Program Analysis

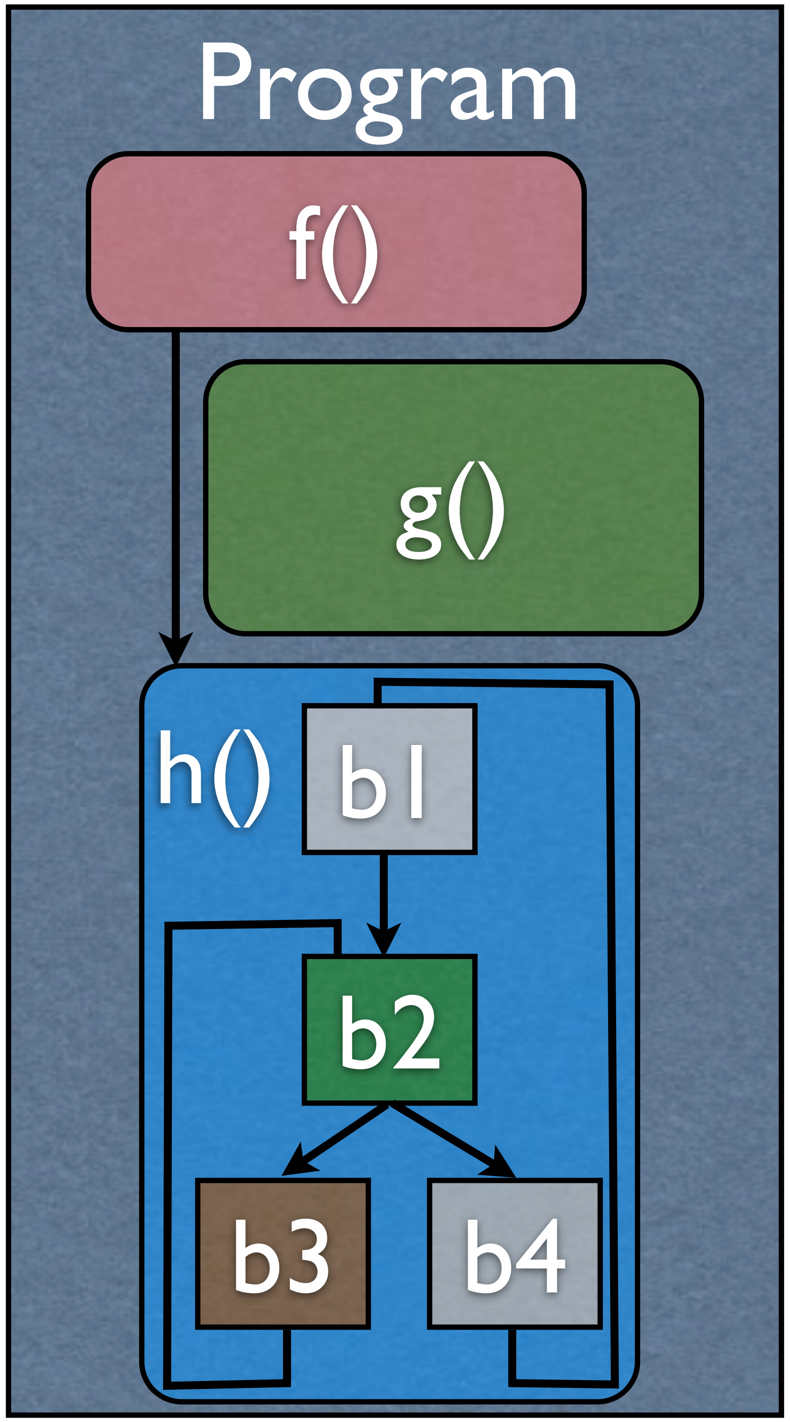
Lecture 10: *Control Flow Analysis II*
Winter term 2011/2012

Prof. Thorsten Holz

Announcements

- Next week (December 22) we will have a lecture, but it is not relevant for the examination
  - Vulnerabilities on document formats
  - Heap spraying
  - We will have a “christmas challenge” with bonus points
- Second part of the exercise after this lecture

Building Blocks



- Program consists of several *procedures*
    - f() calls h()
- Produce consists of several *basic blocks*
    - “Atomic” units of a program

Basic Blocks

- *Basic block* is a sequence of instructions which will always be executed in the given order
- Properties:
  - Basic block has a single entry and single exit
  - Flow of control can only enter at the beginning and leave at the end
  - Only last instruction can be a branch instruction; only first instruction can be target of a branch

Finding BBs

- Identify *leader instructions*, i.e., first instruction of BB:

  1. First instruction of a program is a leader
  2. Any instruction that is the target of a branch is a leader
  3. Any instruction that immediately follows a branch or return instruction is a leader

Example: Finding Leaders

High-Level Language

```
int i, j;
for (i = 0; i < 10; i++)
{
  j=0;

  do
  {
    functionXYZ ( ) ;
  } while (j++< i);
}
```

Assembler

```
00401139   mov    [ebp-4], 0
00401140   jmp    loc 40114B
00401142   mov    eax, [ebp-4]
00401145   add    eax, 1
00401148   mov    [ebp-4], eax
0040114B   cmp    [ebp-4], 0Ah
0040114F   jge    loc 401172
00401151   mov    [ebp-8], 0
00401158   call   functionXYZ
0040115D   mov    eax, [ebp-8]
00401160   mov    ecx, [ebp-4]
00401163   mov    edx, [ebp-8]
00401166   add    edx, 1
00401169   mov    [ebp-8], edx
0040116C   cmp    eax, ecx
0040116E   jl     loc 401158
00401170   jmp    loc 401142
00401172   ...
```

Rule 1

High-Level Language	Assembler

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int i, j;
for (i = 0; i < 10; i++)
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  j=0;

