EECS 583 – Class 4
If-conversion

University of Michigan

January 24, 2024

Announcements & Reading Material

- HW 1 – Deadline Mon Jan 29, midnight
  - Talk to Aditya/Yunjie this week if you are having troubles
  - Refer to EECS 583 piazza group for tips and answers to questions
  - All should have access to eecs583a/eecs583b servers
- Today's class
  - "The Program Dependence Graph and Its Use in Optimization", J. Ferrante, K. Ottenstein, and J. Warren, ACM TOPLAS, 1987
    - This is a long paper – the part we care about is the control dependence stuff. The PDG is interesting and you should skim it over.
  - "On Predicated Execution", Park and Schlansker, HPL Technical Report, 1991.
- Material for Wednesday
  - *Compilers: Principles, Techniques, and Tools,* A. Aho, R. Sethi, and J. Ullman, Addison-Wesley, 1988. (Sections: 10.5, 10.6 Edition 1) (Sections 9.2 Edition 2)

From Last Time: HPL-PD Compare-to-Predicate Operations (CMPPs)

- How do we compute predicates
  - Compare registers/literals like a branch would do
  - Efficiency, code size, nested conditionals, etc
- 2 targets for computing taken/fall-through conditions with 1 operation

p1, p2 = CMPP.cond.D1a.D2a (r1, r2) if p3

p1 = first destination predicate
p2 = second destination predicate
cond = compare condition (ie EQ, LT, GE, …)
D1a = action specifier for first destination
D2a = action specifier for second destination
(r1,r2) = data inputs to be compared (ie r1 < r2)
p3 = guarding predicate

CMPP Action Specifiers

Guarding predicate	Compare Result	UN	UC	ON	OC	AN	AC
0	0	0	0	-	-	-	-
0	1	0	0	-	-	-	-
1	0	0	1	-	1	0	-
1	1	1	0	1	-	-	0

UN/UC = Unconditional normal/complement

This is what we used in the earlier examples

guard = 0, both outputs are 0

guard = 1, UN = Compare result, UC = opposite

ON/OC = OR-type normal/complement

AN/AC = AND-type normal/complement

OR-type, AND-type Predicates

p1 = 0
p1 = cmpp_ON (r1 < r2) if T
p1 = cmpp_OC (r3 < r4) if T
p1 = cmpp_ON (r5 < r6) if T

p1 = (r1 < r2) | (!(r3 < r4)) |
(r5 < r6)

Wired-OR into p1

Generating predicated code for some source code requires OR-type predicates

p1 = 1
p1 = cmpp_AN (r1 < r2) if T
p1 = cmpp_AC (r3 < r4) if T
p1 = cmpp_AN (r5 < r6) if T

p1 = (r1 < r2) & (!(r3 < r4)) &
(r5 < r6)

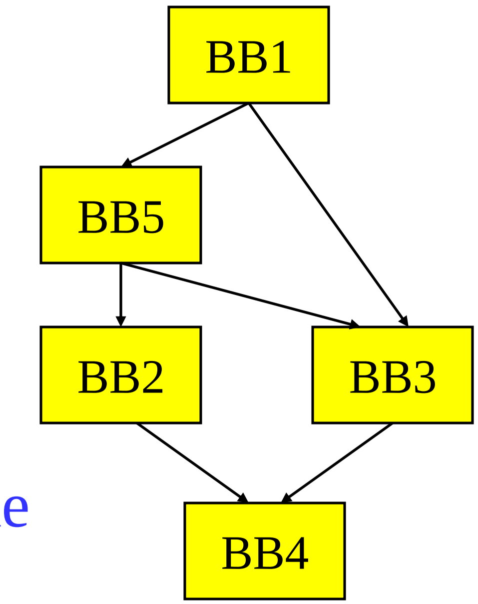
Wired-AND into p1

Talk about these later – used for control height reduction

Use of OR-type Predicates

```
a = b + c
if (a > 0 && b > 0)
    e = f + g
else
    e = f / g
h = i - j
```

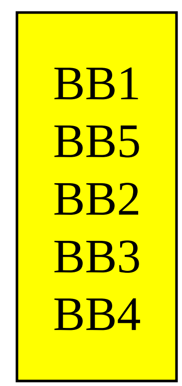
```
BB1    add a, b, c
BB1    ble a, 0, L1
BB5    ble b, 0, L1
BB2    add e, f, g
BB2    jump L2
BB3    L1: div e, f, g
BB4    L2: sub h, i, j
```



Traditional branching code

p2 → BB2
p3 → BB3
p5 → BB5

```
BB1    add a, b, c if T
BB1    p3, p5 = cmpp.ON.UC a <= 0 if T
BB5    p3, p2 = cmpp.ON.UC b <= 0 if p5
BB3    div e, f, g if p3
BB2    add e, f, g if p2
BB4    sub h, i, j if T
```



Predicated code

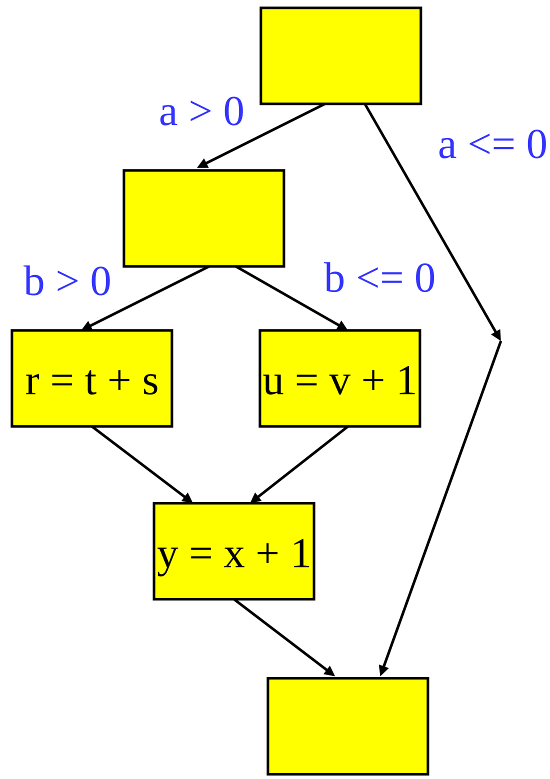
Homework Problem – Answer on next slide but don’t cheat!

```
if (a > 0) {
    if (b > 0)
        r = t + s
    else
        u = v + 1
    y = x + 1
}
```

a. Draw the CFG
b. Predicate the code removing all branches

Homework Problem Answer

```
if (a > 0) {
    if (b > 0)
        r = t + s
    else
        u = v + 1
    y = x + 1
}
```



p1 = cmpp.UN(a > 0) if T
p2, p3 = cmpp.UNUC(b > 0) if p1
r = t + s if p2
u = v + 1 if p3
y = x + 1 if p1

