SOFTWARE TIMELINESS
CS3213 FSE

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WHAT WE DID EARLIER

- System Requirements: Use-cases, Scenarios, Sequence Diagrams
- System structure: Class diagrams
- Discussion on semantics
- System behavior: State diagrams
- Discussion of the thinking behind your course project
- Static analysis and vulnerability detection
- Software Debugging
- White-box Testing: test estimation and generation
- Taint propagation, malicious inputs: secure SE

- Today
  - **Software timeliness: performance gaps, and real-time software**

WCET

- Worst Case Execution Time (WCET) of a program for a given hardware platform.
  - Sequential Terminating Programs.
  - Gets input, computes, produces output.

each stmt is one time unit.

- Many inputs are possible.
  - Leads to different execution times.
- WCET : An upper bound on the execution time for all possible inputs.

for each stmt, a constant amount of exec. time is given

WHY NEED ANALYSIS?

- To find WCET of a program, execute it for all possible inputs.
  - WCET by measurement.
  - Exponentially many possible inputs in terms of input size.
    - Insertion sort program
  - Similar problems will be encountered for WCET Analysis via platform simulation.
- Need access to platforms/simulators also!
  - Go for static analysis.

WCET BY MEASUREMENT?

- What about one-path programs such as matrix multiplication?
  - Execution path is independent of input data.
  - Still execution time can be variable.
    - Latency of floating point operation (e.g., multiplication) depends on the input data.
  - Not possible to try it on all possible platforms and then choose one.
    - Often trying to decide the platform as well.

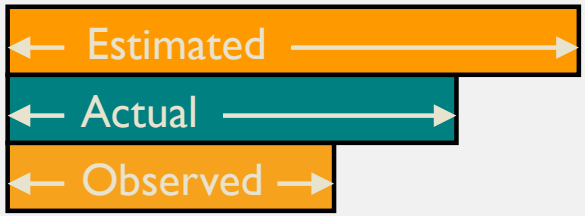
path independent of input.

execution time can be variable.

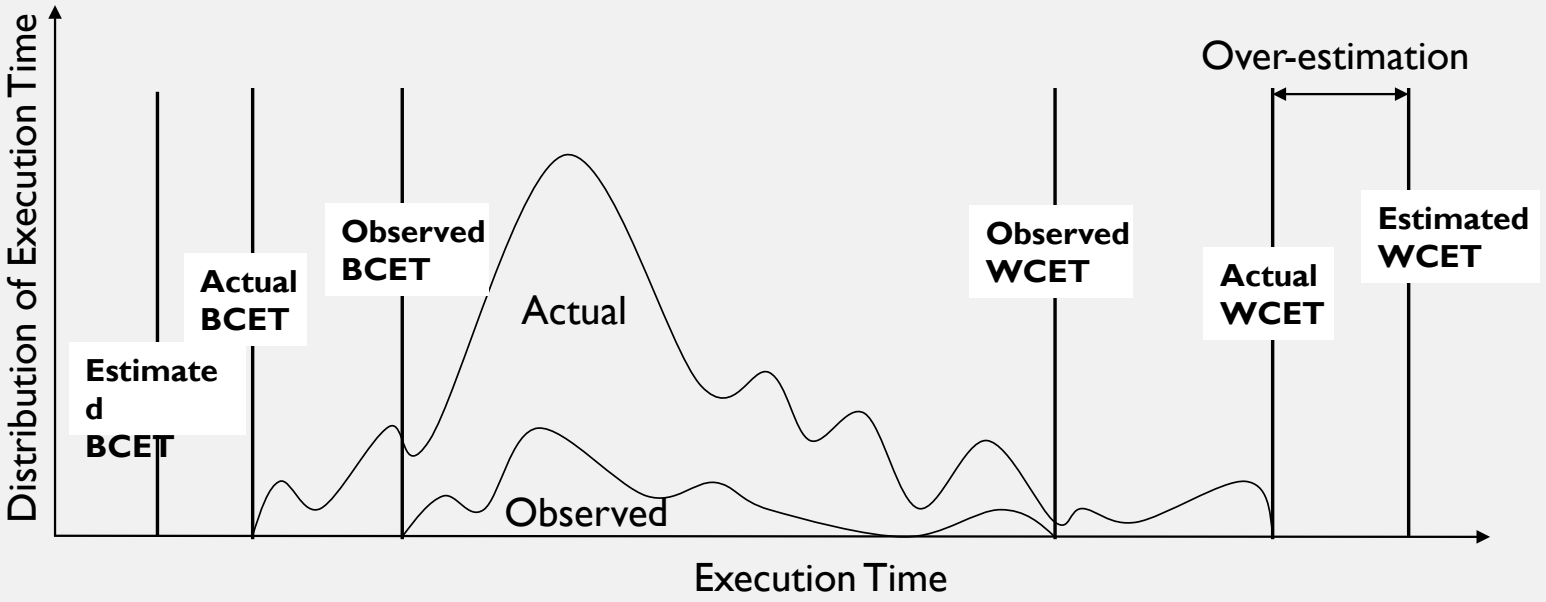
WCET ANALYSIS

- Employ static analysis to compute an upper bound on actual WCET (**Estimated WCET**)
- Run program on selected inputs get a lower bound on actual WCET (**Observed WCET**)

Estimated WCET ≥ Actual WCET ≥ Observed WCET

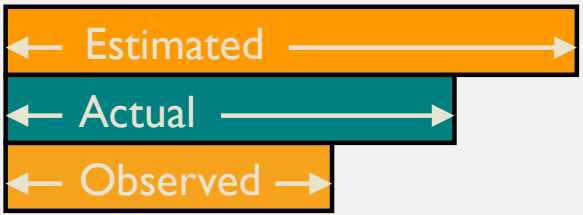


BCET AND WCET



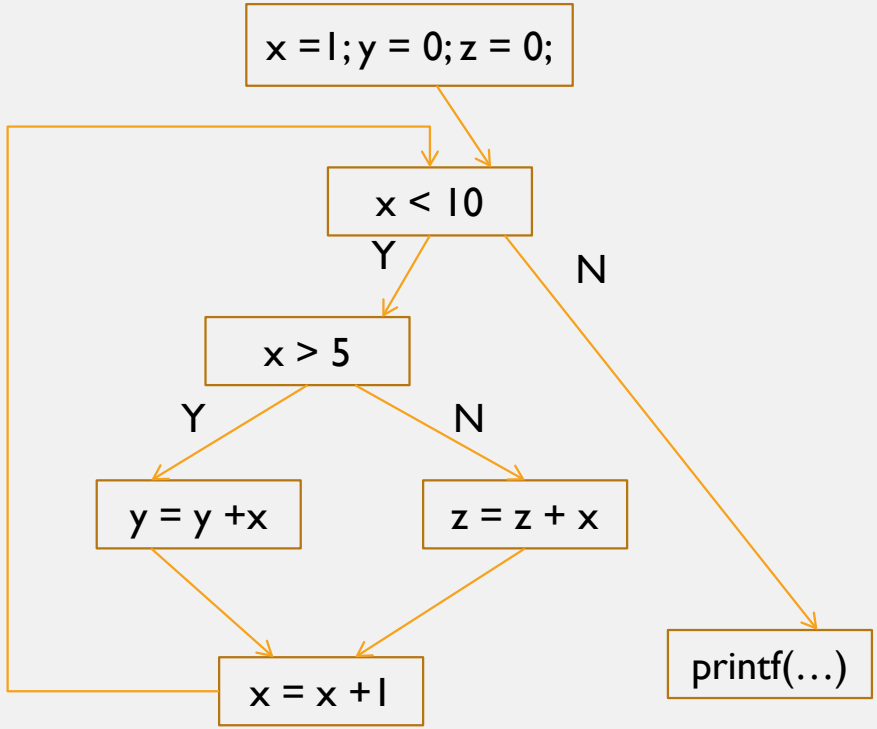
WCET ANALYSIS

- Program path analysis
  - All paths in **control flow graph** are not feasible.
- Micro-architectural modeling
  - Dynamically variable instruction execution time.
    - Cache, Pipeline, Branch Prediction
    - Not covered in our Software Engineering perspective.



