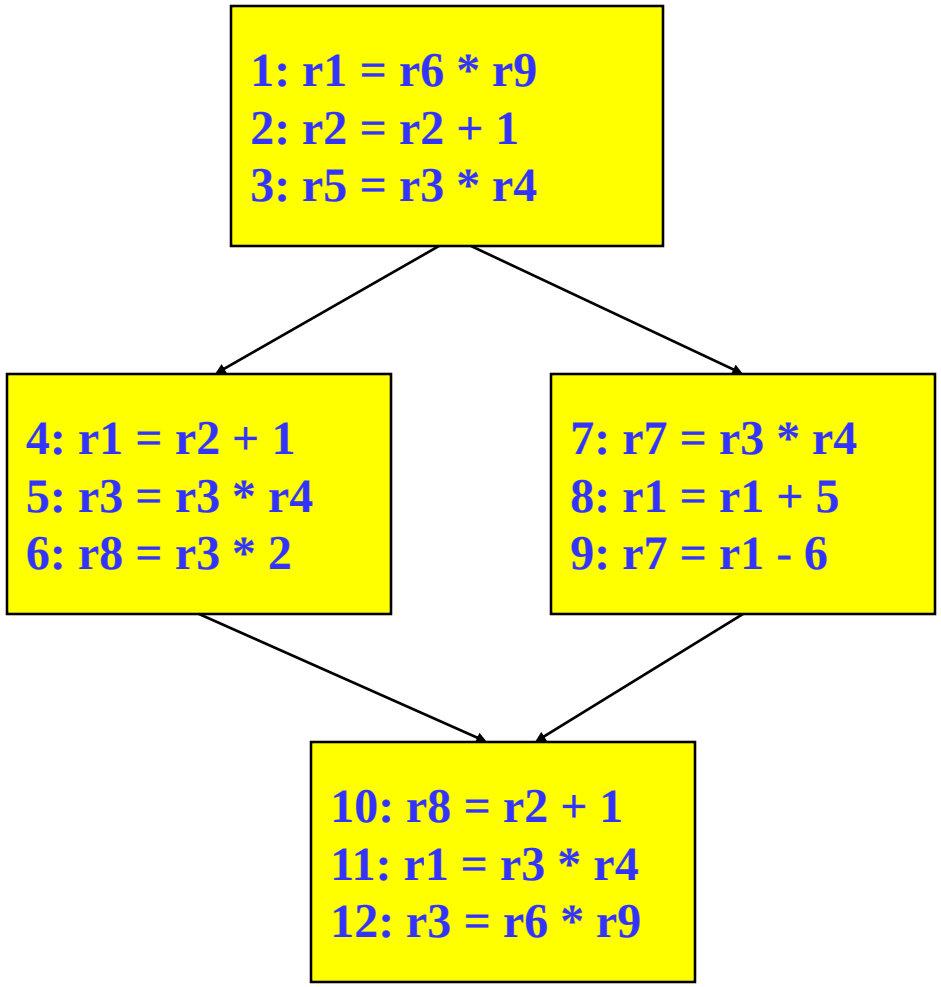
- An expression is a RHS of an operation
  - r2 = r3 + r4, r3+r4 is an expression
- An expression e is available at a point p if along all paths from e to p, e is not killed
- An expression is killed between 2 points when one of its source operands are redefined
  - r1 = r2 + r3 kills all expressions involving r1
- Algorithm
  - Forward dataflow analysis as propagation occurs from defs downwards
  - Use the Intersect function as the meet operator to guarantee the all-path requirement
  - Looks exactly like adefs, except GEN/KILL/IN/OUT are the RHS's of operations rather than the LHS's

Computation of Aexpr GEN/KILL Sets

We can also formulate the GEN/KILL slightly differently so you do not need to break up instructions like "r2 = r2 + 1".

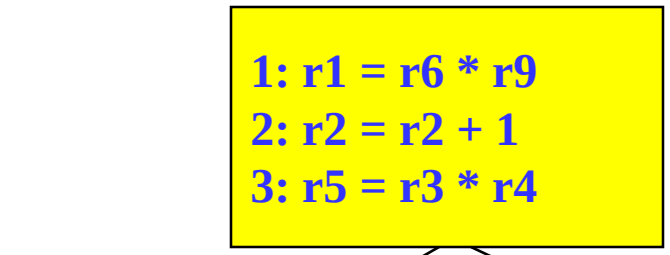
```
for each basic block in the procedure, X, do
   GEN(X) = 0
   KILL(X) = 0
   for each operation in sequential order in X, op, do
      K = 0
      for each destination operand of op, dest, do
         K += {all ops which use dest}
      endfor
      if (op not in K)
            G = op
      else
            G = 0
      GEN(X) = G + (GEN(X) – K)
      KILL(X) = K + (KILL(X) – G)
   endfor
endfor
```

Homework Problem - Aexprs Calculation
Answer on the Next Slide



Homework Problem - Answer

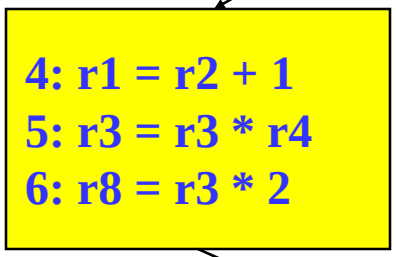
IN/OUT sets
A → B
A = initial state
B = after first iteration



IN = - → -

GEN = 1,3 (remember {1, 3} means {“r6*r9”, “r3*r4”})
KILL = 2, 4, 8, 9, 10

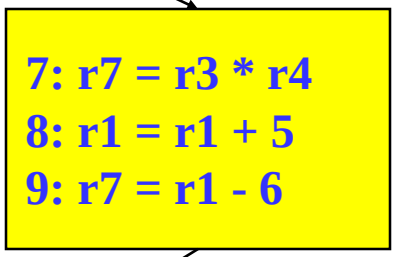
OUT = 1,3,5,6,7,11,12 → 1,3



IN = - → 1,3

GEN = 4, 6
KILL = 3, 5, 7, 8, 9, 11

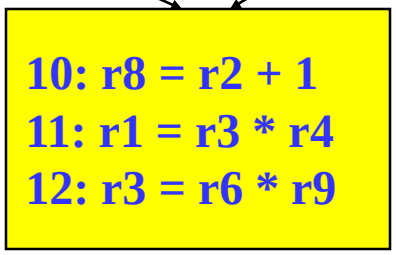
OUT = 1,2,4,6,10,12 → 1,4,6



IN = - → 1,3

GEN = 7, 9
KILL = 8

OUT = 1,2,3,4,5,6,7,9,10,11,12 → 1,3,7,9



IN = - → 1

GEN = 10, 12
KILL = 3, 5, 6, 7, 8, 9, 11

OUT = 1,2,4,10,12 → 1,10,12