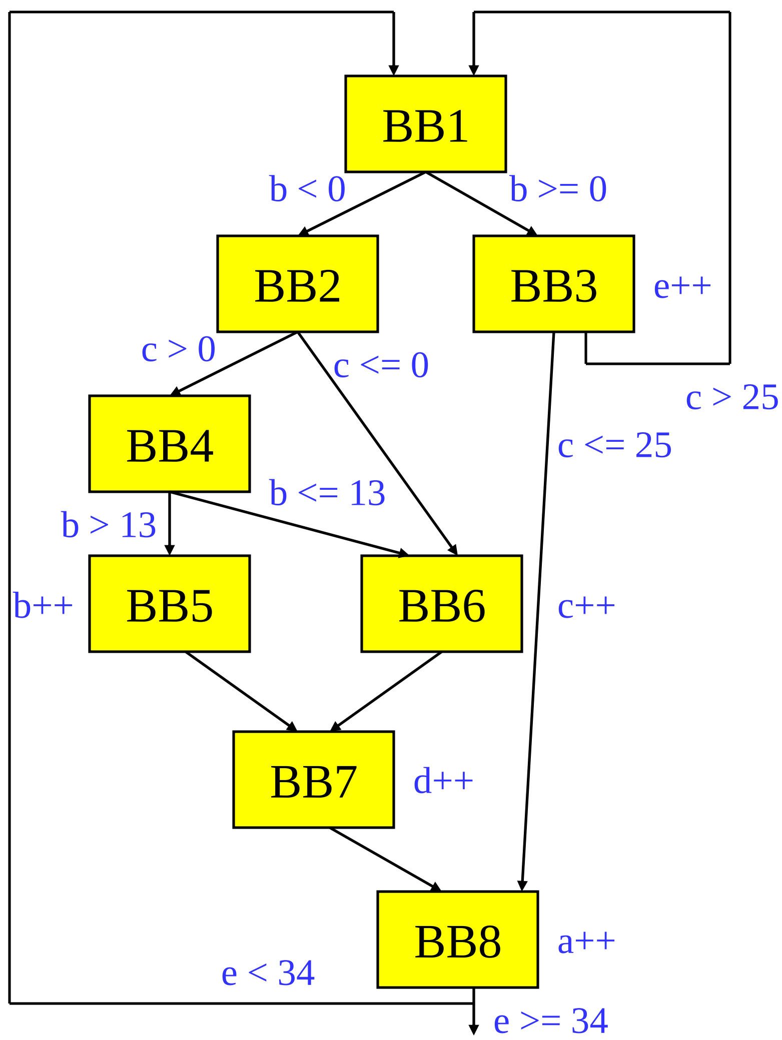
a. Draw the CFG
b. Predicate the code removing all branches

If-conversion

- Algorithm for generating predicated code
  - Automate what we've been doing by hand
  - Handle arbitrary complex graphs
    - But, acyclic subgraph only!!
    - Need a branch to get you back to the top of a loop
  - Efficient
- Roots are from Vector computer days
  - Vectorize a loop with an if-statement in the body
- 4 steps
  - 1. Loop backedge coalescing
  - 2. Control dependence analysis
  - 3. Control flow substitution
  - 4. CMPP compaction
- My version of Park & Schlansker

Running Example – Initial State

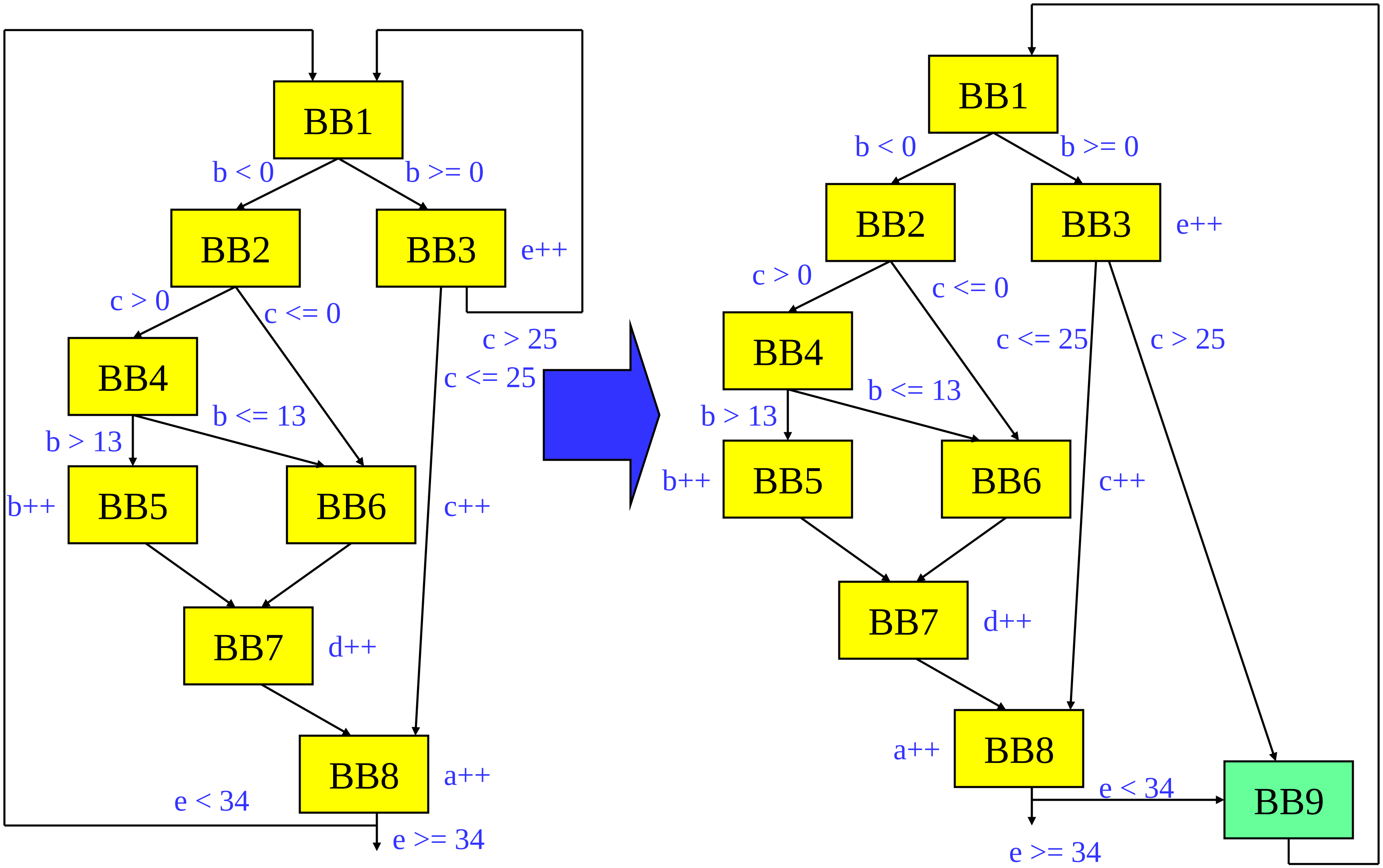
```
do {
    b = load(a)
    if (b < 0) {
        if ((c > 0) && (b > 13))
            b = b + 1
        else
            c = c + 1
        d = d + 1
    }
    else {
        e = e + 1
        if (c > 25) continue
    }
    a = a + 1
} while (e < 34)
```



Step 1: Backedge Coalescing

- Recall – Loop backedge is branch from inside the loop back to the loop header
- This step only applicable for a loop body
  - If not a loop body → skip this step
- Process
  - Create a new basic block
    - New BB contains an unconditional branch to the loop header
  - Adjust all other backedges to go to new BB rather than header
- Why do this?
  - Heuristic step – Not essential for correctness
    - If-conversion cannot remove backedges (only forward edges)
    - But this allows the control logic to figure out which backedge you take to be eliminated
  - Generally this is a good thing to do

Running Example – Backedge Coalescing



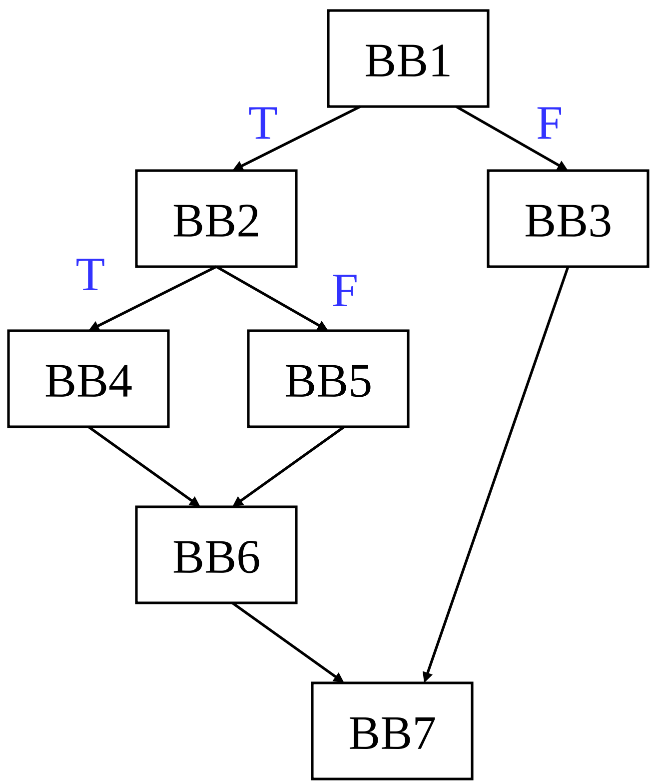
Step 2: Control Dependence Analysis (CD)