CONTROL FLOW GRAPH

```
x = 1; y = 0; z = 0;
while (x < 10){
    if (x > 5)
            y = y + x;
    else   z = z + x;
    x = x + 1;
}
printf(….);
```



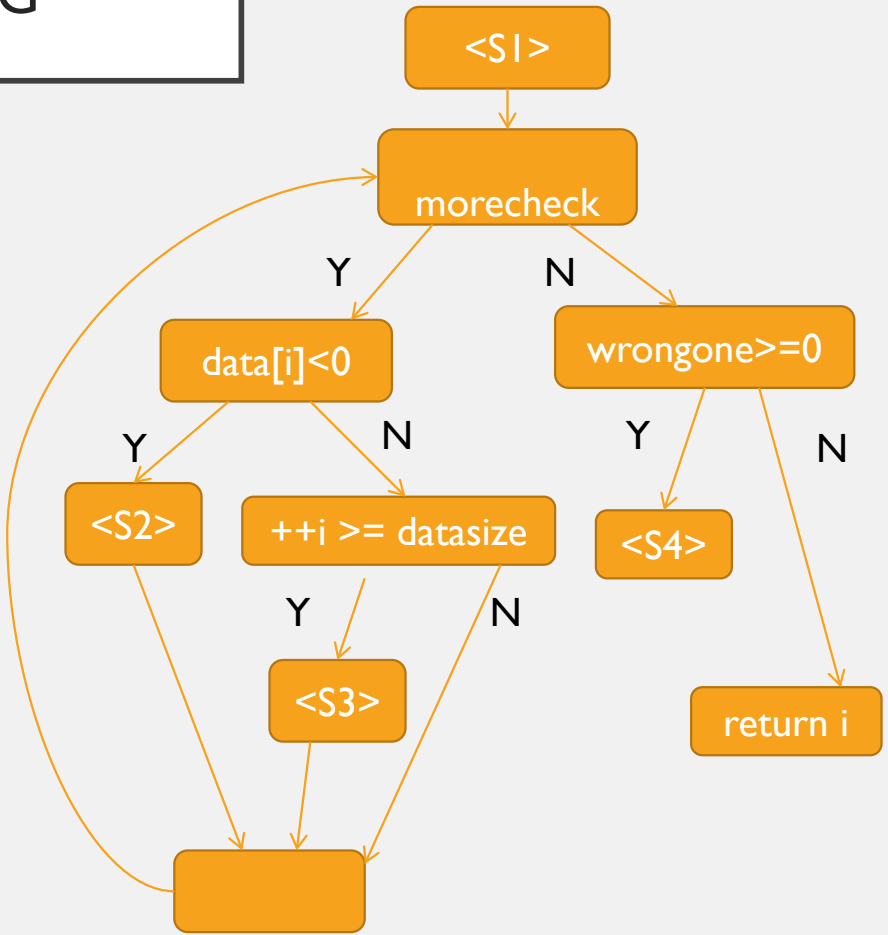
Nodes of the graph, basic blocks, are maximal code fragments executed without control transfer. The edges denote control transfer.

EXERCISE: CFG

```
procedure Check_data()
{       int  i = 0, morecheck = 1, wrongone = -1, datasize = 10;
  L:    while (morecheck)
  LB:   {
              if  (data[i] < 0)
  A:              {  wrongone = i;   morecheck = 0; }
              else
  B:                  if  (++i >= datasize) morecheck = 0;
          }
          if (wrongone >= 0)
   C:             { handle_exception(wrongone); return 0; }
   C':    else  return i;
 }
```

EXERCISE: CFG

```
procedure Check_data()
{       …. <S1>
  L:    while (morecheck)
  LB:   {
              if  (data[i] < 0)
  A:              { …. <S2> }
              else
  B:           if  (++i >= datasize)
                           … <S3>;
        }
        if (wrongone >= 0)
   C:             { … <S4> }
   C':   else  return i;
}
```



EXERCISE ON CFG

How to construct an inter-procedural CFG for a program with many procedures?

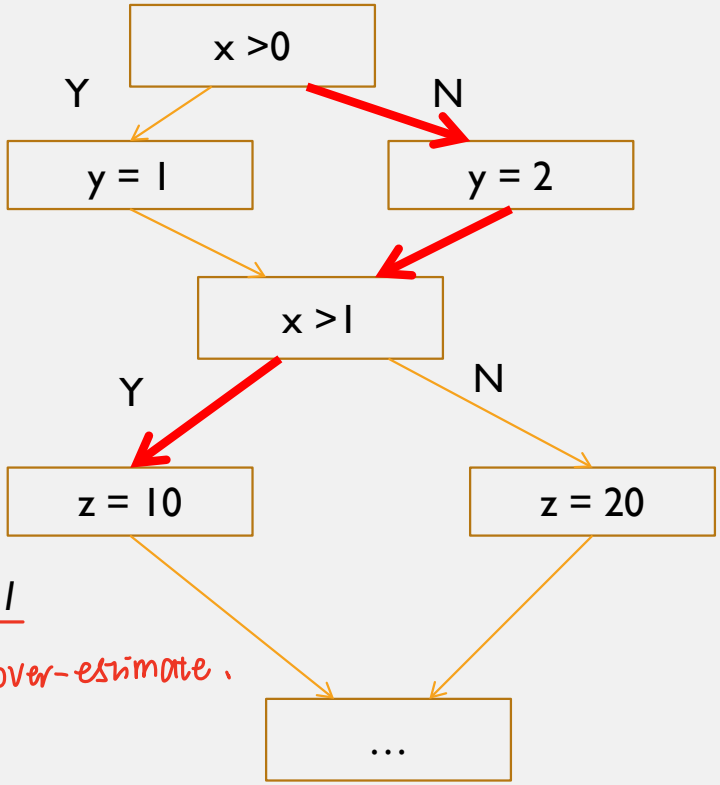
```
main(){
…
   f1();
   f2();
…
}
```

```
f1(){
   …
  f2();
   …
 }
```

```
f2(){
   …
  f2();
   …
 }
```

WHY ALL PATHS MAY NOT BE FEASIBLE?

```
if (x > 0{
    y = 1;
else
    y = 2;
}
if (x > 1){
    z = 10;
else
    z = 20;
}
…
```



$x \leq 0 \wedge x > 1$

Static analysis will over-estimate.

RESTRICTIONS OF ANALYSIS – (1)

- Static analysis need not be on source program.
  - We can perform static analysis on assembly code of a given program.
  - The analysis is only for time taken, and not for the memory locations / values accessed.
  - No restriction on program data structures used for WCET analysis.
  - What about control flow ?

RESTRICTIONS OF ANALYSIS – (2)

- Restrictions on control flow
  - 1. No unbounded loops
    - Common sense.
      - Otherwise how to guarantee time?
  - 2. No unbounded recursion
    - Similar issue.
  - 3. No dynamic function calls
    - Need to statically know the functions called, and the possible call sites of these functions.

ORGANIZATION OF WCET ANALYSIS

- What is Timing Analysis ?
- An Early solution -- Timing Schema.
- Modeling Program Flows.
  - Primarily Control flow.
- Modeling timing effects of Micro-architecture.
  - Cache, pipeline, Not covered in CS3213 FSE

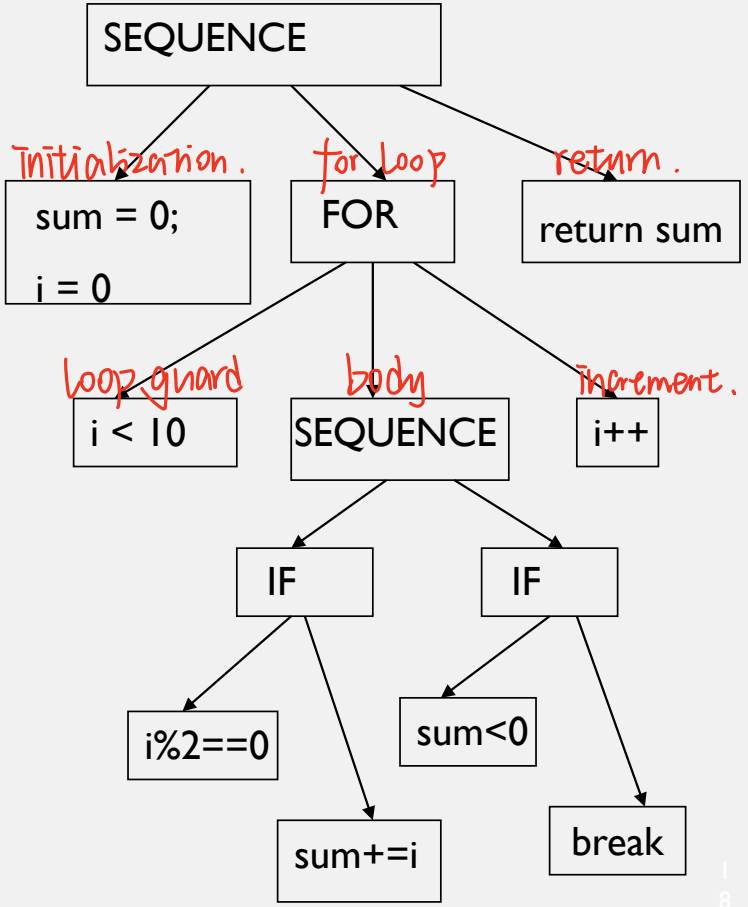
TIMING SCHEMA

- One of the first works on WCET analysis.
- Basically, perform control flow analysis to find the "longest" program path.
- The notion of "longest" is weighted
  - Take into account the cost of executing individual program elements.
  - Timing schema is a simple way of composing these costs.
- Does not work on Control Flow Graphs
  - Works on Abstract Syntax Tree

EXAMPLE

AST: any program can be converted into such a tree.