  do
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```

Rule 1: First instruction of a program is a leader

Rule 2

High-Level Language	Assembler

```
int i, j;
for (i = 0; i < 10; i++)
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```

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Rule 2: Any instruction that is the target of a branch is a leader

Rule 2

High-Level Language

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Rule 2: Any instruction that is the target of a branch is a leader

Rule 2

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High-Level Language	Assembler

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Rule 2: Any instruction that is the target of a branch is a leader

Rule 2

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Rule 2: Any instruction that is the target of a branch is a leader

Rule 3

High-Level Language

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Rule 3: Any instruction that immediately follows a branch or return instruction is a leader

CFGs

- A *control flow graph* (*CFG*) is a graph representation of the different paths that a program might traverse
  - CFG is directed multigraph
  - Nodes are basic blocks
  - Edges represent flow of control (either branches or fall-through execution)
- No information about data is available in CFG
  - An edge means that a program *may* take the path

Dominators

- A node **a** in a CFG *dominates* a node **b** if every path from the start node to node **b** goes through **a**
- We say that node **a** is a *dominator* of node **b**
- The *dominator set* of node **b**, *dom(b)*, is formed by all nodes that dominate **b**
- By definition, each node dominates itself, therefore, **b** $\in$ dom(**b**)

Domination Relation

- *Definition*: Let G = (N, E, s) denote a flowgraph with set of vertices N, set of edges E, starting node **s**, and let **a** $\in$ N, **b** $\in$ N

1. **a** *dominates* **b**, written **a** $\leq$ **b**, if every path from **s** to **b** contains **a**
2. **a** *properly dominates* **b**, written **a** < **b**, if **a** $\leq$ **b** and **a** $\neq$ **b**

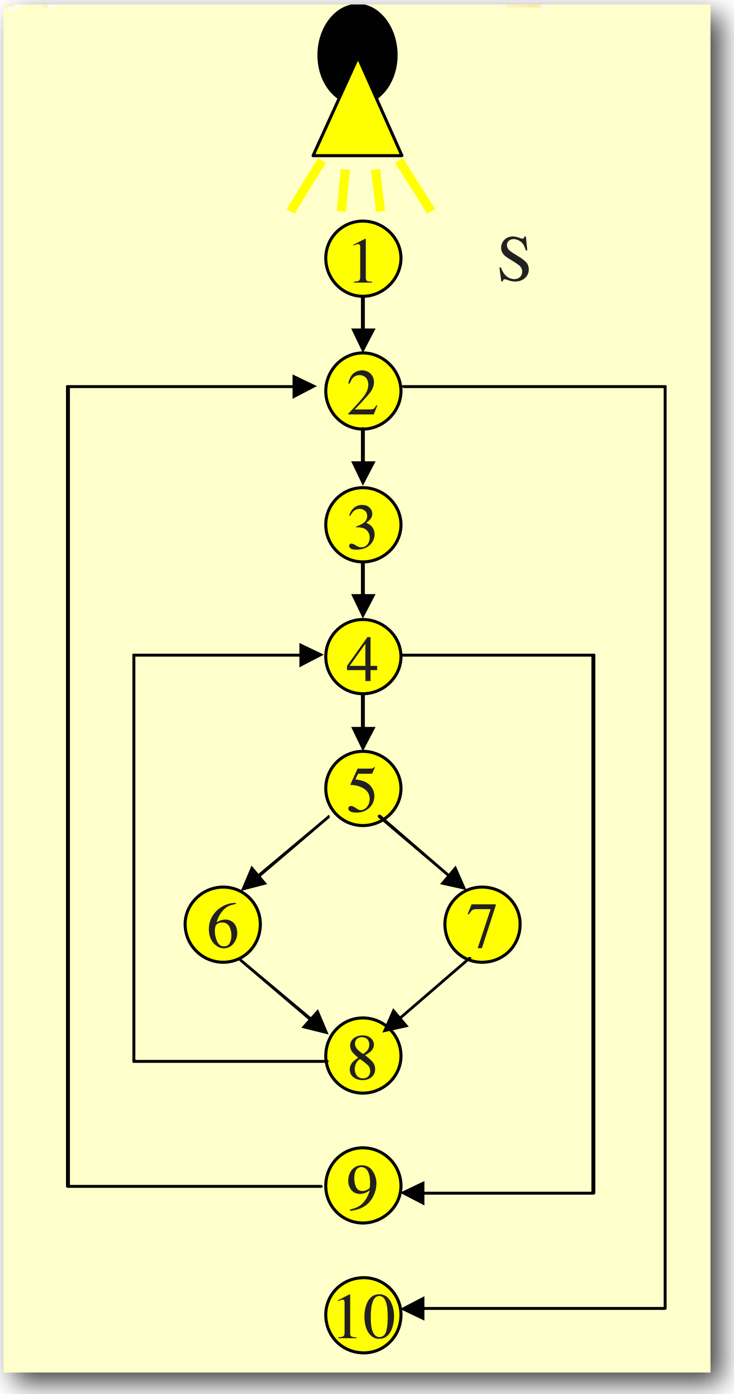
Domination Relation

- *Definition*: Let G = (N, E, s) denote a flowgraph with set of vertices N, set of edges E, starting node **s**, and let **a** $\in$ N, **b** $\in$ N

3. **a** *directly (immediately) dominates* **b**, written **a** $<_d$ **b** if:
   - **a** < **b** and
   - there is no **c** $\in$ N such that **a** < **c** < **b**

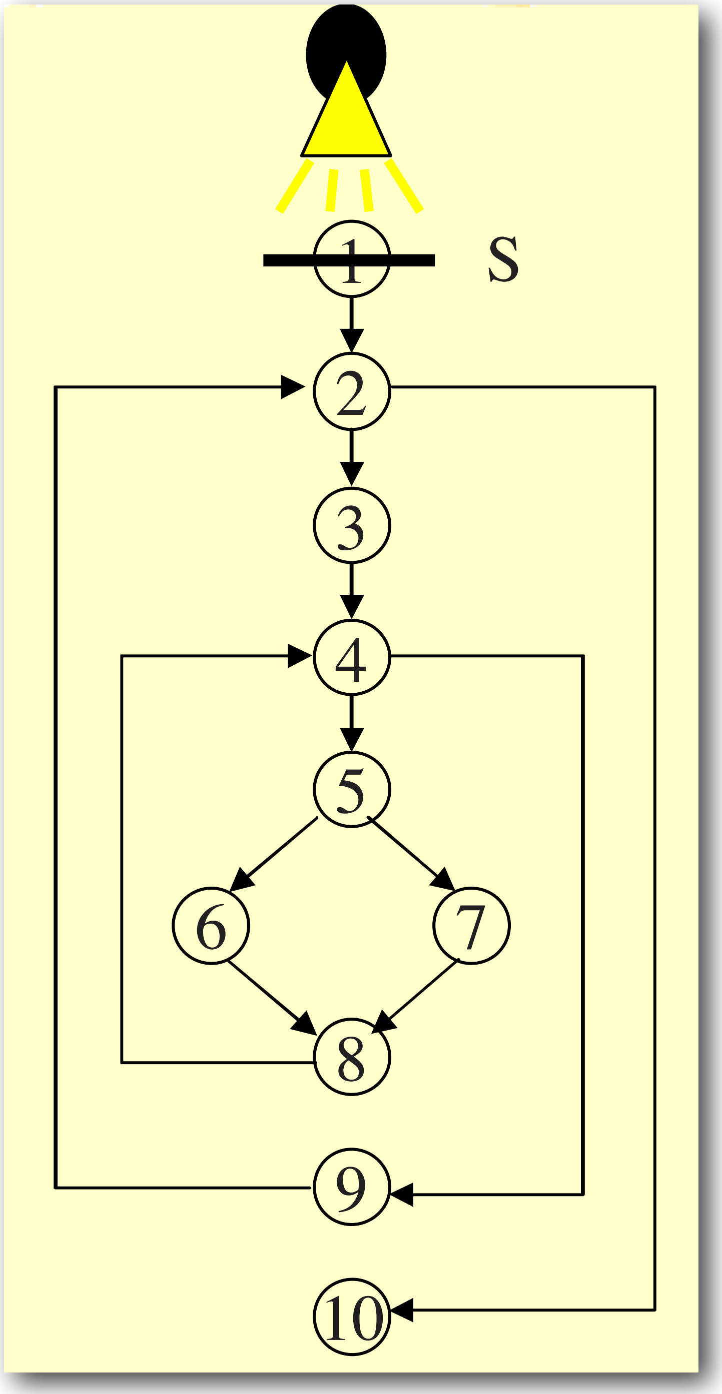
Dominator Intuition

- Imagine a source of light at the start node, and that the edges are optical fibers
- To find which nodes are dominated by a given node **a**, place an opaque barrier at **a** and observe which nodes became dark



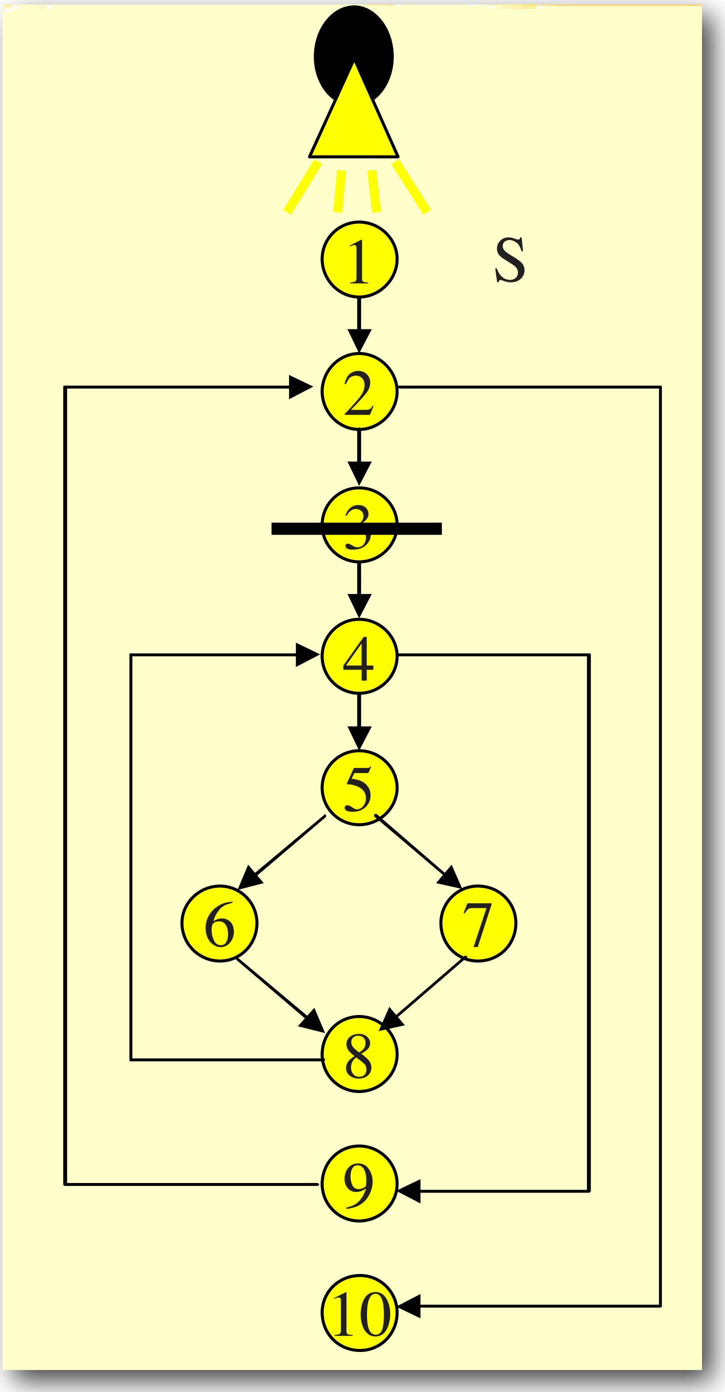
Dominator Intuition

- The start node dominates all nodes in the flowgraph.



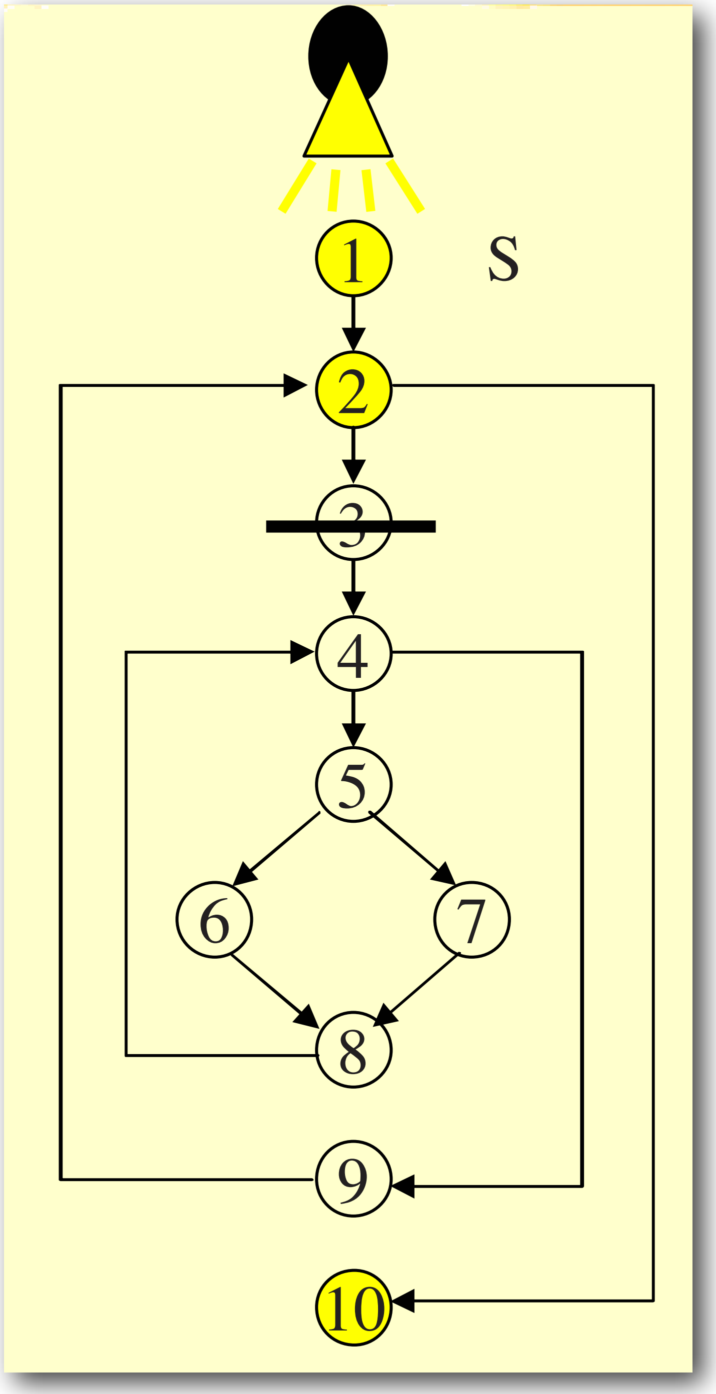
Dominator Intuition

- Which nodes are dominated by node 3?



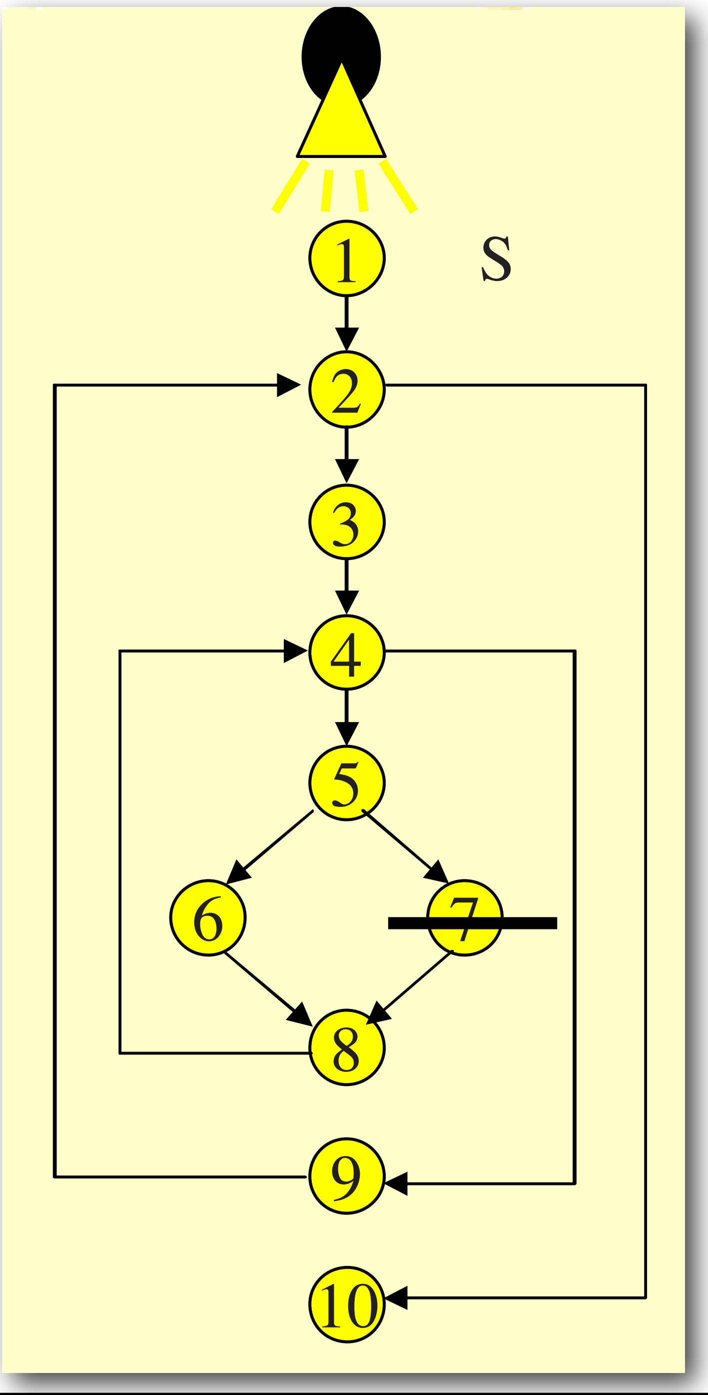
Dominator Intuition

- Which nodes are dominated by node 3?
- Node 3 dominates nodes 3, 4, 5, 6, 7, 8, and 9



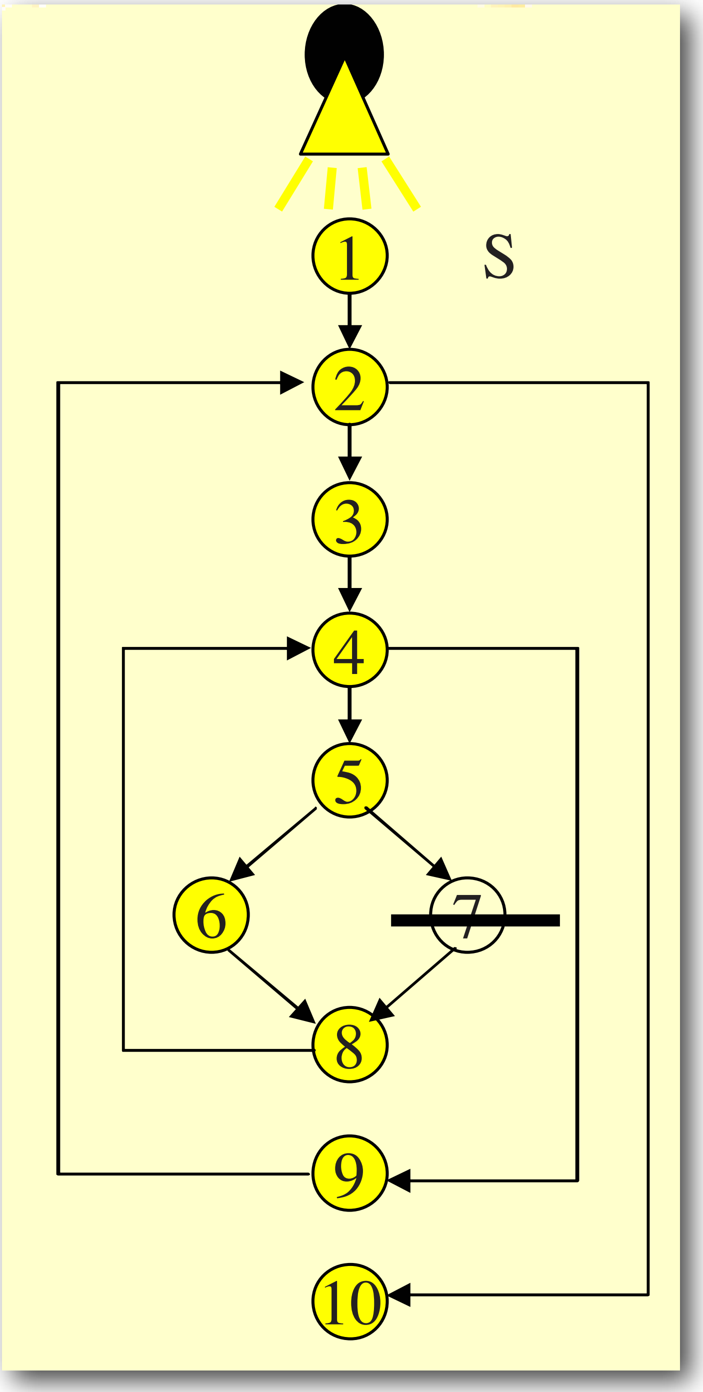
Dominator Intuition

- Which nodes are dominated by node 7?



Dominator Intuition

- Which nodes are dominated by node 7?
- Node 7 only dominates itself



Loop Detection

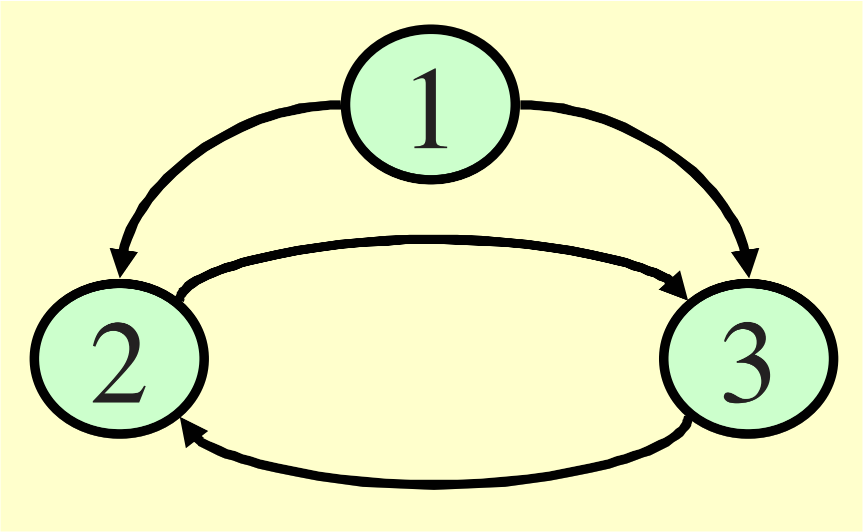
- Loops are defined as repeated execution of the same instructions, typically with different data
- How do we identify loops in a flow graph?