- Control flow – Execution transfer from 1 BB to another via a taken branch or fallthrough path
- Dependence – Ordering constraint between 2 operations
  - Must execute in proper order to achieve the correct result
  - O1: a = b + c
  - O2: d = a – e
  - O2 dependent on O1
- Control dependence – One operation controls the execution of another
  - O1: blt a, 0, SKIP
  - O2: b = c + d
  - SKIP:
  - O2 control dependent on O1
- Control dependence analysis derives these dependences

Control Dependences

- Recall
  - Post dominator – BBX is post dominated by BBY if every path from BBX to EXIT contains BBY
  - Immediate post dominator – First breadth first successor of a block that is a post dominator
- Control dependence – BBY is control dependent on BBX iff
  - 1. There exists a directed path P from BBX to BBY with any BBZ in P (excluding BBX and BBY) post dominated by BBY
  - 2. BBX is not post dominated by BBY
- In English,
  - A BB is control dependent on the closest BB(s) that determine(s) its execution
  - Its actually not a BB, it’s a control flow edge coming out of a BB

Control Dependence Example



Control dependences

BB1:

BB2:

BB3:

BB4:

BB5:

BB6:

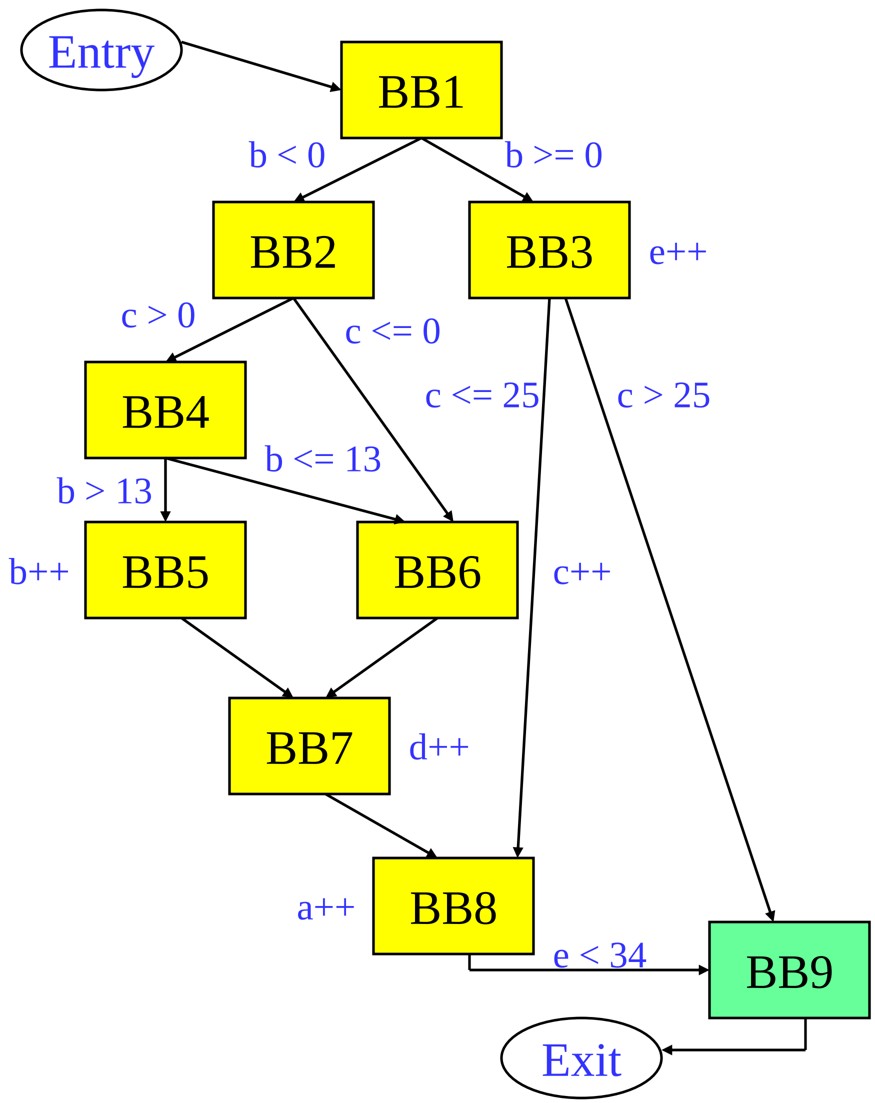
BB7:

Notation

positive BB number = fallthru direction

negative BB number = taken direction

Running Example – CDs



First, nuke backedge(s)
Second, nuke exit edges
Then, Add pseudo entry/exit nodes
- Entry → nodes with no predecessors
- Exit → nodes with no successors

<u>Control deps (left is taken)</u>

BB1:
BB2:
BB3:
BB4:
BB5:
BB6:
BB7:
BB8:
BB9:

Algorithm for Control Dependence Analysis

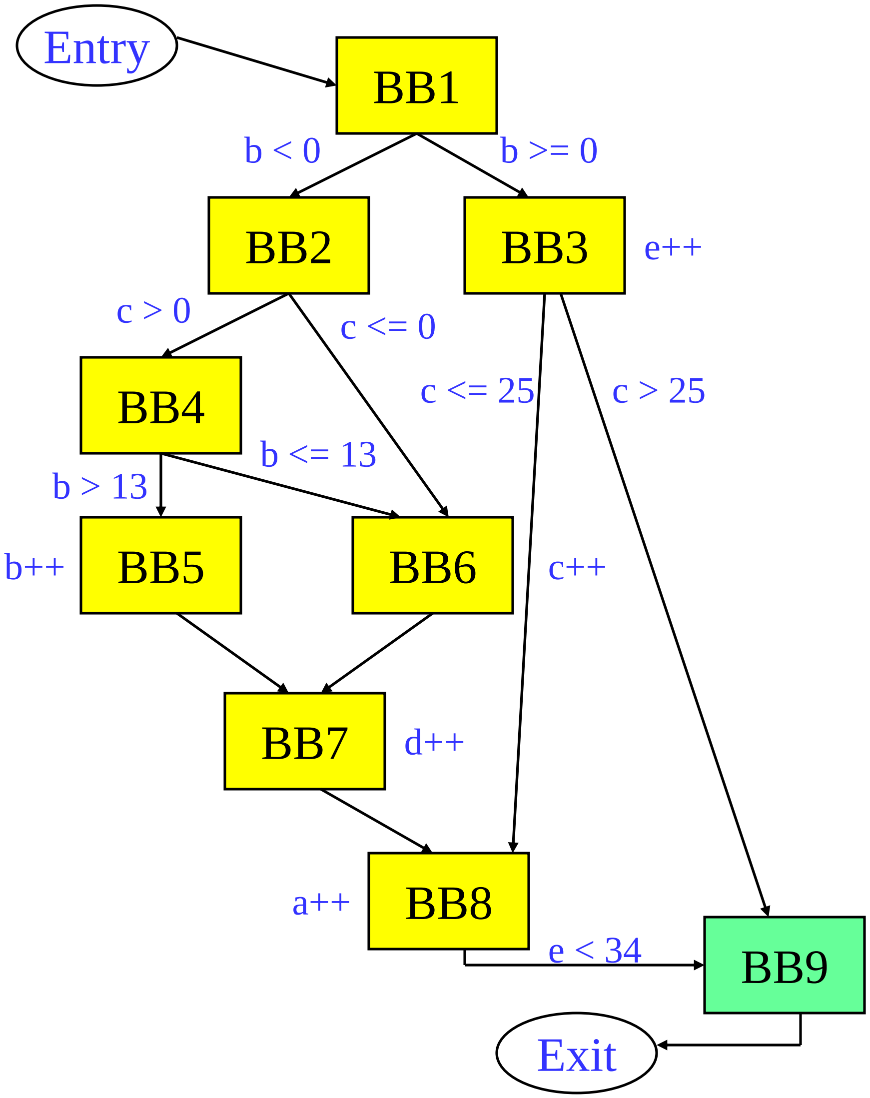
```
for each basic block x in region
    for each outgoing control flow edge e of x
        y = destination basic block of e
        if (y not in pdom(x)) then
            lub = ipdom(x)
            if (e corresponds to a taken branch) then
                x_id = -x.id
            else
                x_id = x.id
            endif
            t = y
            while (t != lub) do
                cd(t) += x_id;
                t = ipdom(t)
            endwhile
        endif
    endfor
endfor
```