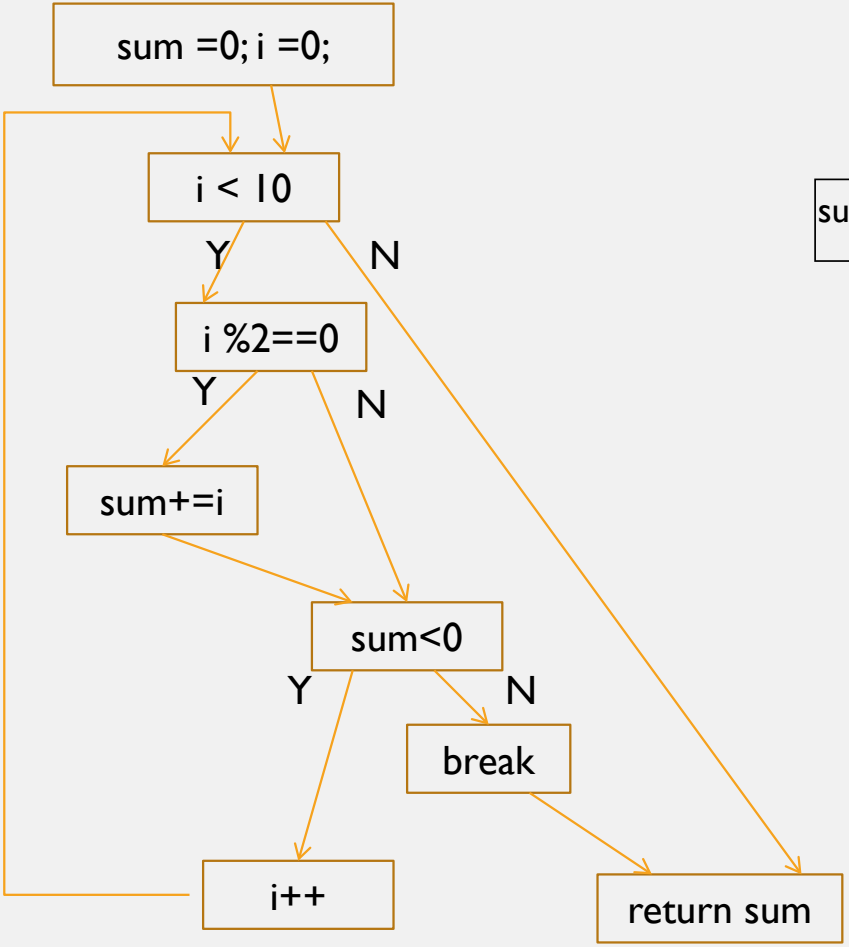
```
sum = 0;
for (i=0; i< 10; i++){
    if (i % 2 == 0)
            sum += i;
    if (sum < 0)
            break;
}
return sum;
```

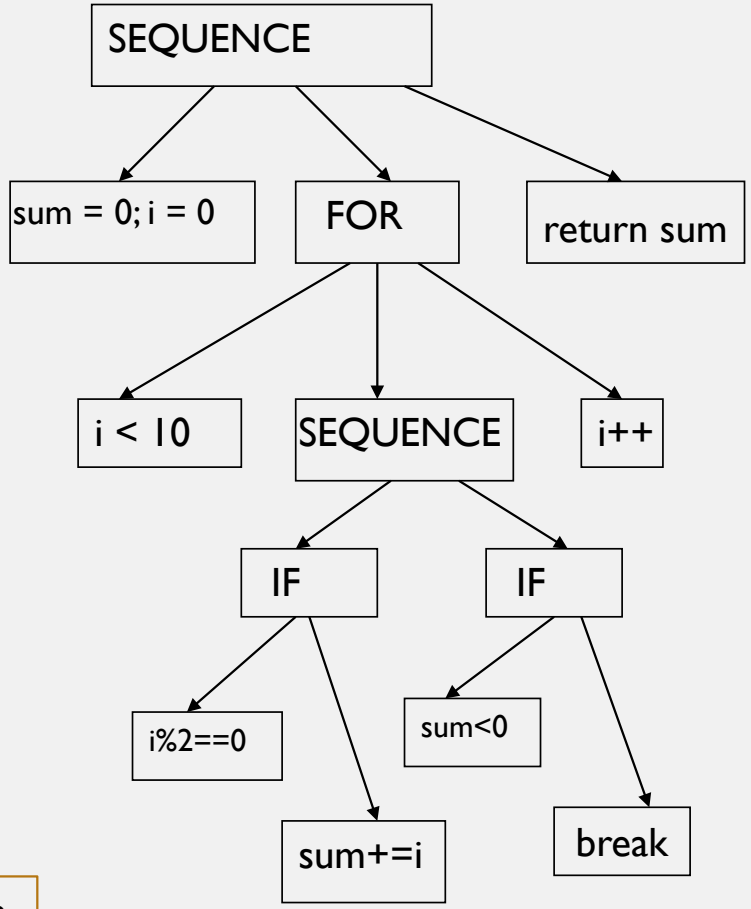


AST AND CFG

- Hierarchy
  - AST shows the different scopes at different levels
  - CFG has no hierarchy.
- Loops
  - AST is tree, free from cycles
  - Any loop in the program is a cycle in the CFG.

REPRESENTATIONS: AST AND CFG





TIMING SCHEMA – (WORKS ON AST)

- Time(S1;S2) = Time(S1) + Time(S2)
- Time(if B {S1} else {S2})
  - = Time (B) + max(Time(S1), Time(S2))
- Time(while B {S1})
  - = (n+1) * Time(B) + n * Time(S1)
  - n is the loop bound.

timing schema rule - for each control structure

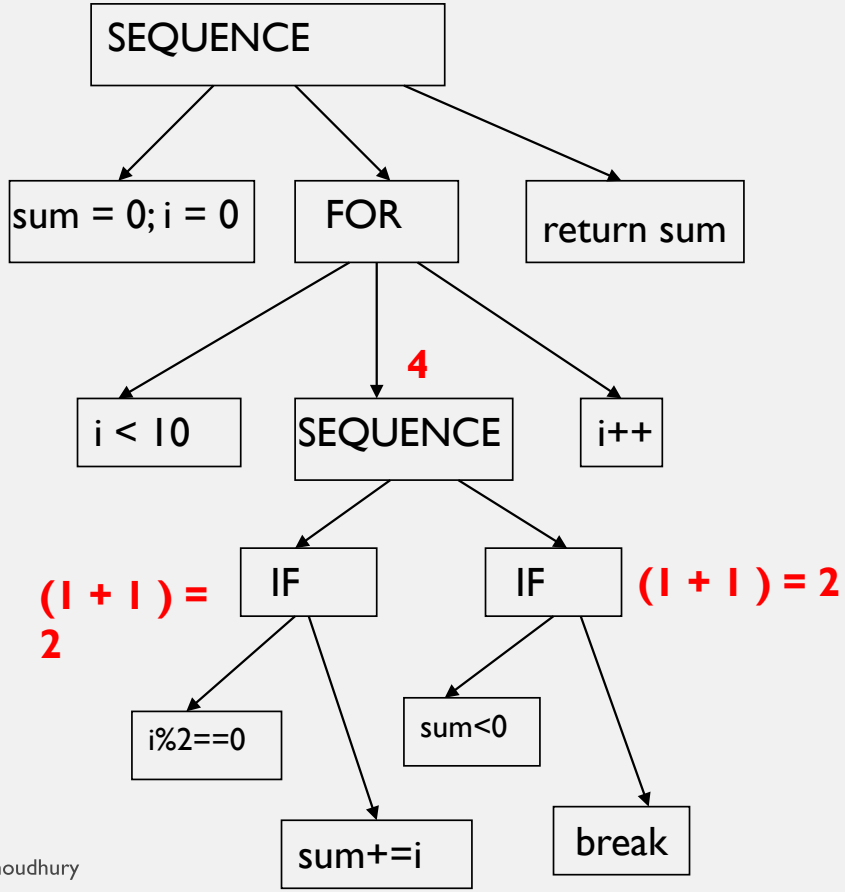
- Time(for(Init; B; Incr.){ S })
  - = Time(Init) + (n+1)*Time(B) + n*Time(S) + n*Time(Incr.)
- Time(if (B) { S}) = Time(B) + Time(S)

TIMING SCHEMA

Time(for-loop)
= Time(i= 0) +
11 * Time(i < 10) +
10 * 4 + 10 * Time(i++)
= 1 + 11 + 10*4 + 10*1
= 62 time units

loop bound n=10.