- The goal is to create an uniform treatment for program loops written using different loop structures (e.g. while, for) and loops constructed out of `goto`
- *Basic idea*: Use a general approach based on analyzing graph-theoretical properties of the CFG

Definitions

- A *strongly-connected component* (SCC) of a flowgraph G = (N, E, s) is a subgraph G' = (N', E', s') in which there is a path from each node in N' to every node in N'
- A strongly-connected component G' = (N', E', s') of a flowgraph G = (N, E, s) is a loop with entry s' *if s' dominates all nodes in N'*

Example

In the flow graph below, do nodes 2 and 3 form a loop?



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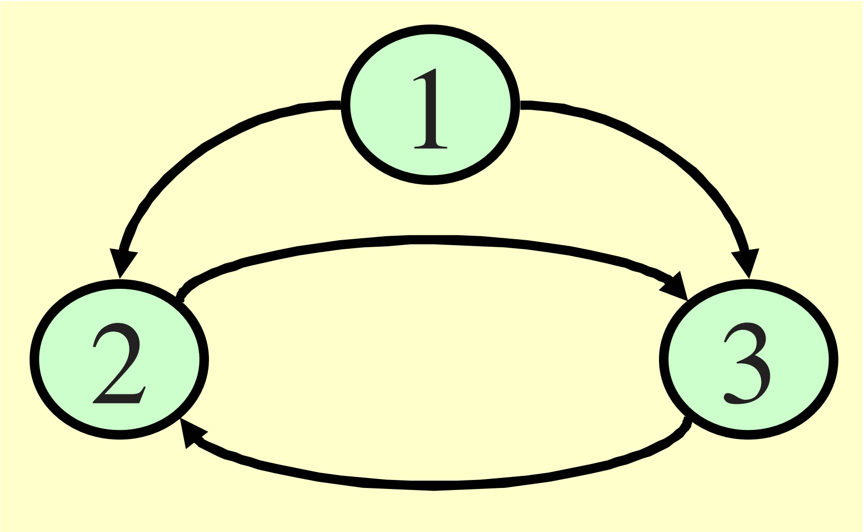
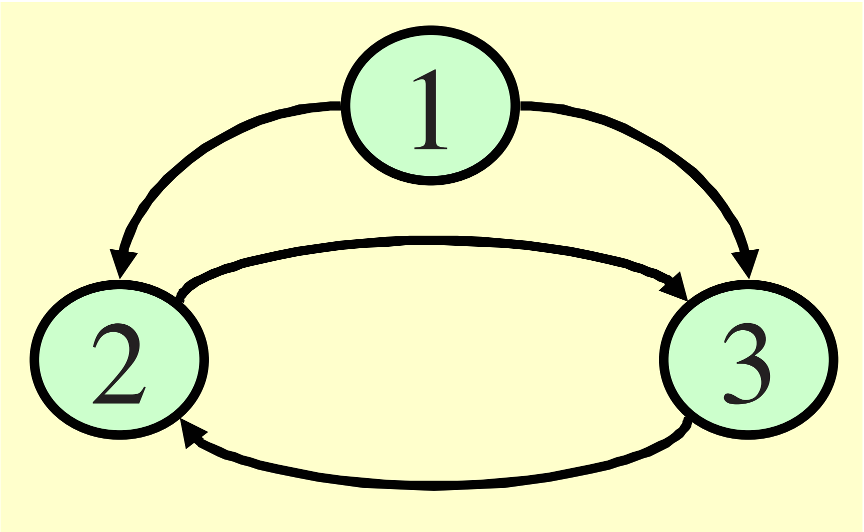


- Nodes 2 and 3 form a strongly connected component, but they are not a loop. Why?

Example

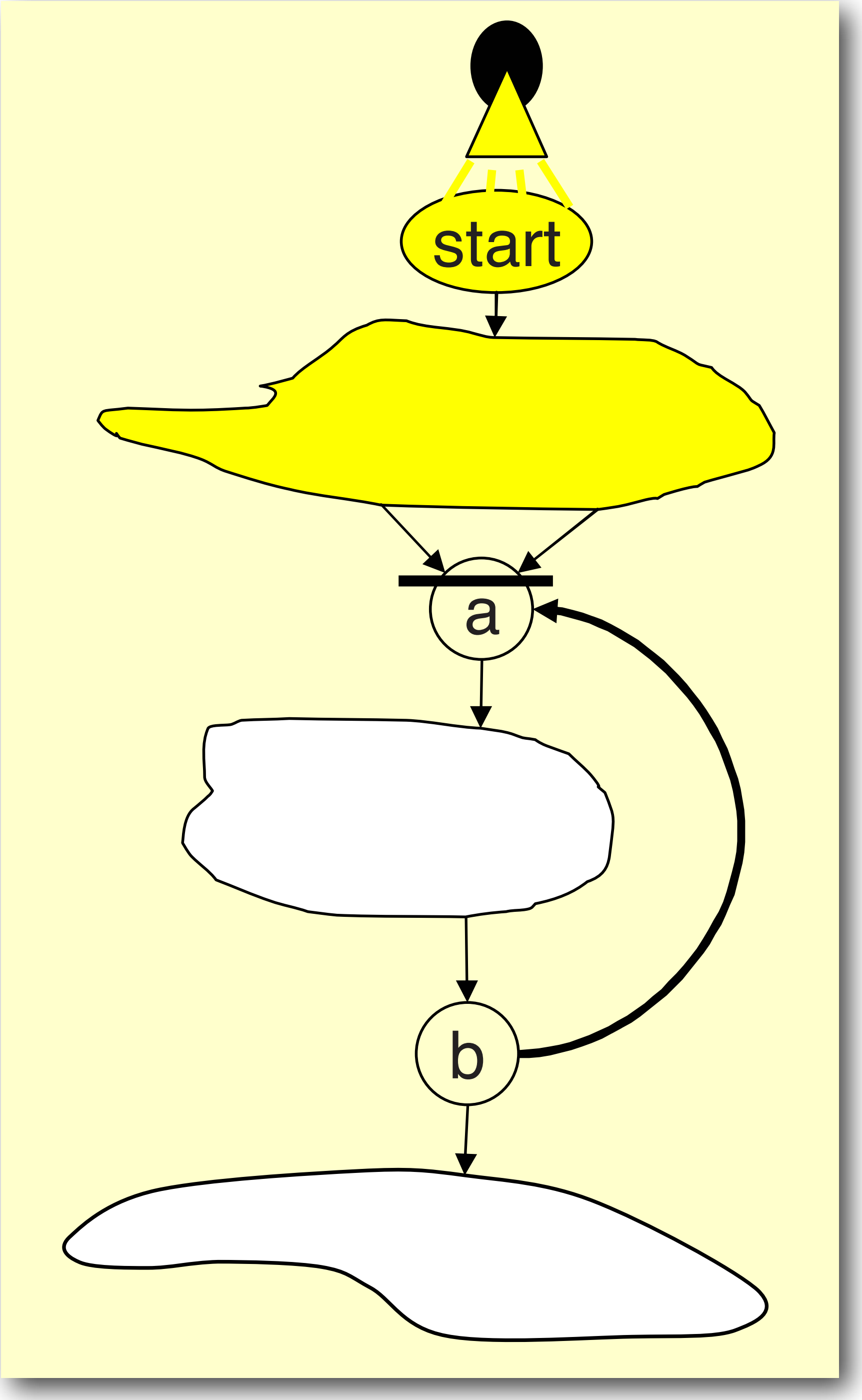
In the flow graph below, do nodes 2 and 3 form a loop?



- Nodes 2 and 3 form a strongly connected component, but they are not a loop. Why?
- No node in the subgraph dominates all the other nodes, therefore this subgraph is not a loop

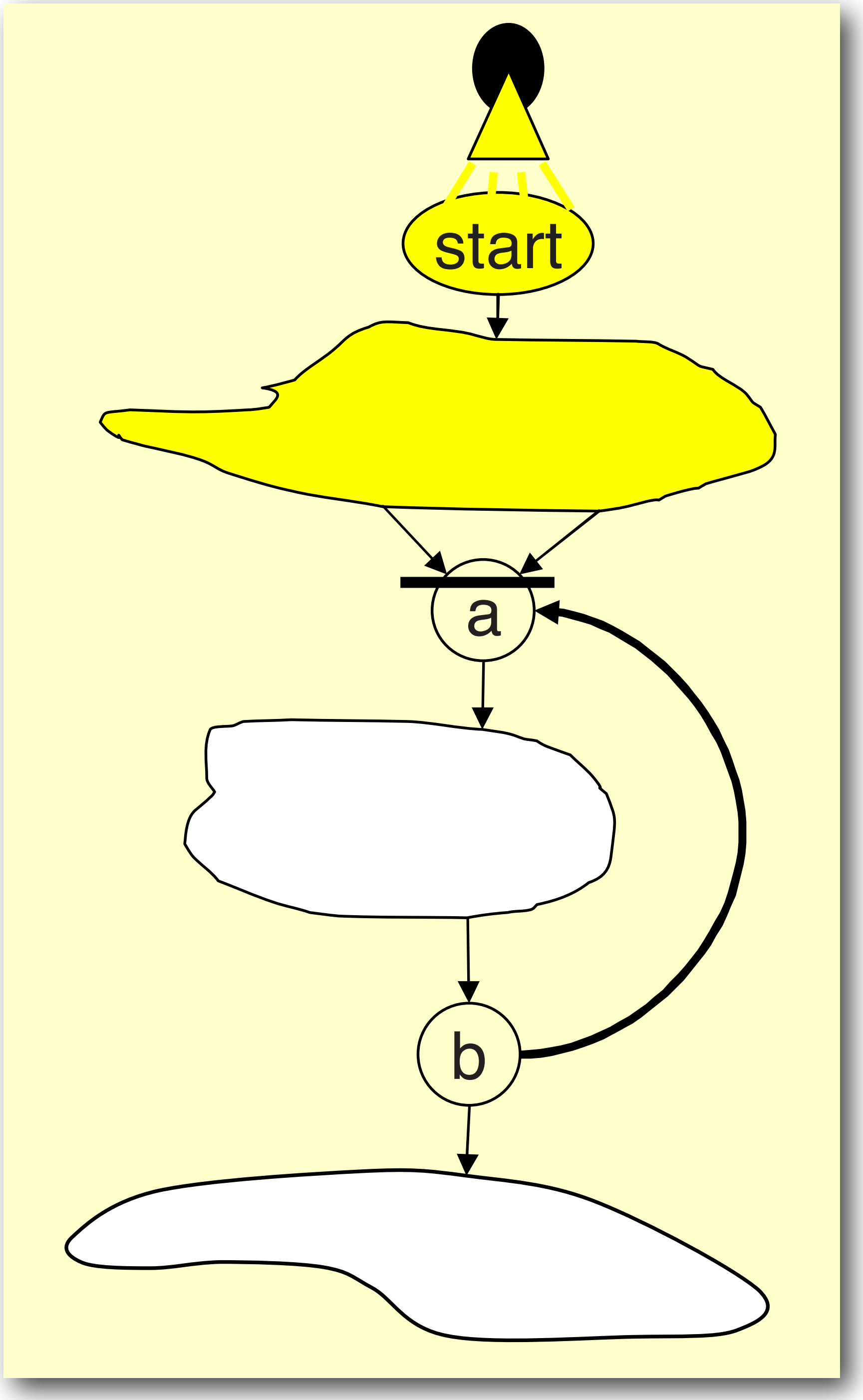
How to Find Loops?

- Look for "back edges"