Notes

Compute cd(x) which contains those BBs which x is control dependent on

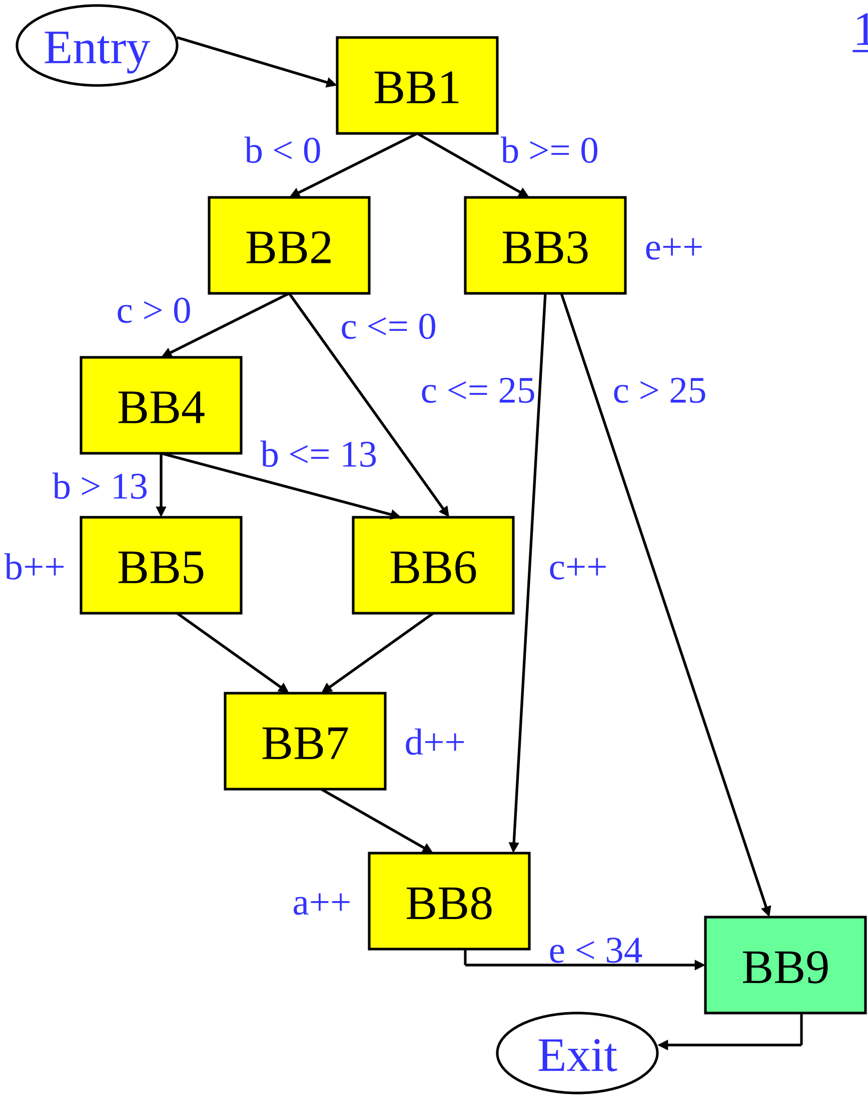
Iterate on per edge basis, adding edge to each cd set it is a member of

Running Example – Post Dominators



	pdom	ipdom
BB1:	1, 9, ex	9
BB2:	2, 7, 8, 9, ex	7
BB3:	3, 9, ex	9
BB4:	4, 7, 8, 9, ex	7
BB5:	5, 7, 8, 9, ex	7
BB6:	6, 7, 8, 9, ex	7
BB7:	7, 8, 9, ex	8
BB8:	8, 9, ex	9
BB9:	9, ex	ex

Running Example – CDs Via Algorithm



1 → 2 edge (aka –1)

x = 1
e = taken edge 1 → 2
y = 2
y not in pdom(x)
lub = 9
x_id = -1
t = 2

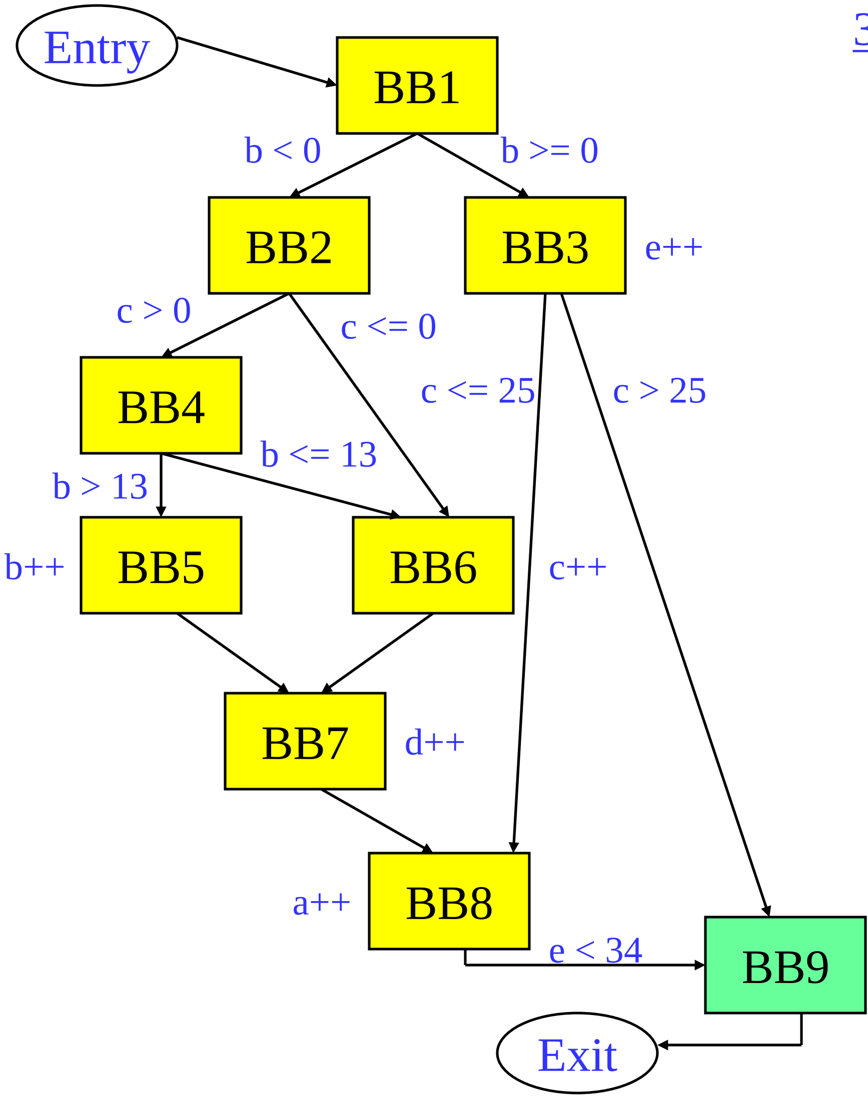
2 != 9
cd(2) += -1
t = 7

7 != 9
cd(7) += -1
t = 8

8 != 9
cd(8) += -1
t = 9

9 == 9

Running Example – CDs Via Algorithm (2)