Assumption:
Each assignment/condition takes 1 time unit (not realistic in practice).



PROBLEMS WITH TIMING SCHEMA

- Language Level:
  - Just a control flow analysis.
  - Insensitive to knowledge of infeasible paths.
- Compiler level:
  - How to integrate effect of compiler opt?
    - Easy to handle – schema on optimized code.
- Architecture level:
  - Instructions take constant time – Not true.
  - Cache hits, pipelining and other performance enhancing features.

timing schema will always calculate infeasible paths

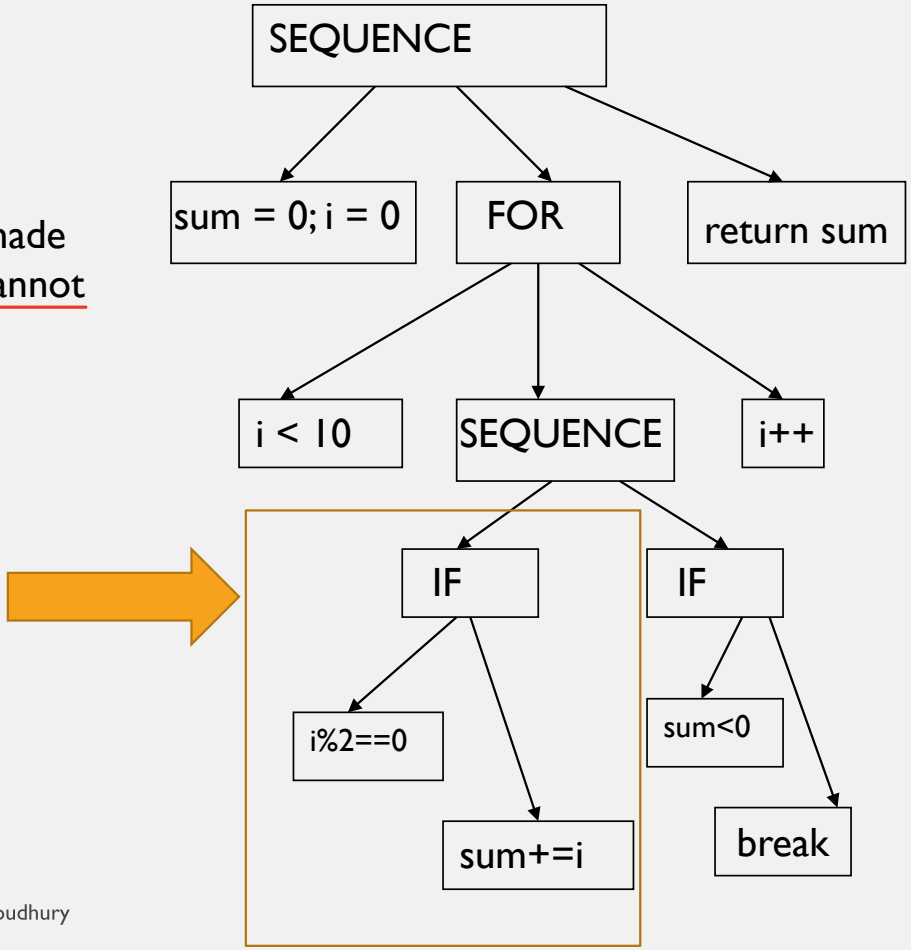
INFEASIBLE PATHS NOT CONSIDERED

It is impossible to execute i%2==0 to be true in two consecutive iterations.

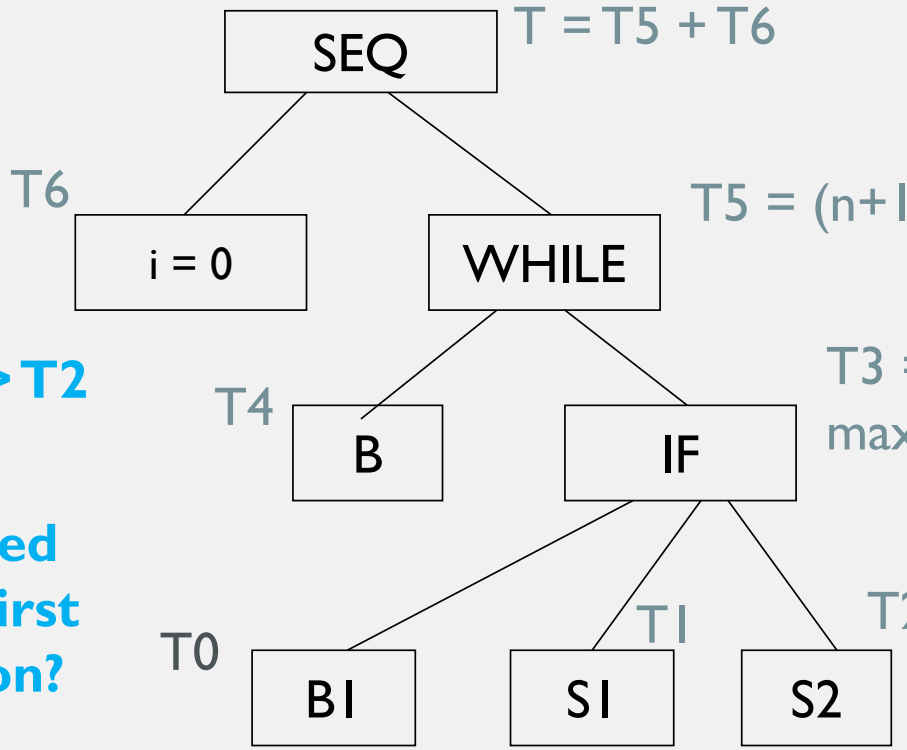
Even if this information is made available – timing schema cannot use it.

The time assigned to this block of code is Time(i%2==0) + Time(sum+=i)

This is the max. time taken by this statement in *any* iteration.



INFEASIBLE PATHS



What if T1 > T2 and

S1 is executed only in the first loop iteration?

T3 is still T0 + T1. Doesn't care about infeasible path

INFEASIBLE PATHS

- Infeasible sequence of statements in general

```
if (J== 0) {
        K = 1
} else {
        K = 10
}
if (K < 5){
        J++;
} else {
      J--;
}
```

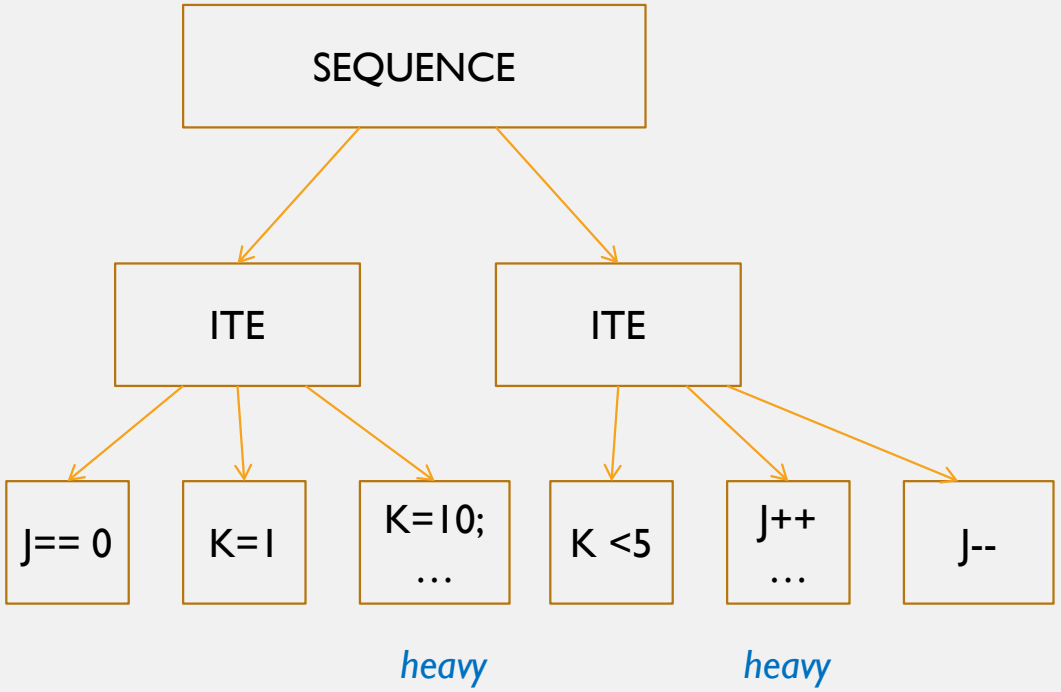
Cannot be executed together

Such infeasible paths should not be a witness to our WCET estimate.

should not calculate infeasible paths. but it still does

INFEASIBLE PATH HANDLING IN TIMING SCHEMA

```
if  (J== 0) {
        K = 1
} else {
    K = 10; …
}
if  (K < 5){
        J++;…
} else {
      J--;
}
```



How will timing schema work on this example?