- An edge (**b**, **a**) of a flowgraph G is a *back edge* if **a** dominates **b**, **a** < **b**



Natural Loops

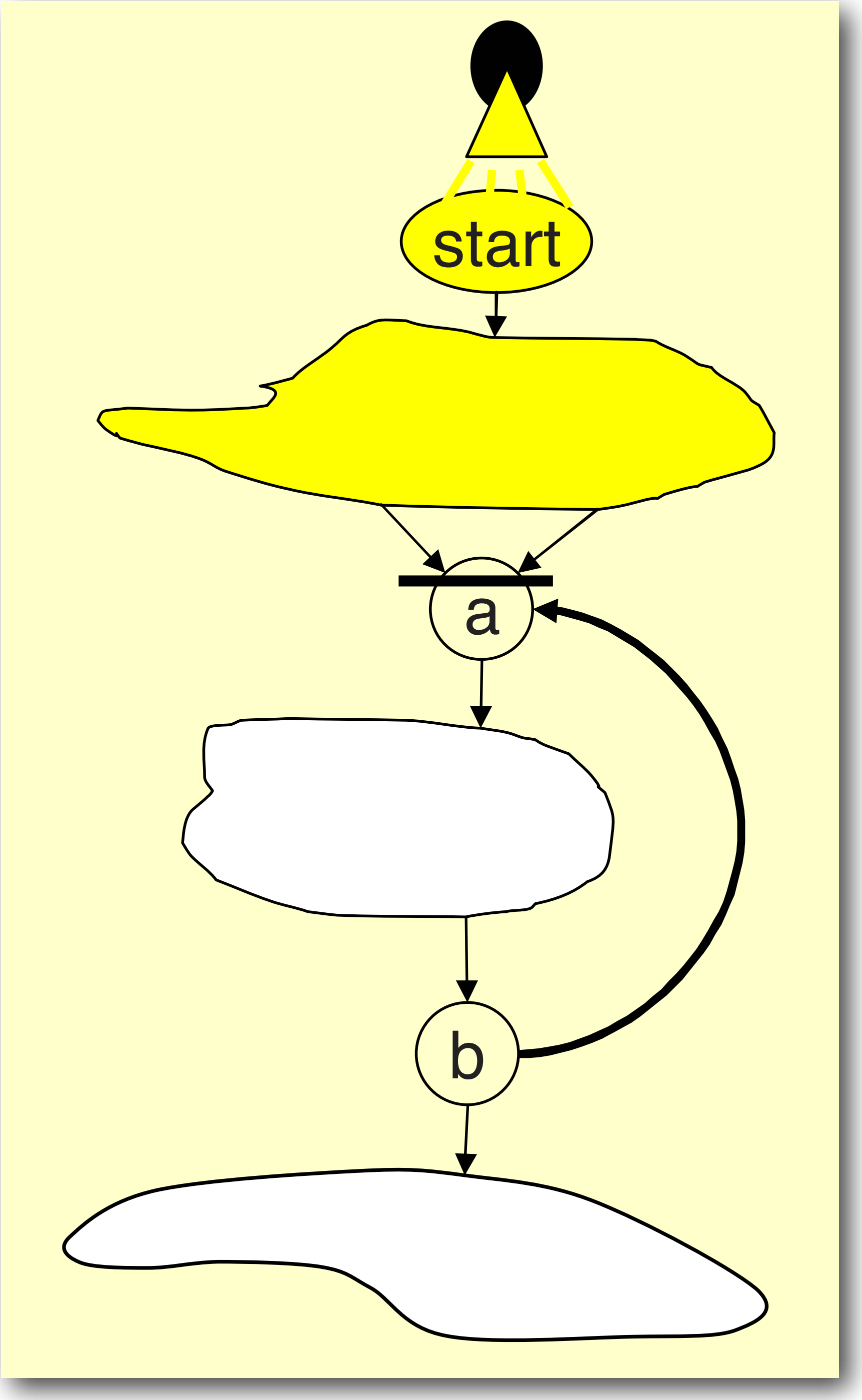
Given a back edge (**b**, **a**), a *natural loop* associated with (**b**, **a**) with entry in node **a** is the subgraph formed by **a** plus all nodes that can reach **b** without going through **a**



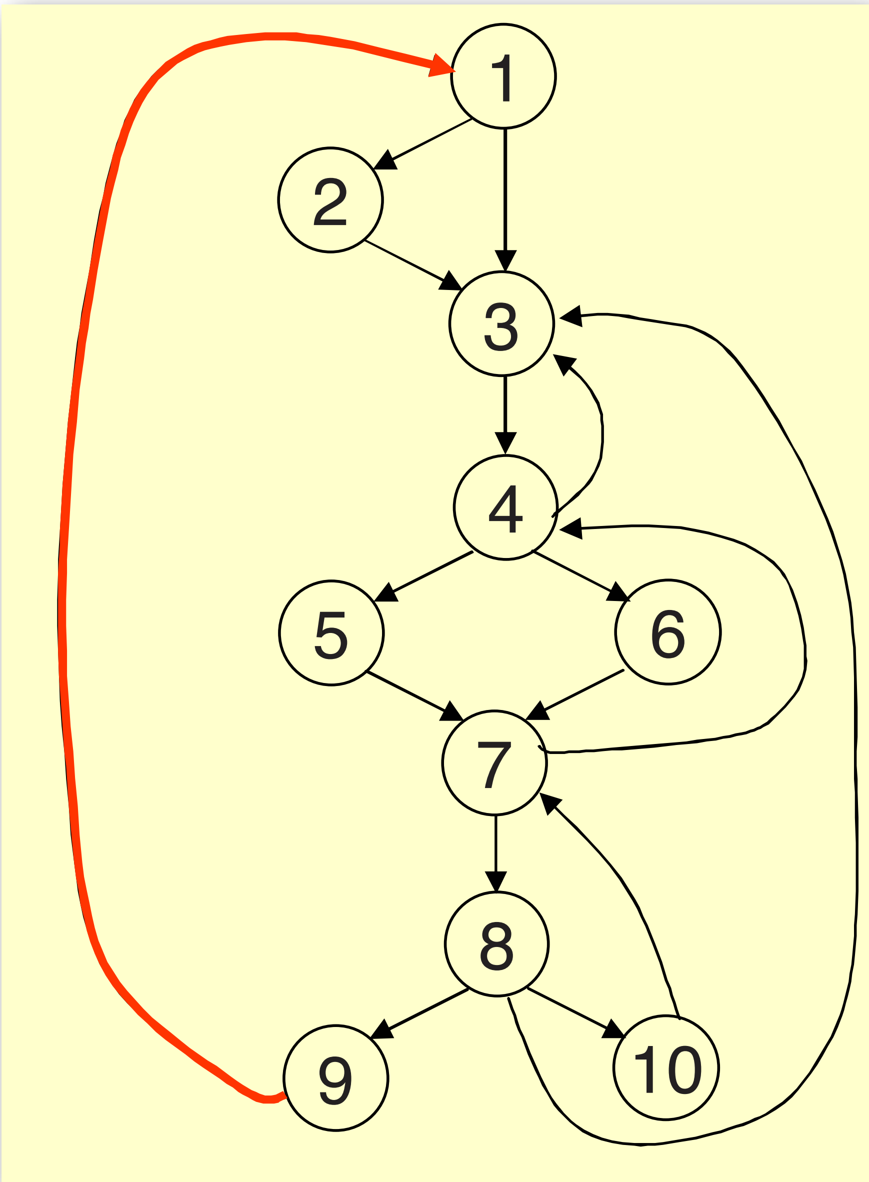
Natural Loops

One way to find natural loops is:

1. find a back edge (**b**, **a**)
2. find the nodes that are dominated by **a**
3. look for nodes that can reach **b** among the nodes dominated by **a**



Example



Find all back edges in this graph and the natural loop associated with each back edge

(9, 1)

(1) find a back edge (**b**, **a**)
(2) find the nodes that are dominated by **a**
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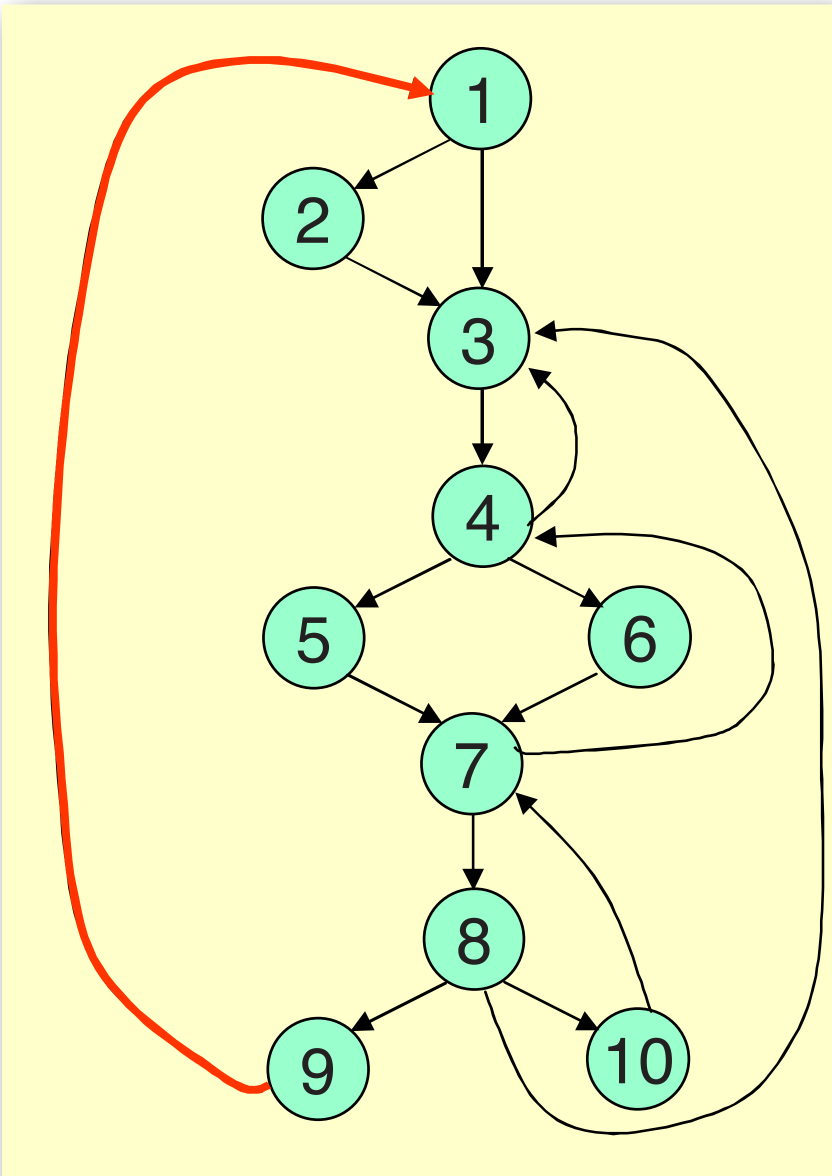
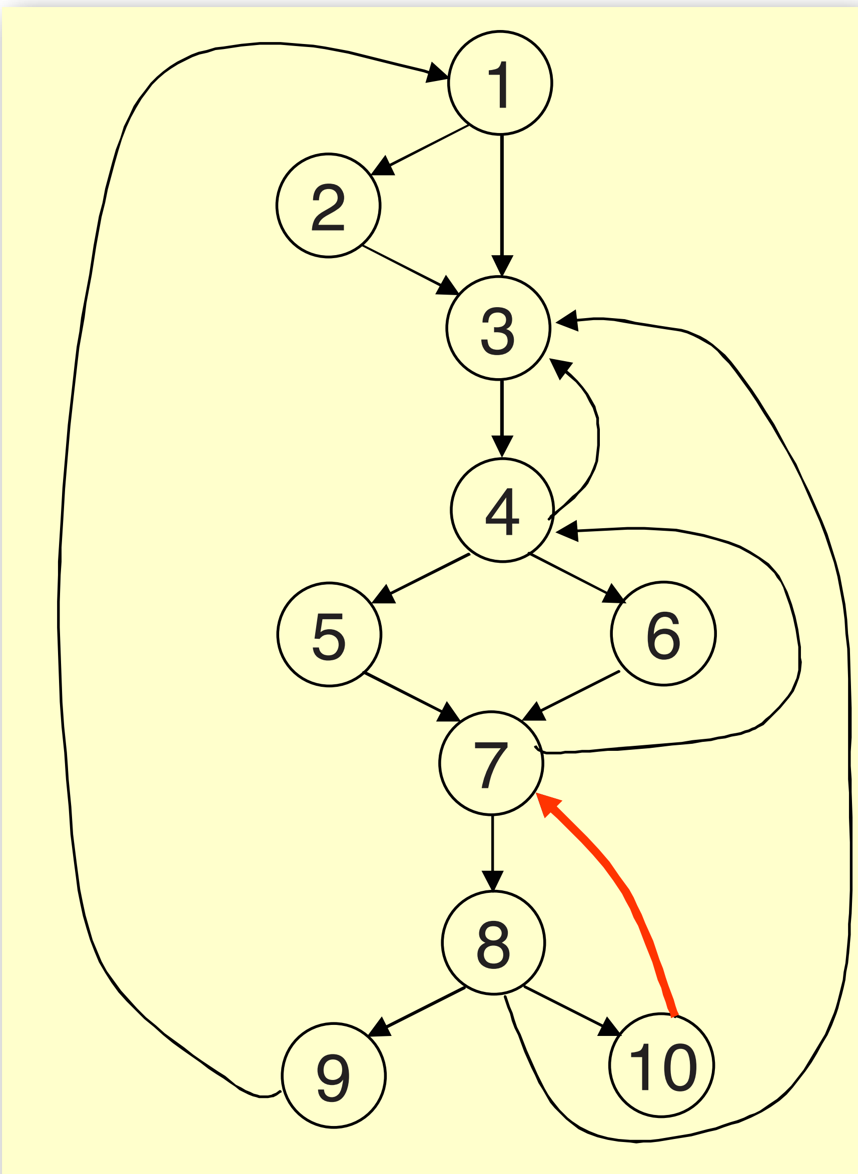
Example



Find all back edges in this graph and the natural loop associated with each back edge

(9, 1) Entire graph

Example



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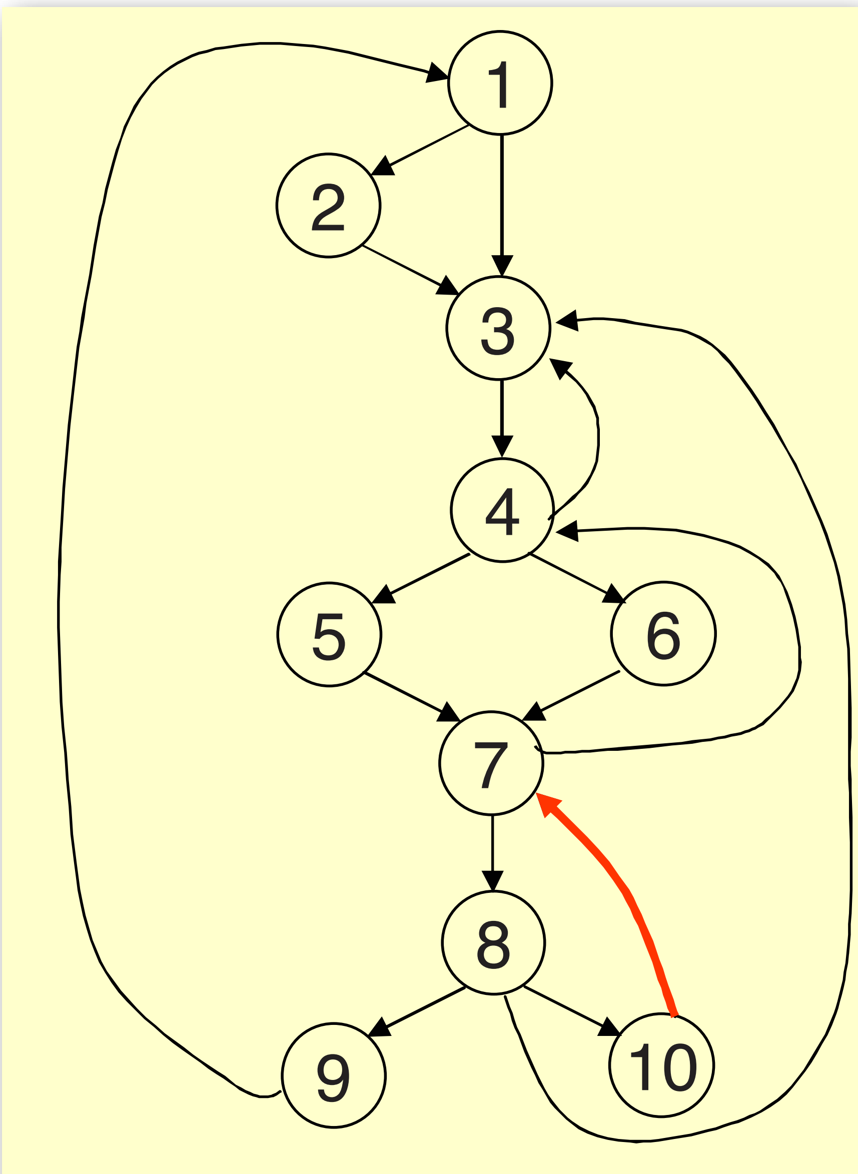
(9, 1)	Entire graph
(10, 7)	

Example