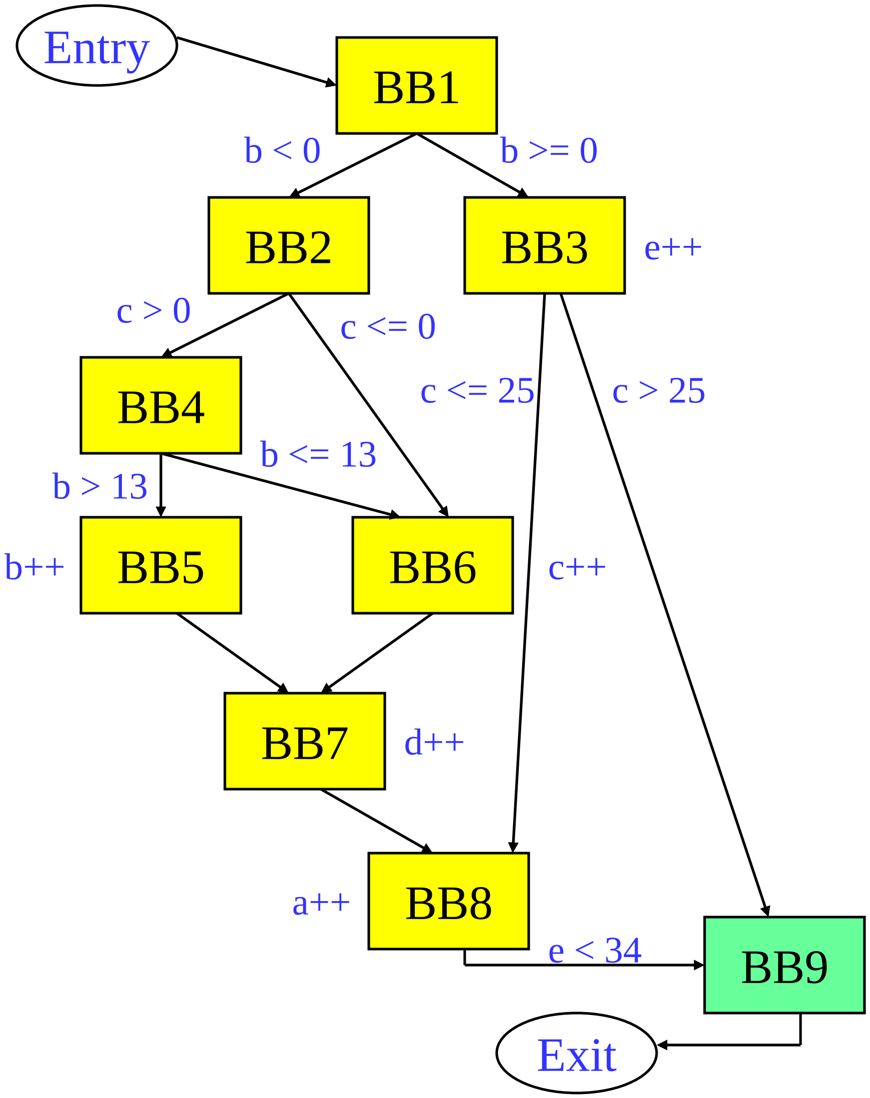
<u>3 → 8 edge (aka -3)</u>

x = 3
e = taken edge 3 → 8
y = 8
y not in pdom(x)
lub = 9
x_id = -3
t = 8

8 != 9 cd(8) += -3 t = 9
9 == 9

<u>Class ProblemA: 1 → 3 edge (aka 1)</u>
<u>Class ProblemB: 7 → 8 edge (aka -7)</u>

Running Example – CDs Via Algorithm (3)



Control deps (left is taken)

BB1: none
BB2: -1
BB3: 1
BB4: -2
BB5: -4
BB6: 2, 4
BB7: -1
BB8: -1, -3
BB9: none

Step 3: Control Flow Substitution

- Go from branching code → sequential predicated code
- 5 baby steps
  - 1. Create predicates
  - 2. CMPP insertion
  - 3. Guard operations
  - 4. Remove branches
  - 5. Initialize predicates

Predicate Creation

- R/K calculation – Mapping predicates to blocks
  - Paper more complicated than it really is
  - K = unique sets of control dependences
  - Create a new predicate for each element of K
  - R(bb) = predicate that represents CD set for bb, ie the bb's assigned predicate (all ops in that bb guarded by R(bb))

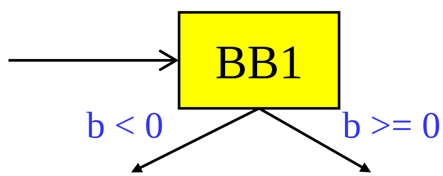
K	=	{{-1},	{1},	{-2},	{-4},	{2,4},	{-1,-3}}			
predicates	=	p1,	p2,	p3,	p4,	p5,	p6			
bb	=	1,	2,	3,	4,	5,	6,	7,	8,	9
CD(bb)	=	{{none},	{-1},	{1},	{-2},	{-4},	{2,4},	{-1},	{-1,-3},	{none}
R(bb)	=	T	p1	p2	p3	p4	p5	p1	p6	T

CMPP Creation/Insertion

- For each control dependence set
  - For each edge in the control dependence set
    - Identify branch condition that causes edge to be traversed
    - Create CMPP to compute corresponding branch condition
      - OR-type – handles worst case
      - guard = True
      - destination = predicate assigned to that CD set
      - Insert at end of BB that is the source of the edge