WORKING OF TIMING SCHEMA

Time(first-if-statement)
= 1 + max(1,5) = 6

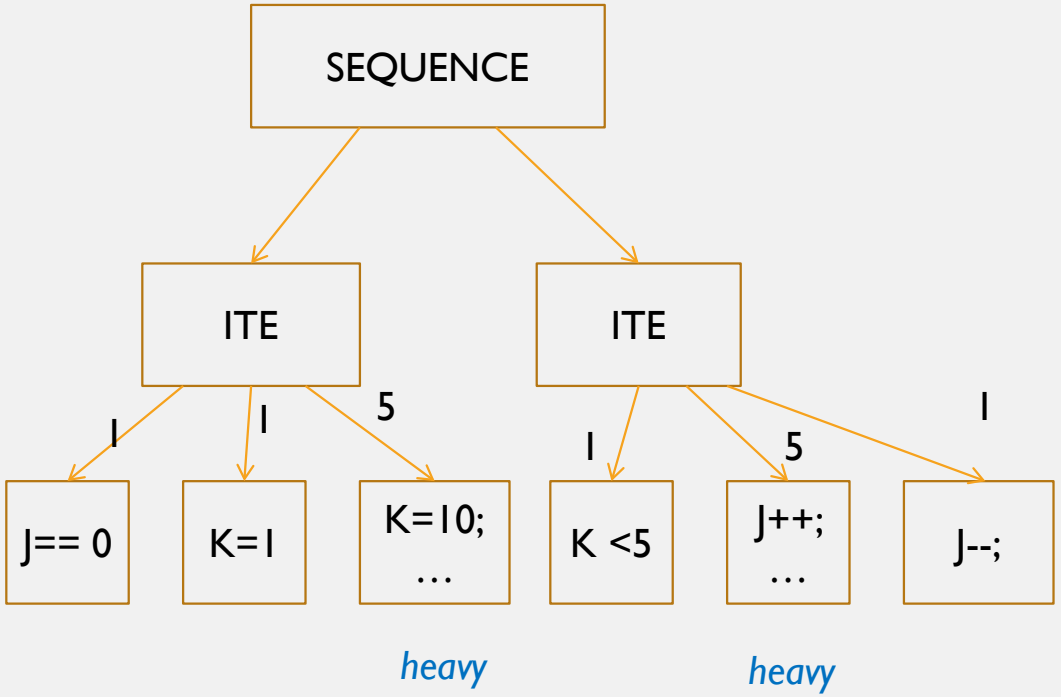
Time(second-if-statement)
= 1 + max(5,1) = 6

Estimated worst case time = 6 + 6 = 12

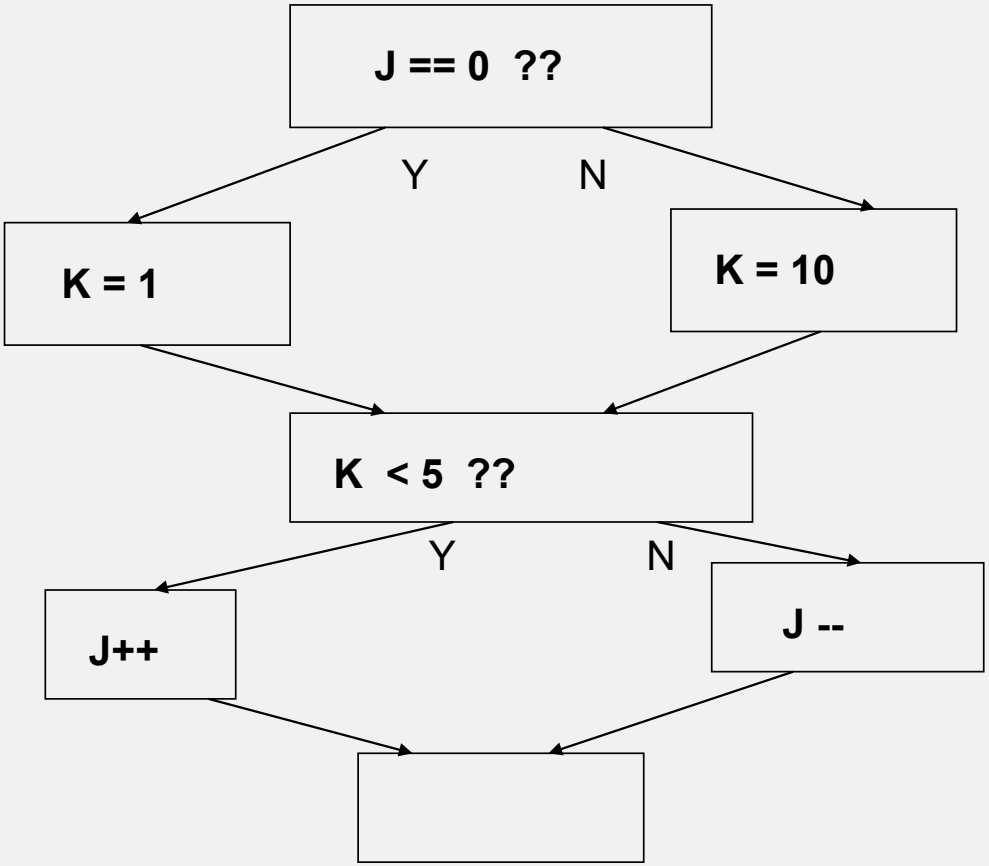
Actual worst-case time = 2 +6 = 8

Why?

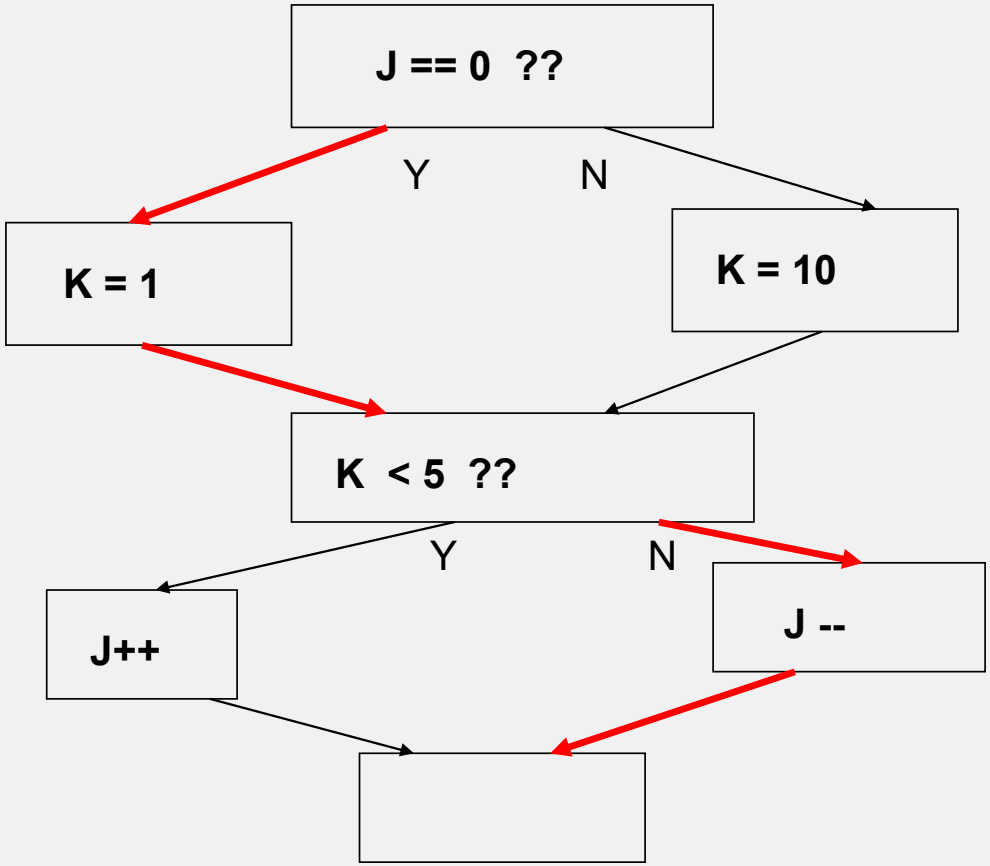
Where is the overestimate from?