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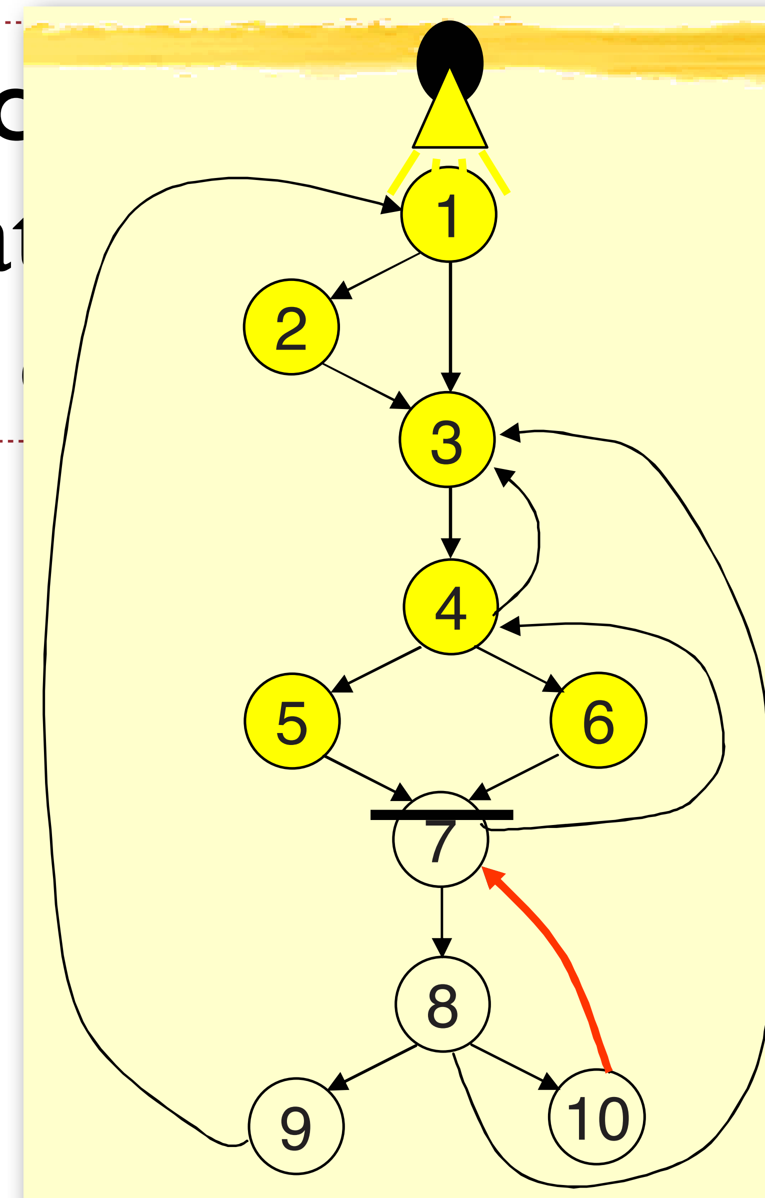

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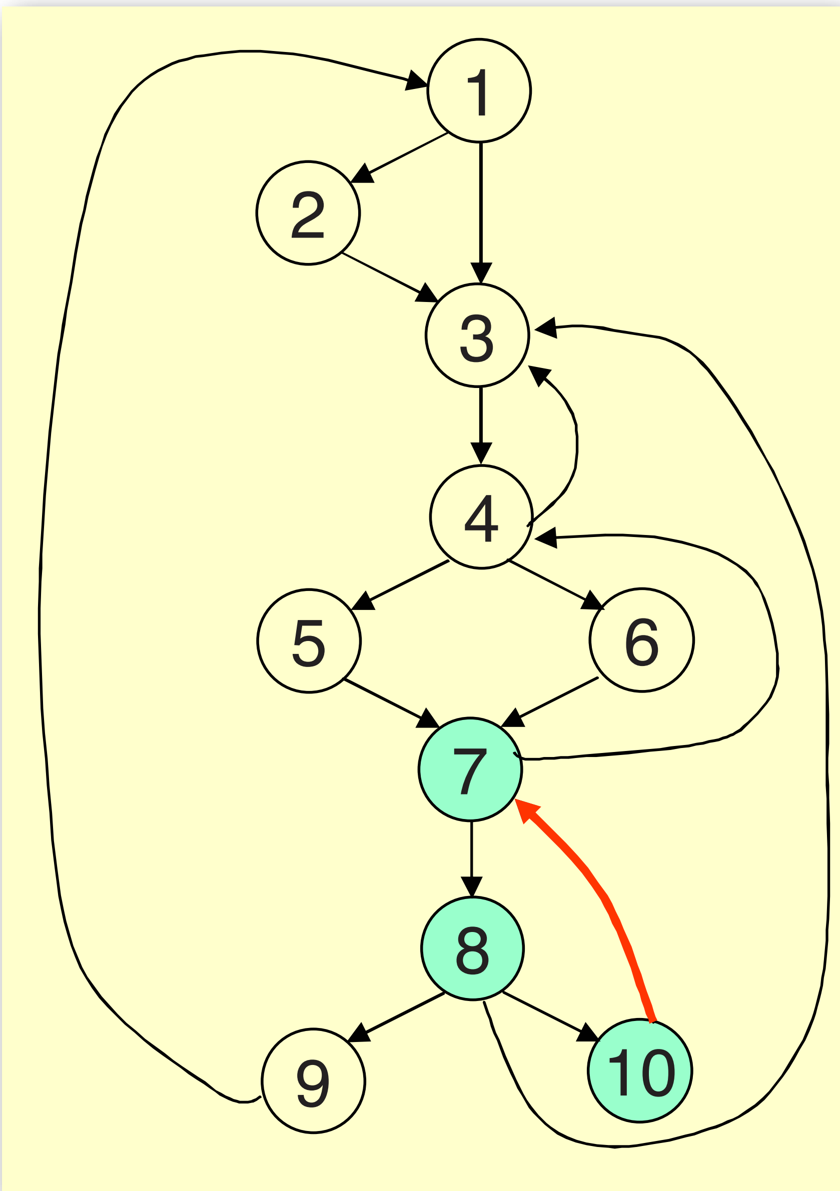
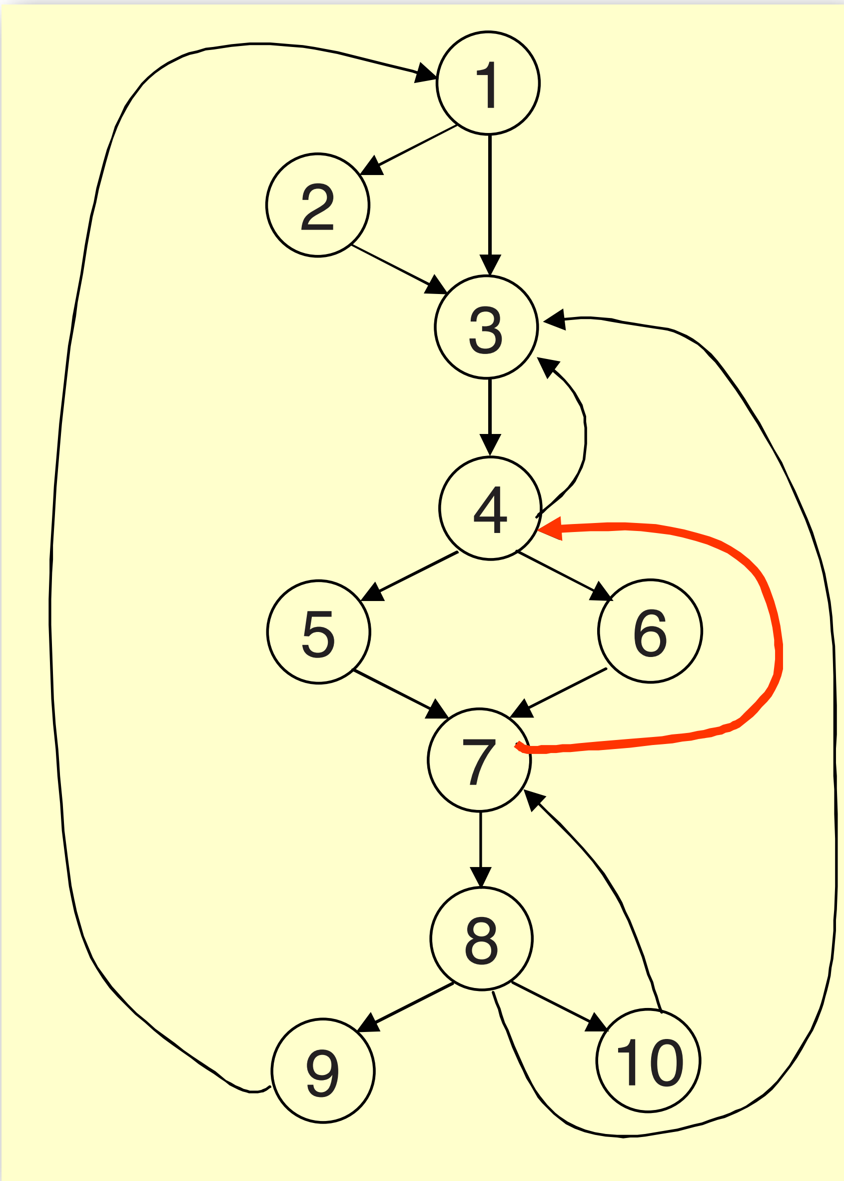
Example



Find all back edges in this graph and the natural loop associated with each back edge

(9, 1)	Entire graph
(10, 7)	{7, 8, 10}

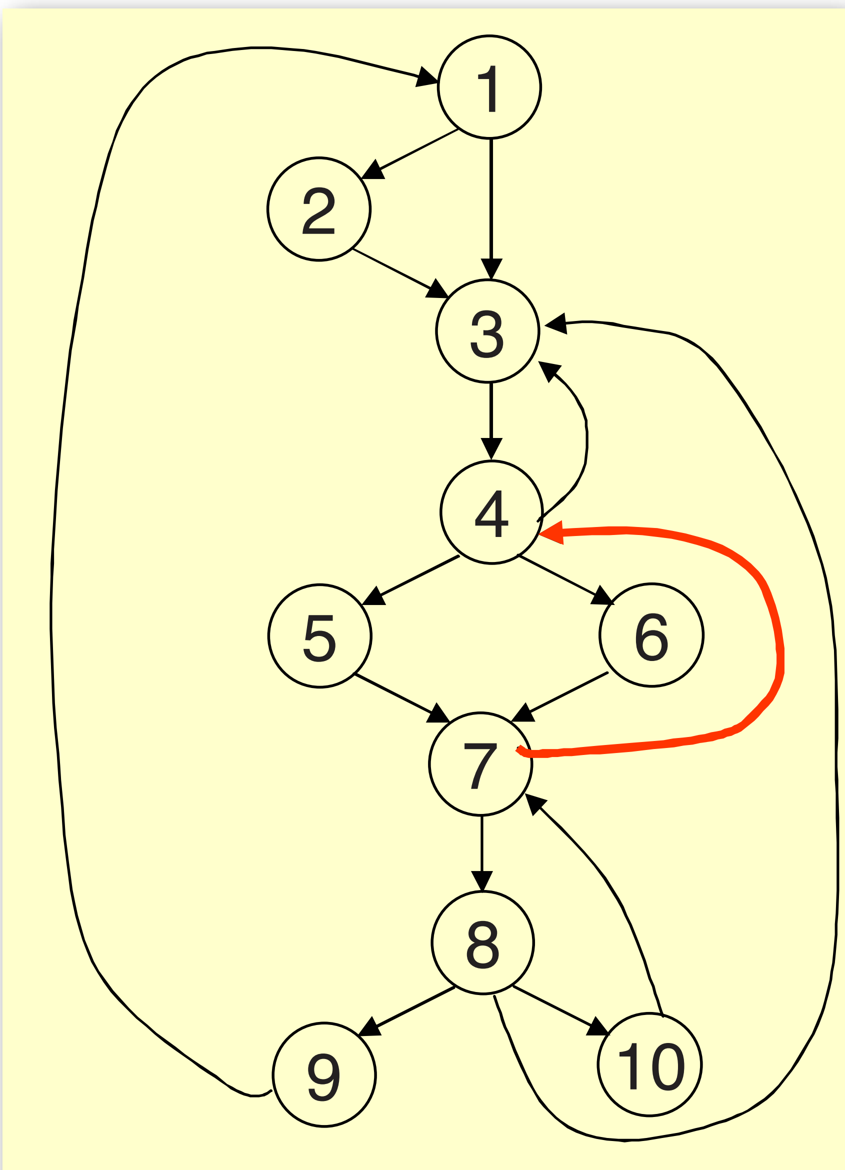
Example



Find all back edges in this graph and the natural loop associated with each back edge

(9, 1)	Entire graph
(10, 7)	{7, 8, 10}
(7, 4)	

Example



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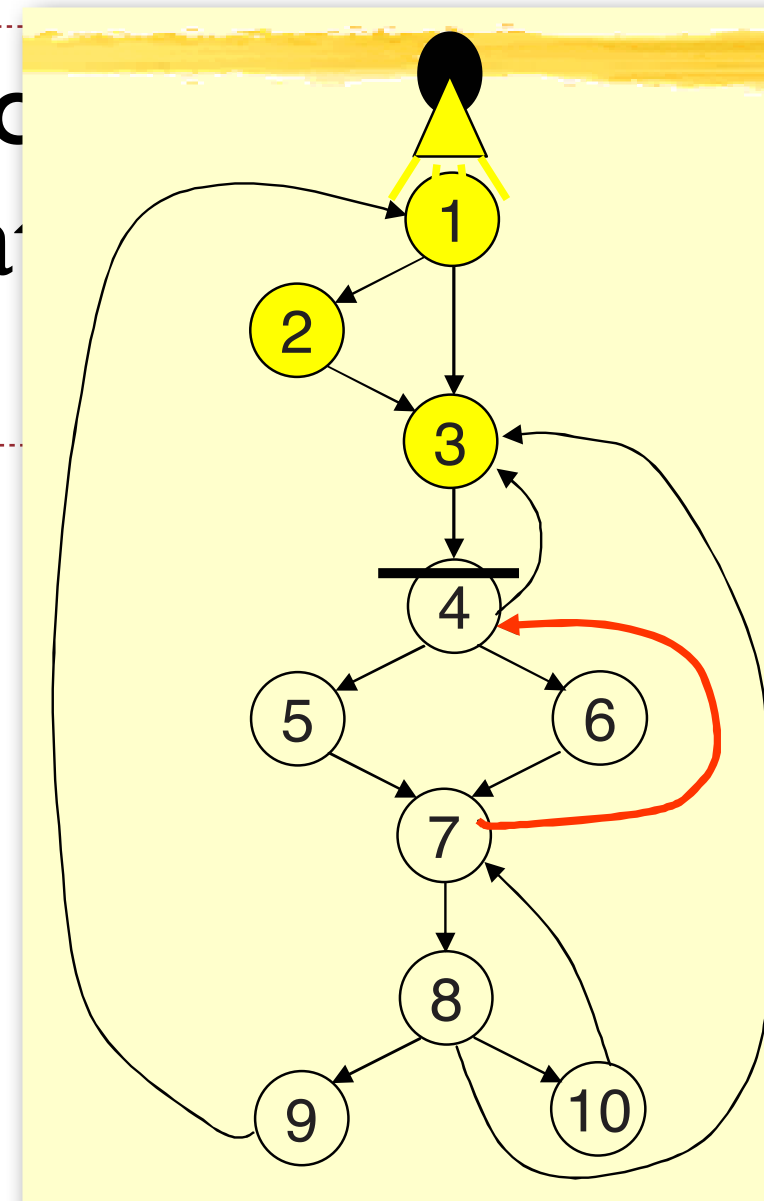

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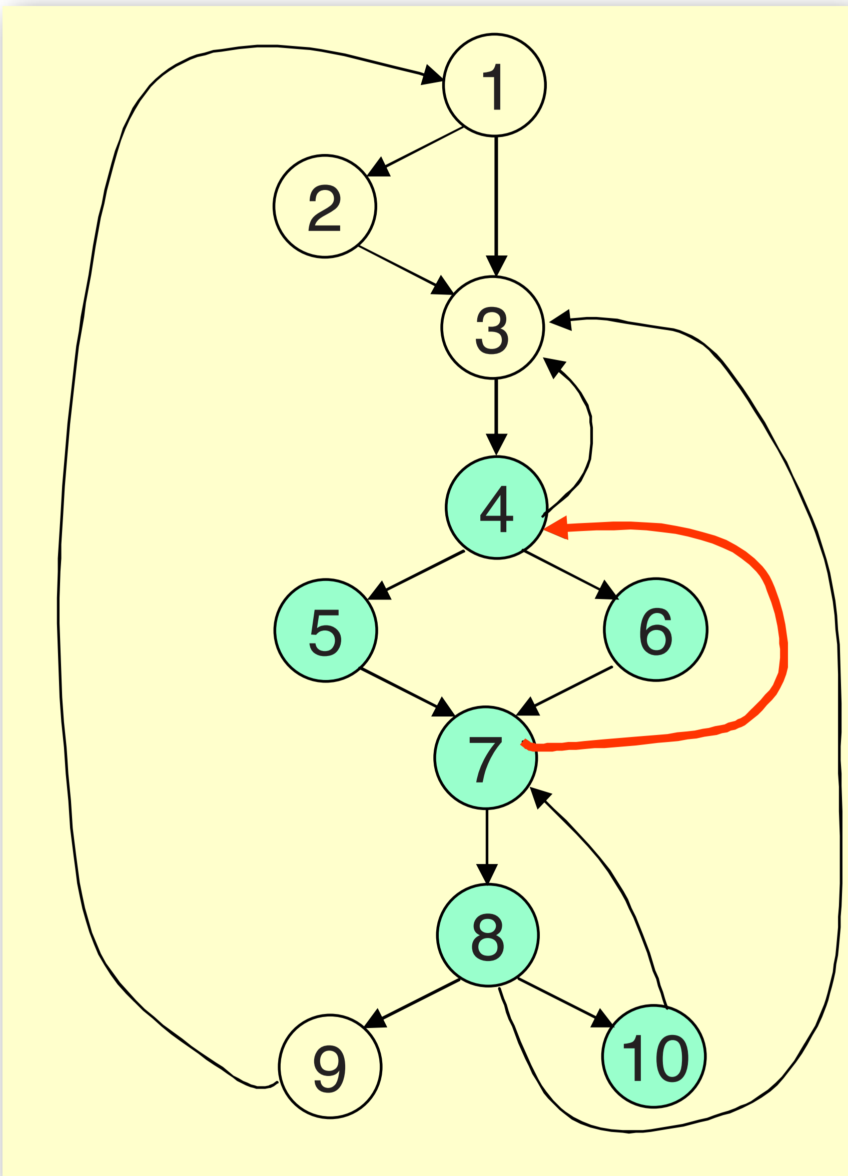

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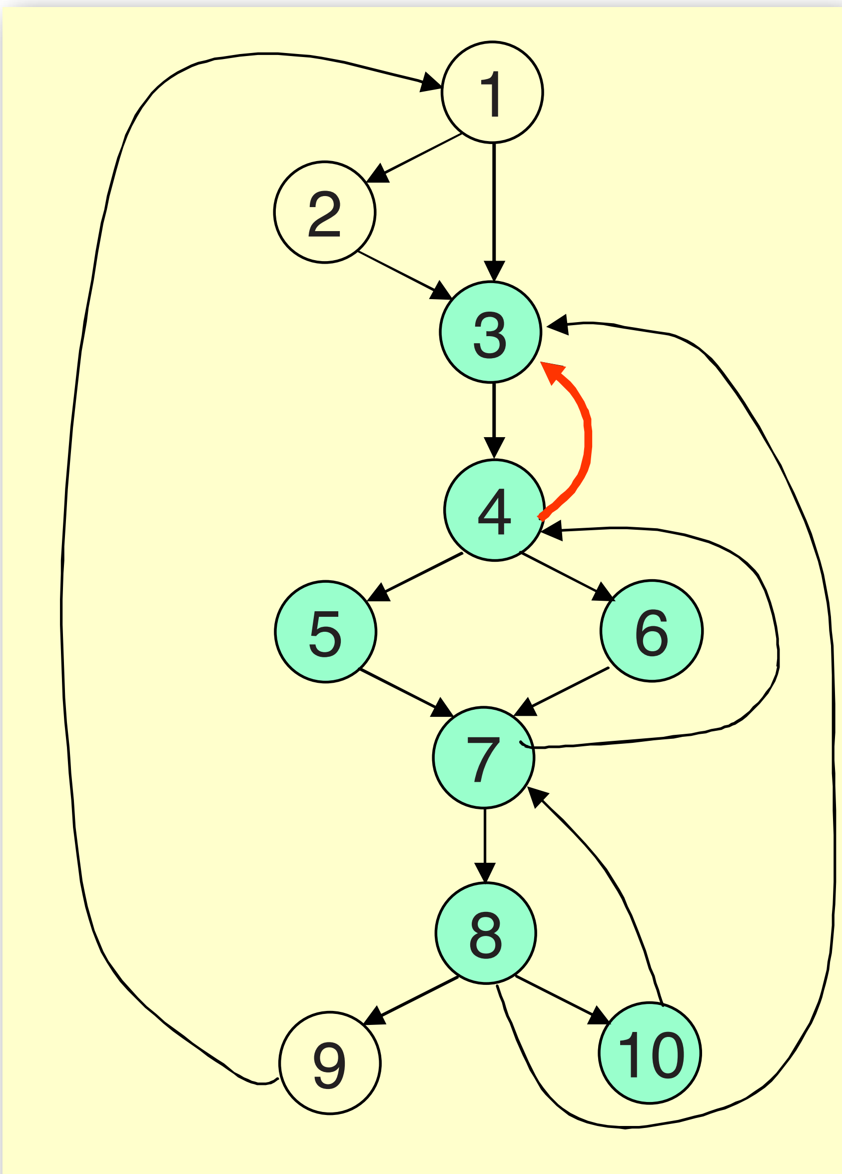


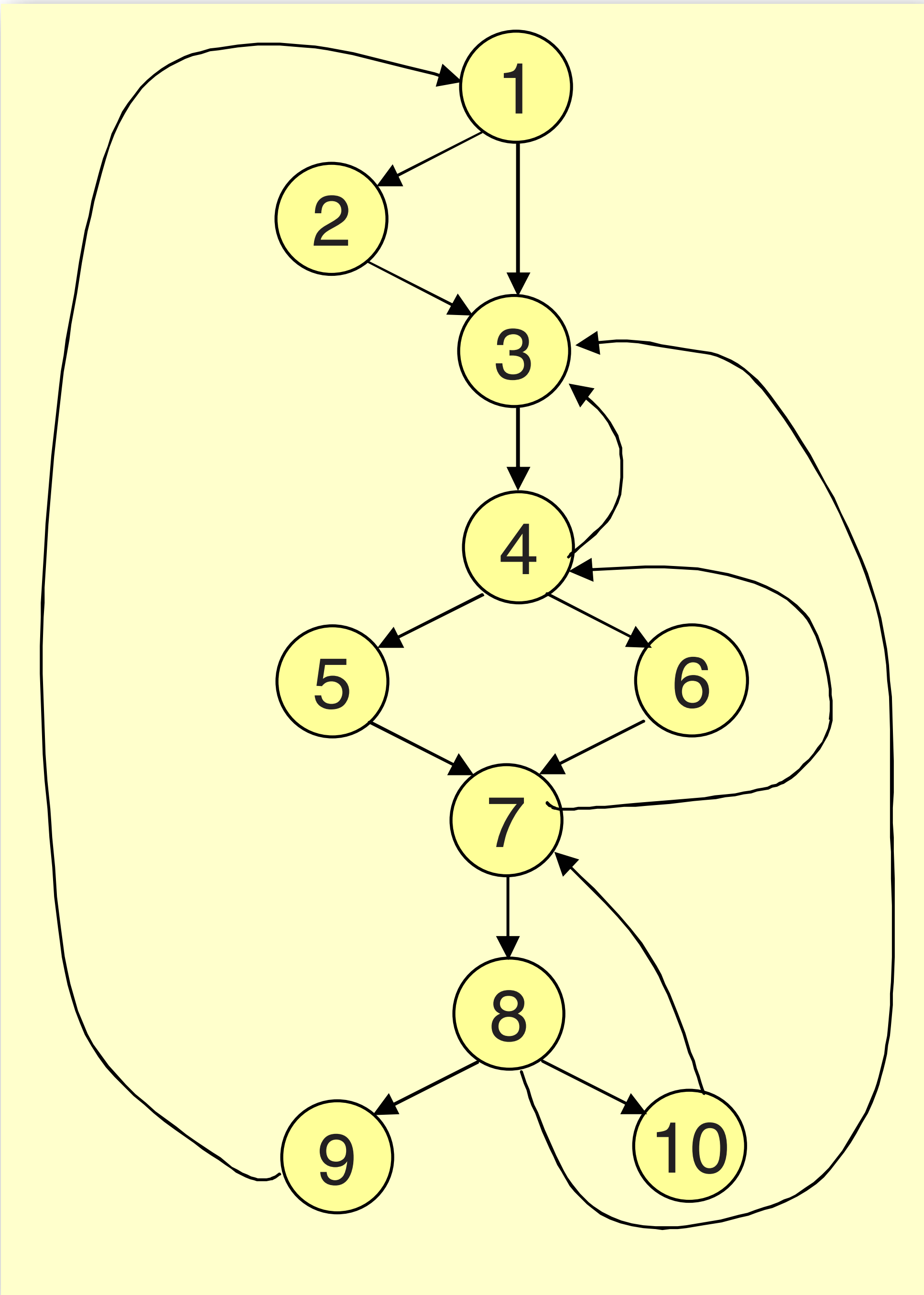
Find all back edges in this graph and the natural loop associated with each back edge

(9, 1)	Entire graph
(10, 7)	{7, 8, 10}
(7, 4)	{4, 5, 6, 7, 8, 10}
(8, 3)	{3, 4, 5, 6, 7, 8, 10}
(4, 3)	{3, 4, 5, 6, 7, 8, 10}

Dominator Tree

- A *dominator tree* is a useful way to represent the dominance relation