K = {{-1}, {1}, {-2}, {-4}, {2,4}, {-1,-3}}
predicates = p1, p2, p3, p4, p5, p6

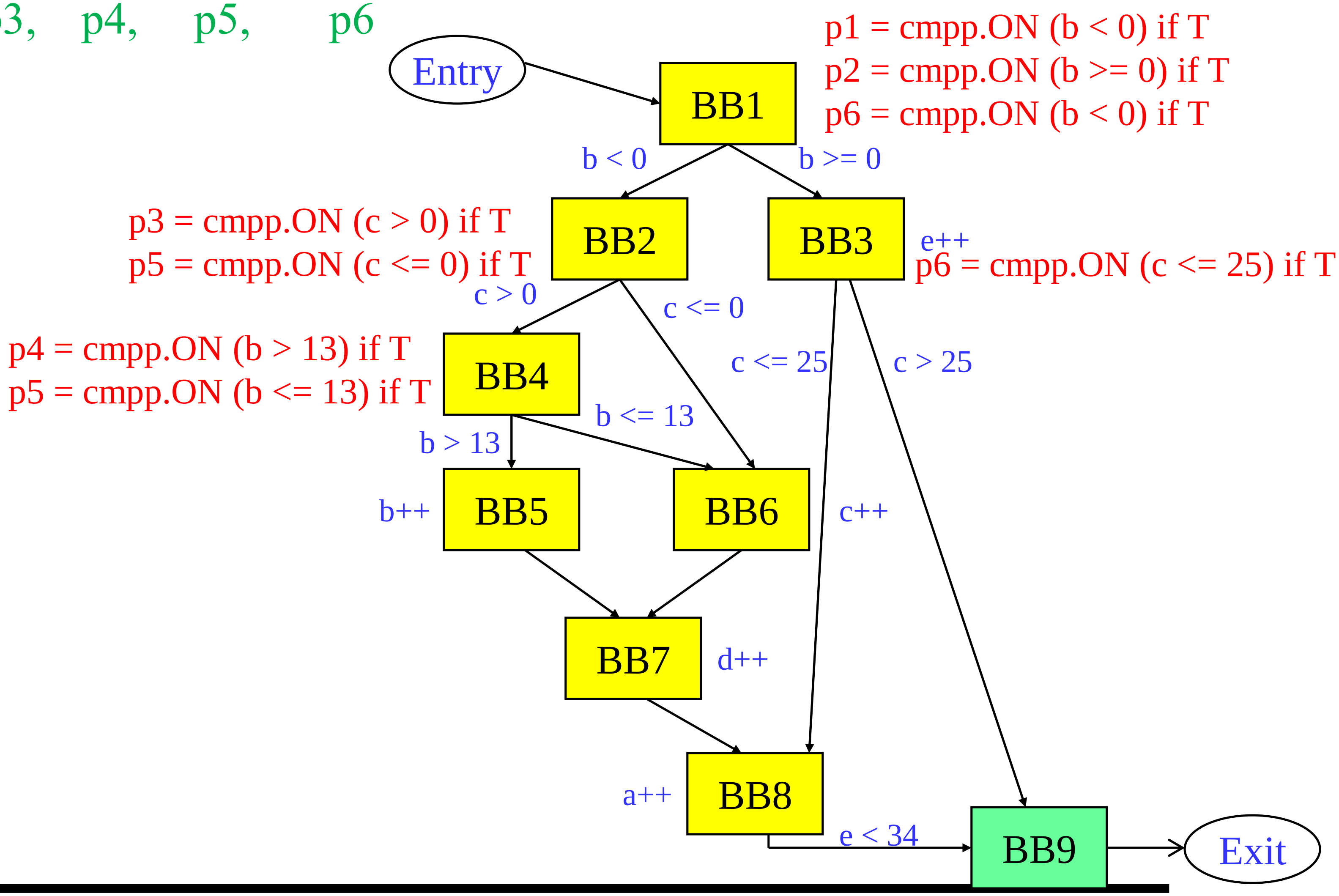
Example: p1 = cmpp.ON (b < 0) if T



Running Example – CMPP Creation

K = {{-1}, {1}, {-2}, {-4}, {2,4}, {-1,-3}}

p's = p1, p2, p3, p4, p5, p6

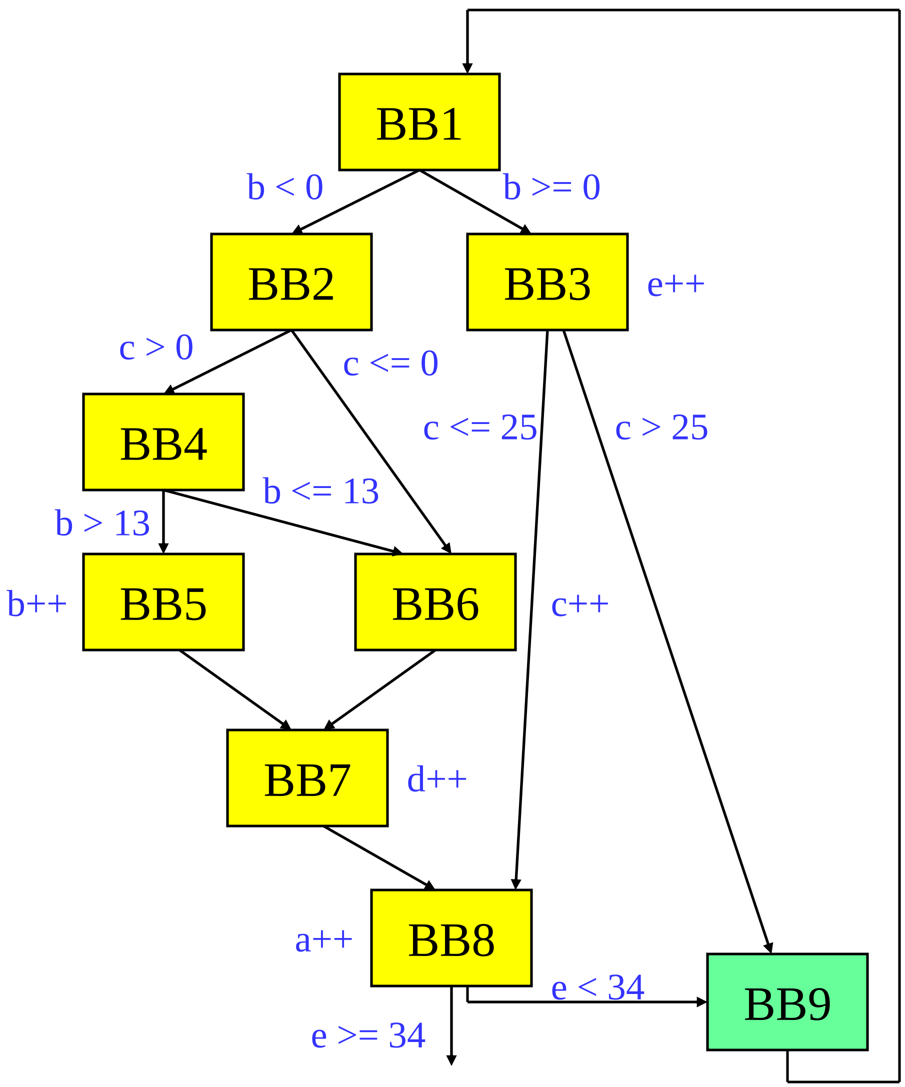


Control Flow Substitution – The Rest

- Guard all operations in each bb by R(bb)
  - Including the newly inserted CMPPs
- Nuke all the branches
  - Except exit edges and backedges
- Initialize each predicate to 0 in first BB

bb	=	1,	2,	3,	4,	5,	6,	7,	8,	9
CD(bb)	=	{{none},	{-1},	{1},	{-2},	{-4},	{2,4},	{-1},	{-1,-3},	{none}}
R(bb)	=	T	p1	p2	p3	p4	p5	p1	p6	T

Running Example – Control Flow Substitution



Loop:
    p1 = p2 = p3 = p4 = p5 = p6 = 0
    b = load(a) if T
    p1 = cmpp.ON (b < 0) if T
    p2 = cmpp.ON (b >= 0) if T
    p6 = cmpp.ON (b < 0) if T
    p3 = cmpp.ON (c > 0) if p1
    p5 = cmpp.ON (c <= 0) if p1
    p4 = cmpp.ON (b > 13) if p3
    p5 = cmpp.ON (b <= 13) if p3
    b = b + 1 if p4
    c = c + 1 if p5
    d = d + 1 if p1
    p6 = cmpp.ON (c <= 25) if p2
    e = e + 1 if p2
    a = a + 1 if p6
    bge e, 34, Done if p6
    jump Loop if T
Done:

Step 4: CMPP Compaction

- Convert ON CMPPs to UN
  - All singly defined predicates don’t need to be OR-type
  - OR of 1 condition → Just compute it !!!
  - Remove initialization (Unconditional don’t require init)
- Reduce number of CMPPs
  - Utilize 2nd destination slot
  - Combine any 2 CMPPs with:
    - Same source operands
    - Same guarding predicate
    - Same or opposite compare conditions

Running Example - CMPP Compaction

```
Loop:
   p1 = p2 = p3 = p4 = p5 = p6 = 0
   b = load(a) if T
   p1 = cmpp.ON (b < 0) if T
   p2 = cmpp.ON (b >= 0) if T
   p6 = cmpp.ON (b < 0) if T
   p3 = cmpp.ON (c > 0) if p1
   p5 = cmpp.ON (c <= 0) if p1
   p4 = cmpp.ON (b > 13) if p3
   p5 = cmpp.ON (b <= 13) if p3
   b = b + 1 if p4
   c = c + 1 if p5
   d = d + 1 if p1
   p6 = cmpp.ON (c <= 25) if p2
   e = e + 1 if p2
   a = a + 1 if p6
   bge e, 34, Done if p6
   jump Loop if T
Done:
```

```
Loop:
   p5 = p6 = 0
   b = load(a) if T
   p1,p2 = cmpp.UN.UC (b < 0) if T
   p6 = cmpp.ON (b < 0) if T
   p3,p5 = cmpp.UN.OC (c > 0) if p1
   p4,p5 = cmpp.UN.OC (b > 13) if p3
   b = b + 1 if p4
   c = c + 1 if p5
   d = d + 1 if p1
   p6 = cmpp.ON (c <= 25) if p2
   e = e + 1 if p2
   a = a + 1 if p6
   bge e, 34, Done if p6
   jump Loop if T
Done:
```