CONTROL FLOW GRAPH (CFG)



INFEASIBLE PATH IN CFG



MODELING OF CONTROL FLOW

- Path-based
  - Enumerate paths and find longest path
    - Expensive !
    - Need to remove longest path if it is infeasible.
- Tree-based
  - Bottom-up pass of Syntax Tree
    - Timing Schema
  - Difficult to integrate infeasible path info
- Integer Linear Programming
  - Can take into account certain infeasible path information if available.
  - Efficient solvers available e.g. CPLEX
    - Forms the back-end of most state-of-the-art timing analyzers.

INTEGER LINEAR PROGRAMMING

- ILP: Integer Linear Programming
  - Variables and linear constraints on them.
  - Cost function (linear) to optimize.

```
f = 3x + 5y + z
0 <= x, y, z <= 100
x + y + z = 200
x + 2y <= 160
```

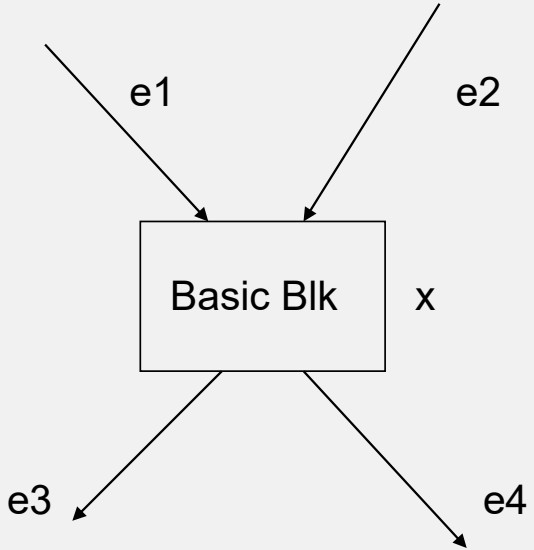
give maximum value of f, and the value of x, y, z to achieve f, respecting all linear constraints. give any possible xyz => find the maximum value of f

---

Optimal: `f = 520; x = 40; y = 60; z = 100`

Non-Optimal: `f = 480; x = 80; y = 30; z = 90`

ILP MODELING



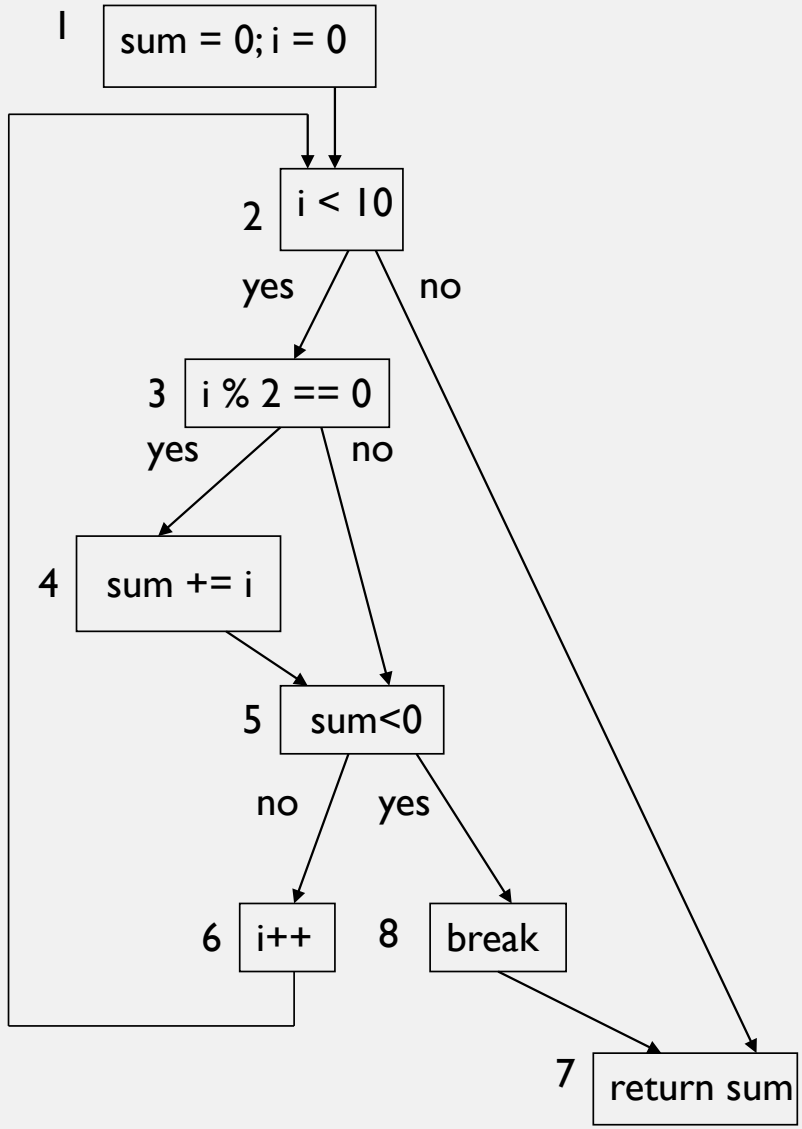
no. of times exec(x) = no. of times of e1 + no. of times e2 = e3 + e4

$$x = e1 + e2$$

$$= e3 + e4$$

We are dealing with aggregated execution counts of nodes/edges of CFG.

```
sum = 0;
for (i=0; i< 10; i++){
    if (i % 2 == 0)
            sum += i;
    if (sum < 0)
            break;
}
return sum;
```



Maximize Time =

ci: time per node
Ni: times it is executed

$c_1N_1 + c_2N_2 + c_3N_3 + c_4N_4 + c_5N_5 + c_6N_6 + c_7N_7 + c_8N_8$

$1 = N_1 = E_{1,2}$

$E_{6,2} + E_{1,2} = N_2 = E_{2,3} + E_{2,7}$

$E_{2,3} = N_3 = E_{3,4} + E_{3,5}$

$E_{3,4} = N_4 = E_{4,5}$

$E_{3,5} + E_{4,5} = N_5 = E_{5,6} + E_{5,8}$

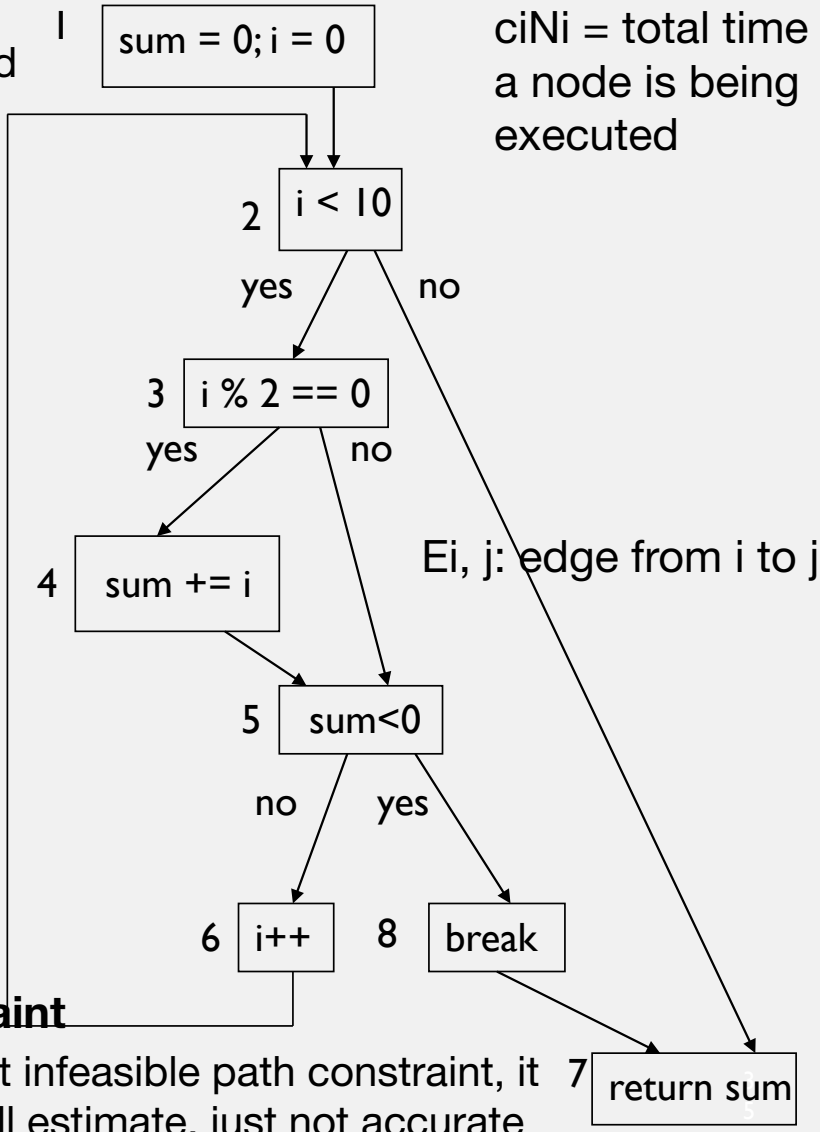
$E_{5,6} = N_6 = E_{6,2}$

$E_{5,8} = N_8 = E_{8,7}$

$E_{8,7} + E_{2,7} = N_7 = 1$

$E_{6,2} \leq 10$ loop bound

$N_4 \leq 5$ **infeasible path constraint**



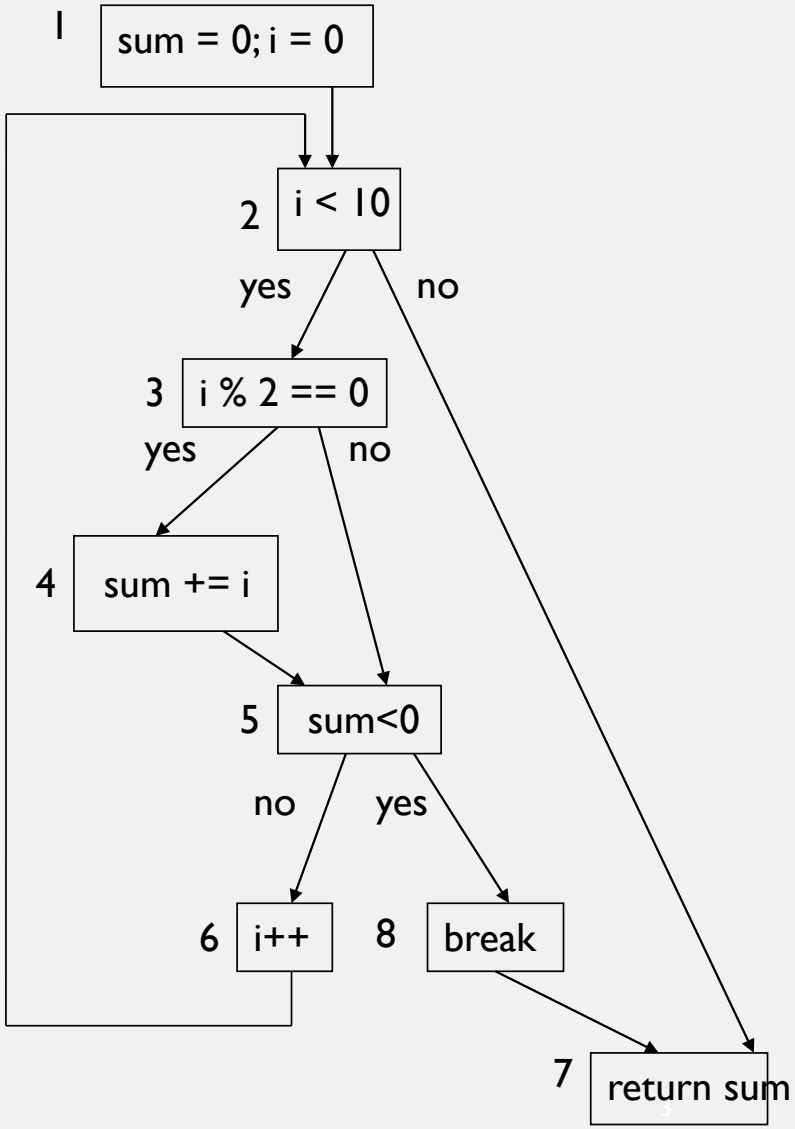
ciNi = total time a node is being executed

Ei, j: edge from i to j

without infeasible path constraint, it can still estimate. just not accurate

- The break statement is executed at most once.
  - $N_8 \leq 1$

INFEASIBLE PATH



aggregate exec. counts of nodes

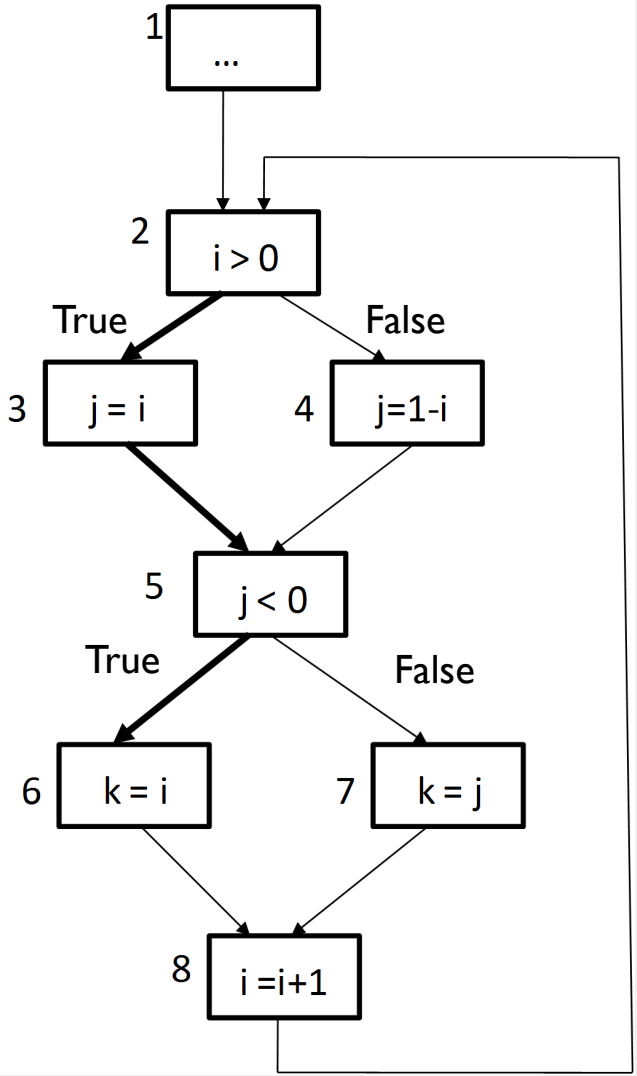
Blocks 3 and 6 are never executed in same loop iteration