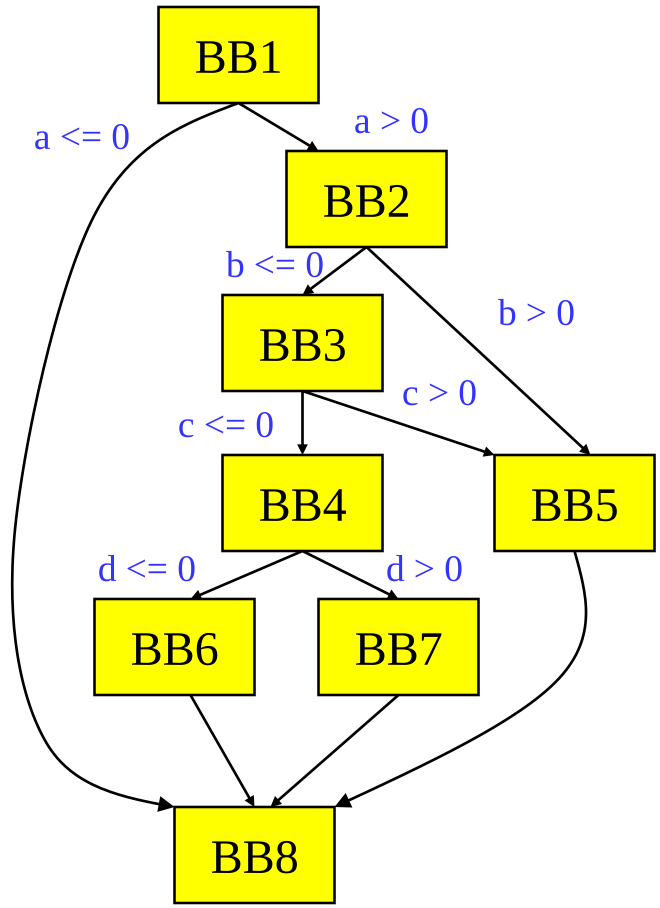
Homework Problem

```
if (a > 0) {
    r = t + s
    if (b > 0 || c > 0)
        u = v + 1
    else if (d > 0)
        x = y + 1
    else
        z = z + 1
}
```

a. Draw the CFG
b. Compute CD
c. If-convert the code

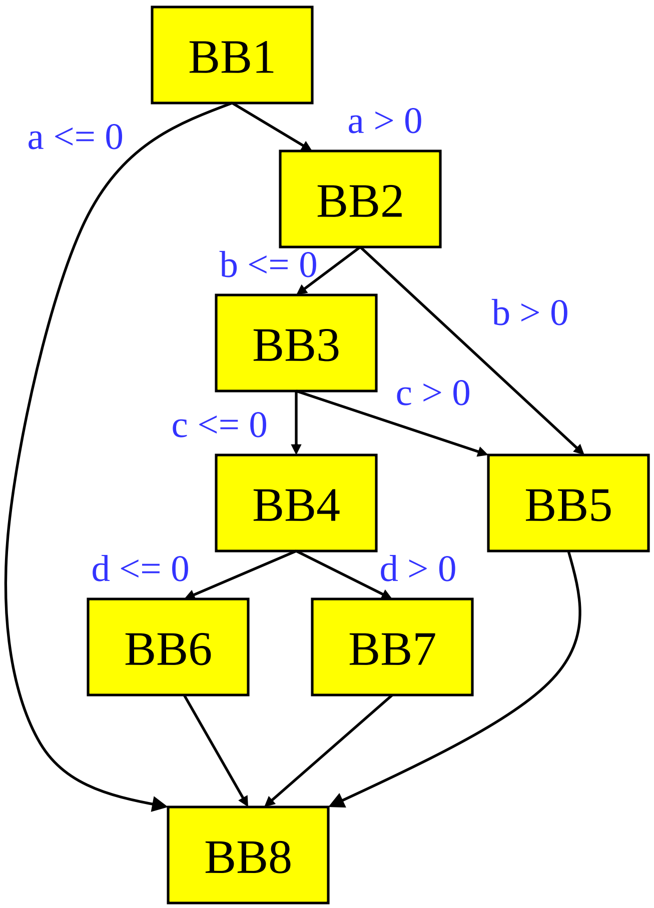
Homework Problem Answer (1)

```
if (a > 0) {
    r = t + s
    if (b > 0 || c > 0)
        u = v + 1
    else if (d > 0)
        x = y + 1
    else
        z = z + 1
}
```



a. Draw the CFG
b. Compute CD
c. If-convert the code

Homework Problem Answer (2)



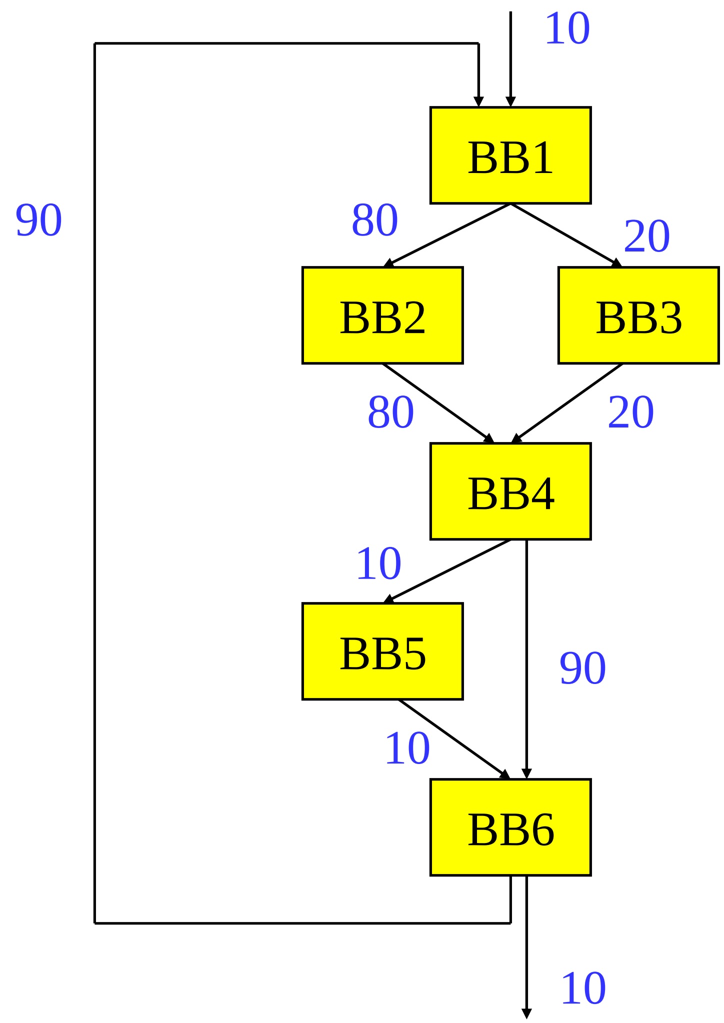
BB	CD
1	-
2	1
3	-2
4	-3
5	2,3
6	-4
7	4
8	-

BB	Assigned Predicate
1	-
2	p1
3	p2
4	p4
5	p3
6	p5
7	p6
8	-

```
p3 = 0
p1 = CMPP.UN (a > 0) if T
r = t + s if p1
p2,p3 = CMPP.UC.ON (b > 0) if p1
p4,p3 = CMPP.UC.ON (c > 0) if p2
u = v + 1 if p3
p5,p6 = CMPP.UC.UN (d > 0) if p4
x = y + 1 if p6
z = z + 1 if p5
```

When to Apply If-conversion?

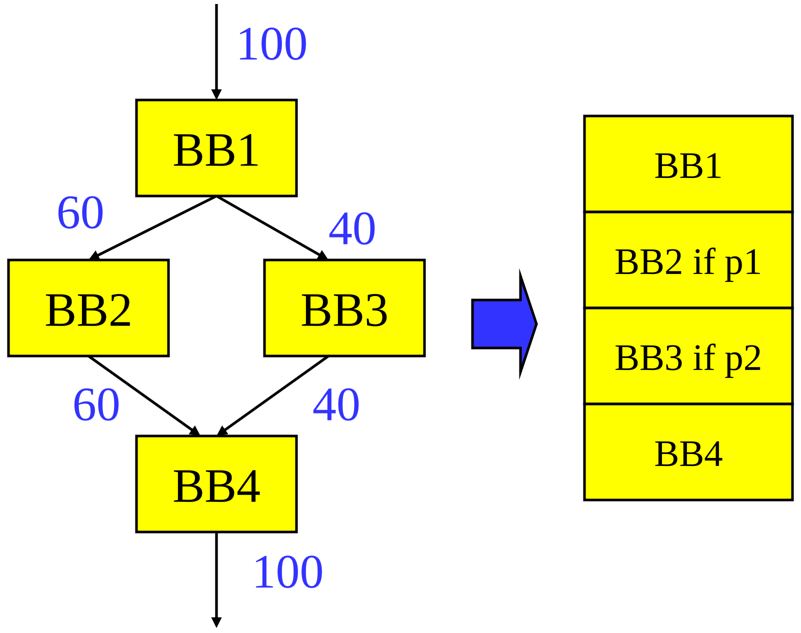
- Positives
  - Remove branch
    - No disruption to sequential fetch
    - No prediction or mispredict
    - No draining of pipeline for mispredict
    - No use of branch resource
  - Increase potential for operation overlap
    - Creates larger basic blocks
    - Convert control dependences into data dependences
  - Enable more aggressive compiler xforms
    - Software pipelining
    - Height reduction
- What about the negatives?



Negative 1: Resource Usage

Instruction execution is additive for all BBs that are if-converted, thus require more processor resources

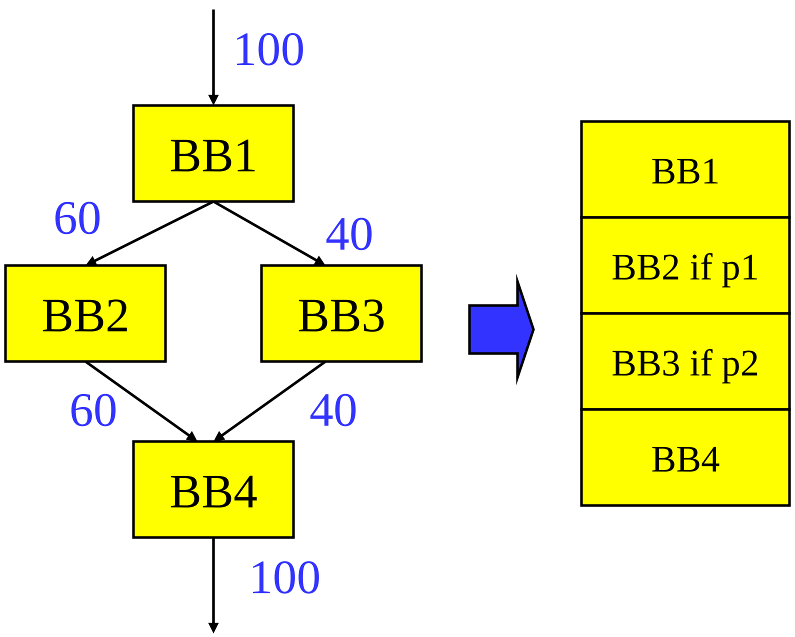
Be careful applying if-conversion too liberally when processor resources constrained OR blocks have large numbers of instructions



Negative 2: Dependence Height

Dependence height is max of for all BBs that are if-converted (dep height = schedule length with infinite resources)

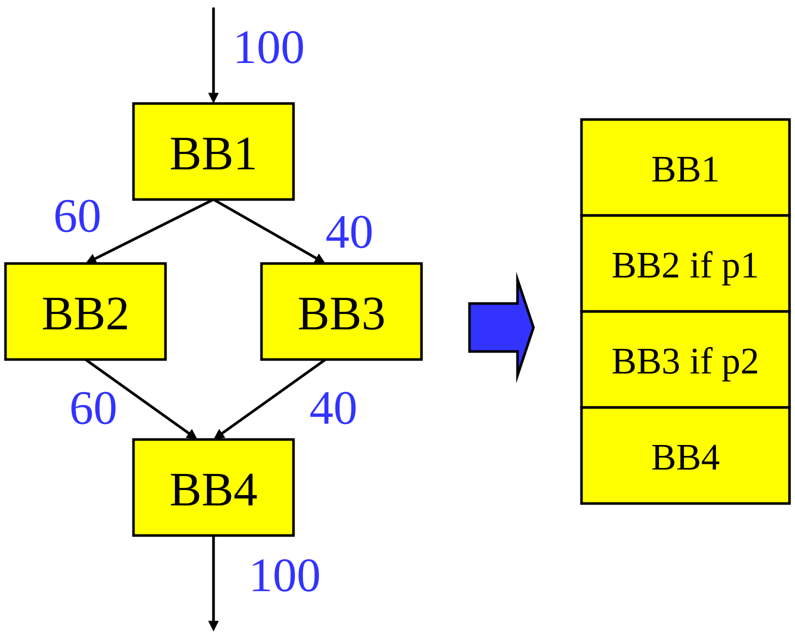
Be careful with if-converting blocks with mismatched dependence heights



Negative 3: Hazard Presence

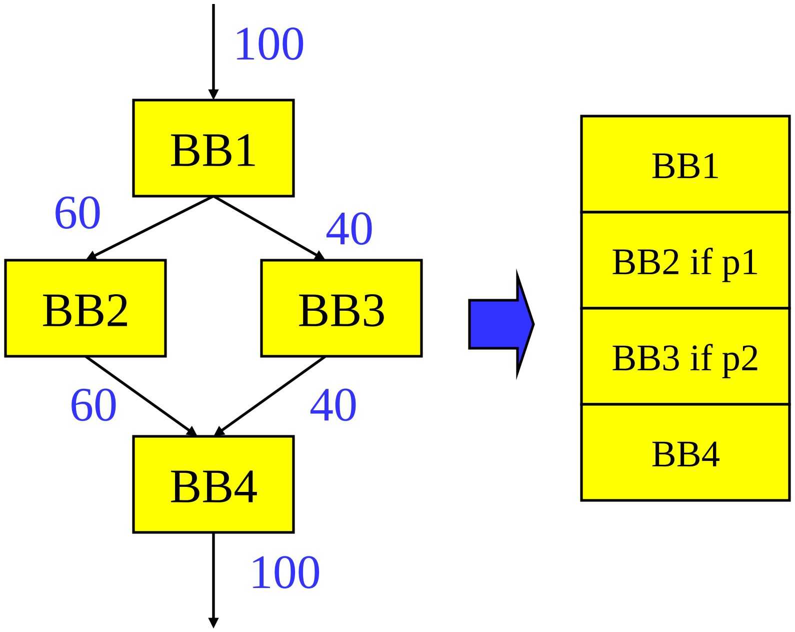
Hazard = operation that forces the compiler to be conservative, so limited reordering or optimization, e.g., subroutine call, pointer store, …

Hazards should be avoided except on the “main path”



Deciding When/What To If-convert

- Resources
  - Small resource usage ideal for less important paths
- Dependence height
  - Matched heights are ideal
  - Close to same heights is ok
- Remember everything is relative for resources and dependence height !
- Hazards
  - Avoid hazards unless on most important path
- Estimate of benefit
  - Branches/Mispredicts removed
  - Increased instruction overlap



For More on If-conversion/Predicated Execution

- Selective if-conversion: "Effective Compiler Support for Predicated Execution using the Hyperblock", S. Mahlke et al., MICRO-25, 1992.
- Use of AND-type predicates: "Control CPR: A Branch Height Reduction Optimization for EPIC Processors", M. Schlansker et al., PLDI-99, 1999.
- Security: Data oblivious computing for making code side channel resistant