$N_3 + N_6 \leq$ loopbound

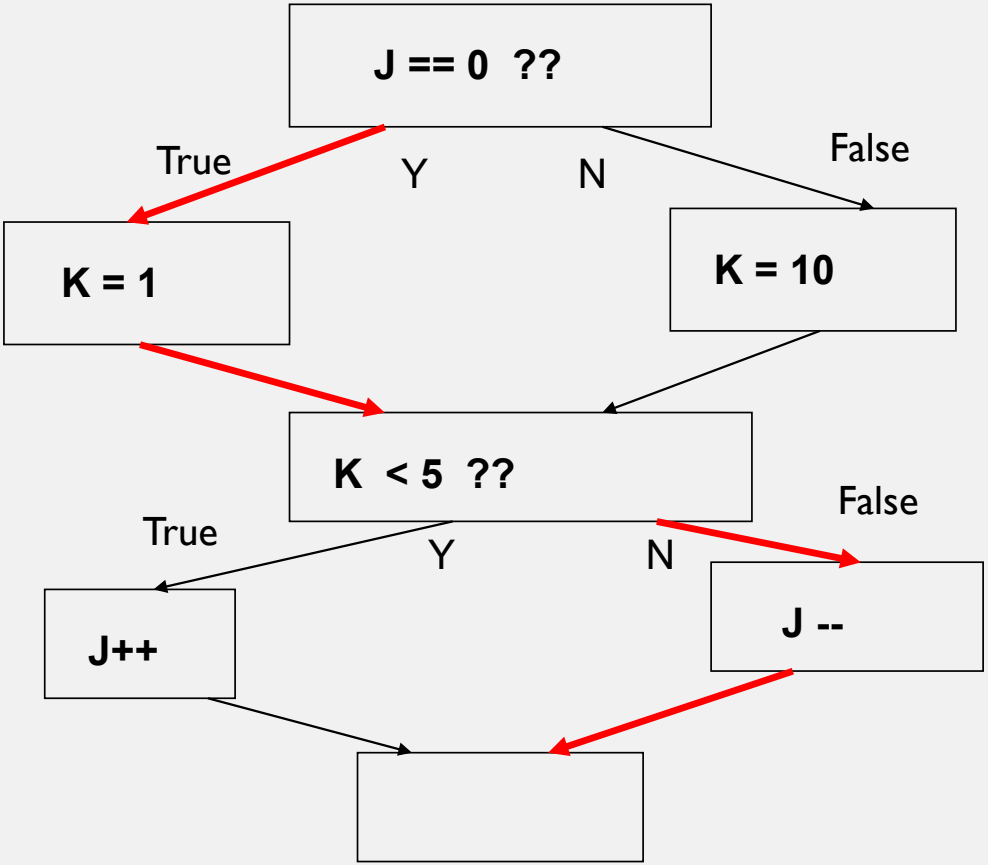
Edges (2,3) and (5,6) are not executed together.

$E_{2,3} = E_{5,7}$

```
while (...){
    if ( i > 0 ){
        j = i;
    } else{
        j = 1-i;
    }
    if  (j < 0){
        k = i;
    } else{
        k = j;
    }
    i = i+1;
}
```



HOW TO EXPRESS THIS INF. PATH CONSTRAINT?



EXERCISE: WHAT ARE THE INFEASIBLE PATHS?

```
procedure Check_data()
{       int  i = 0, morecheck = 1, wrongone = -1, datasize = 10;
        while (morecheck)
        {
              if  (data[i] < 0)
                  {  wrongone = i;   morecheck = 0; }
              else
                    if  (++i >= datasize) morecheck = 0;
           }
           if (wrongone >= 0)
                 { handle_exception(wrongone); return 0; }
           else  return i;
 }
```

REVISION OF TIMING ANALYSIS

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Q1. TIMING SCHEMA

Consider the following program fragment that computes in z the product of x and y. Thus, x and y serve as inputs to the program fragment, and z serves as the output of the program fragment. Both the inputs are positive integers, given as unsigned 8 bit numbers (when represented in binary). Using *Timing Schema* WCET analysis method discussed in class, derive the maximum execution time of the program fragment. Each assignment/return/condition-evaluation takes 1 time unit.

```
z = 0;
while (x !=0){
  if (x %2 != 0){ z = z +y; }
  y = 2 * y; x = x/2;
}
return z;
```

maximum time in while body:
2 + 2 = 4. (not include condition)

maximum loop bound = 8;
log(2^8) = 8

ans: 2 + (8+1) * 1 + 8 * 4

ANSWER TO Q2

```
z = 0;
while (x !=0){
      if (x %2 != 0){ z = z +y
      y = 2 * y; x = x/2;
 }
 return z;
```

Based on the control flow graph, the flow constraints are as follows. N_i is the execution count of basic block i, and $E_{i,j}$ is the execution count of the edge from basic block i to basic block j

$I = N_1 = E_{1,2}$

$E_{1,2} + E_{5,2} = N_2 = E_{2,6} + E_{2,3}$

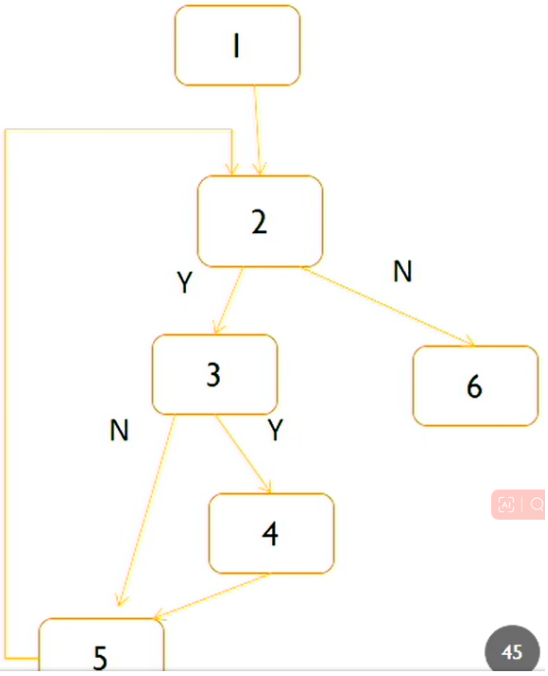
$E_{2,3} = N_3 = E_{3,4} + E_{3,5}$

$E_{3,4} = N_4 = E_{4,5}$

$E_{4,5} + E_{3,5} = N_5 = E_{5,2}$

$E_{2,6} = N_6 = I$

The loop bound accounts for the additional constraint $E_{5,2} \leq 8$



Q2: ILP MODELING

Formulate the maximum execution time estimation of the program fragment in Question 3(A) using Integer Linear Programming (ILP). Clearly show the objective function and all constraints. Your ILP problem should only perform program path analysis and not micro-architectural modeling. The estimate produced by your ILP problem should be as tight as possible.

Q3: COMPARISON

- Also, comment on how the estimate from your ILP problem will compare with the estimate you produced using Timing schema.

BONUS QUESTIONS

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1. TESTING

Consider a function *triangle* which takes three integers x,y,z which are the lengths of triangle sides and then calculates whether the triangle is equilateral (that is x == y == z), isosceles (exactly two sides are equal), or scalene (otherwise).

Suppose your professor has generated the test-suite for such a function by some means. How would you evaluate whether the professor's test-suite is good enough? Well you can start by asking some questions, to the professor like the following.

1. TESTING

Do you have a test case for an equilateral triangle?
Do you have a test case for an isosceles triangle?
Do you have at least three test cases for isosceles triangles, where all permutations are considered? (e.g. (x,x,y), (x,y,x), (y,x,x))
Do you have a test case with one side zero?

Now, I could go on and on – but I need your help here ☺ Tell some more questions that you should ask to evaluate whether the test-suite generated by the professor is good enough. The more questions you can ask which point to possible corner cases – the more marks you will get.

ANSWER

There can be many other questions such as

Do you have the test case (0,0,0)?
Do you have a test case with negative values?
Do you have a test case where the sum of two sides equals the third one?
Do you have at least three test cases for such non-triangles, where all permutations of sides are considered?
Do you have a test case where the sum of the two smaller inputs is greater than the third one?
Do you have at least three such test cases, considering all permutations?
Do you have test cases with very large integers (exceeding MAXINT) ?
Do you have a test case with non-integer values but numbers?
Do you have a test case with non-numbers e.g. strings, characters …
Do you have a test case where 2 or 4 inputs are provided?

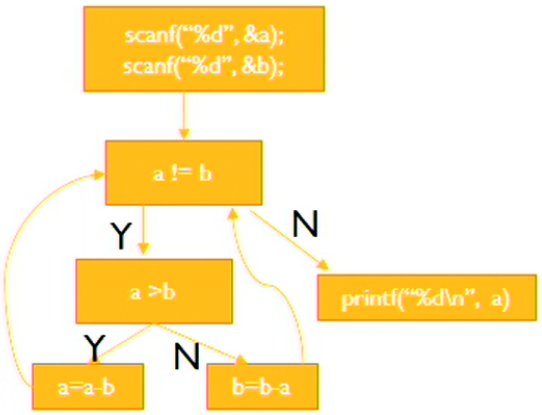
2. COVERAGE

Consider the following program which computes the greatest common divisor of two numbers a and b.

```
scanf("%d", &a); scanf("%d", &b);
while (a != b){ if (a >b) { a = a-b;} else
{b = b - a;} }
printf("%d\n", a);
```

Construct test-suites to achieve node and edge coverage of the control flow graph.

COVERAGE - ANSWERS



We need to find values of a and b such that the loop is entered, and both the outgoing edges of a>b are traversed in different iterations of the loop.

In that case, a test-suite with a single test will be sufficient to ensure node and edge coverage.

T = {(6,9)}

T = {(6, 3)} 不行