- In a dominator tree the start node **s** is the root, and each node **d** dominates only its descendents in the tree
- Efficient construction with the help of the *Lengauer Tarjan algorithm* (see Moodle for link to paper)

Example



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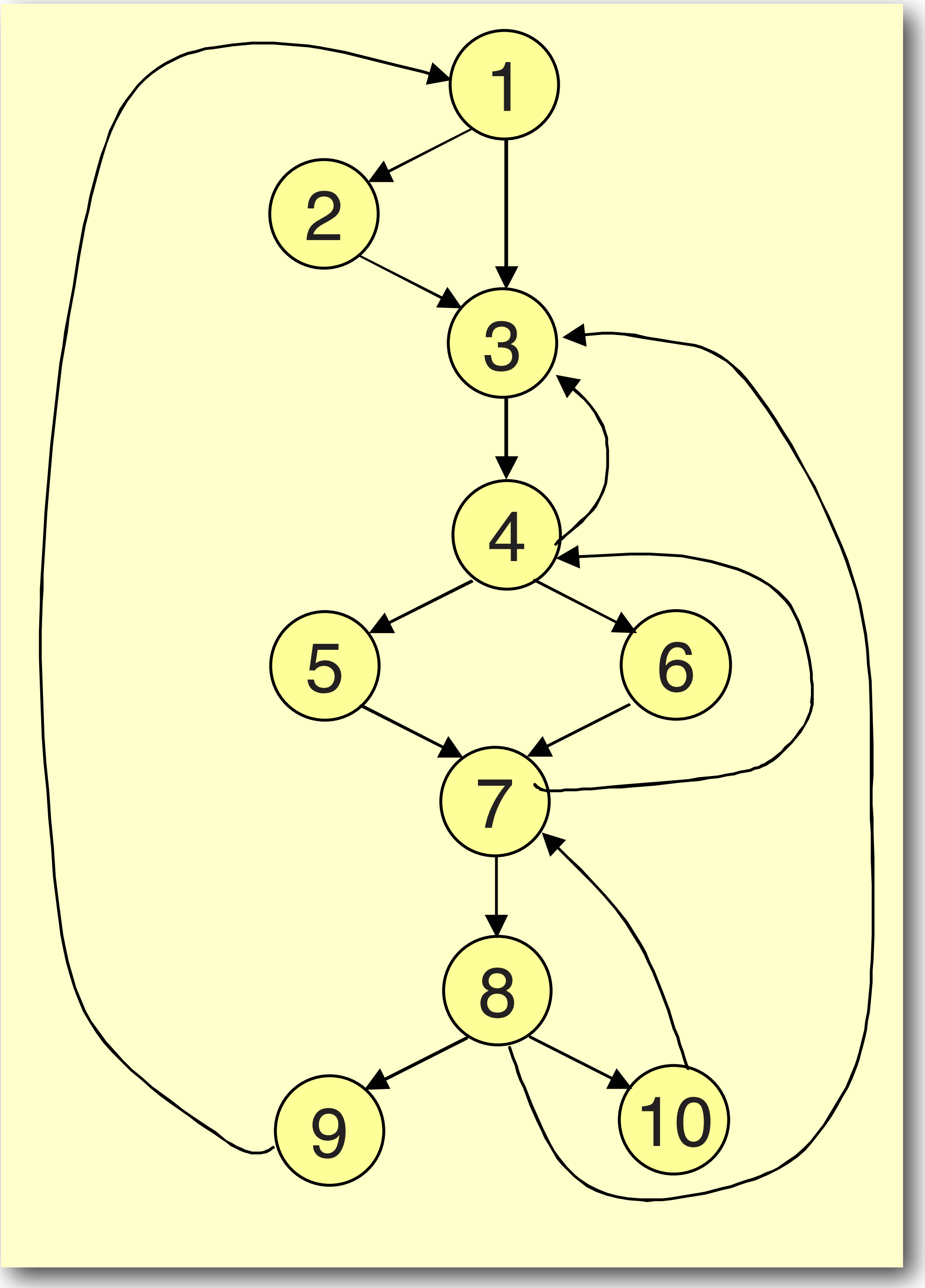
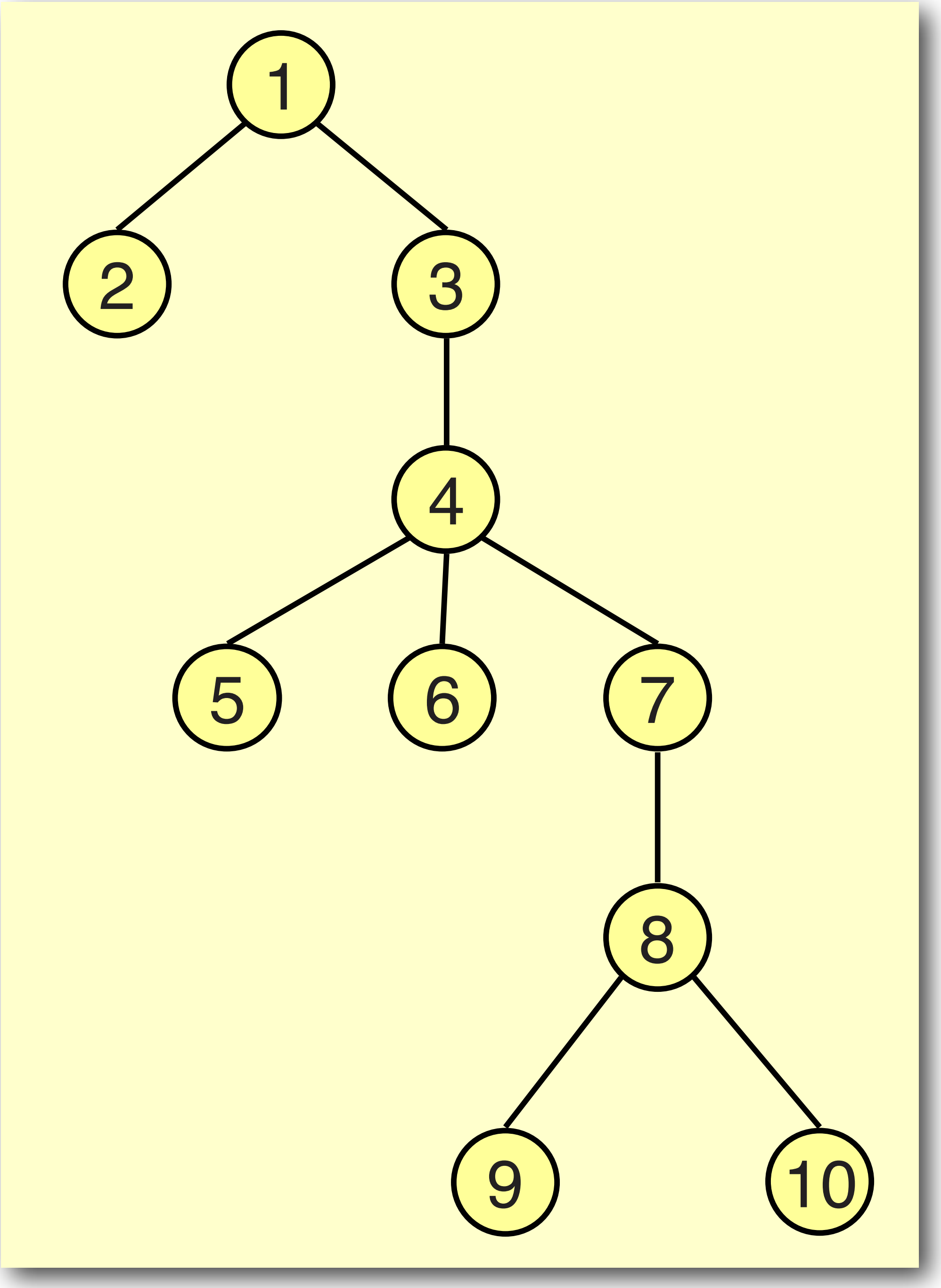
Example





Regions

- A *region* is a set of nodes N that include a *header* with the following properties:
  1. header must dominate all the nodes in the region
  2. all the edges between nodes in N are in the region (except for some edges that enter the header)
- A loop is a special region with additional properties:
  1. it is strongly connected
  2. all back edges to the header are included in loop

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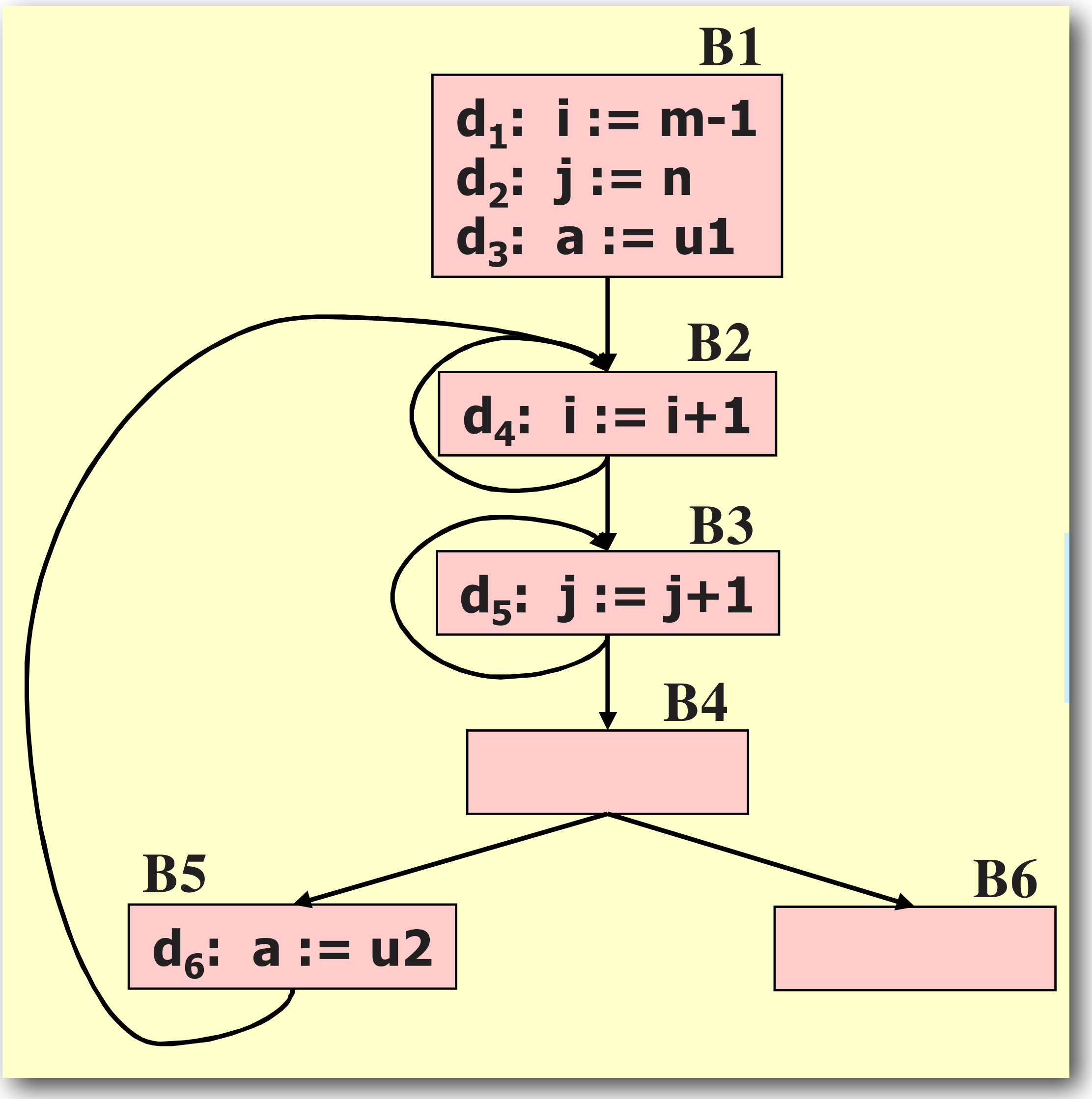
   1. header must dominate all the nodes in the region
   2. all the edges between nodes in N are in the region (except for some edges that enter the header)
- A loop is a special region with additional properties:

Typically we are interested on studying the data flow into and out of regions. For instance, which definitions reach a region

Points and Paths

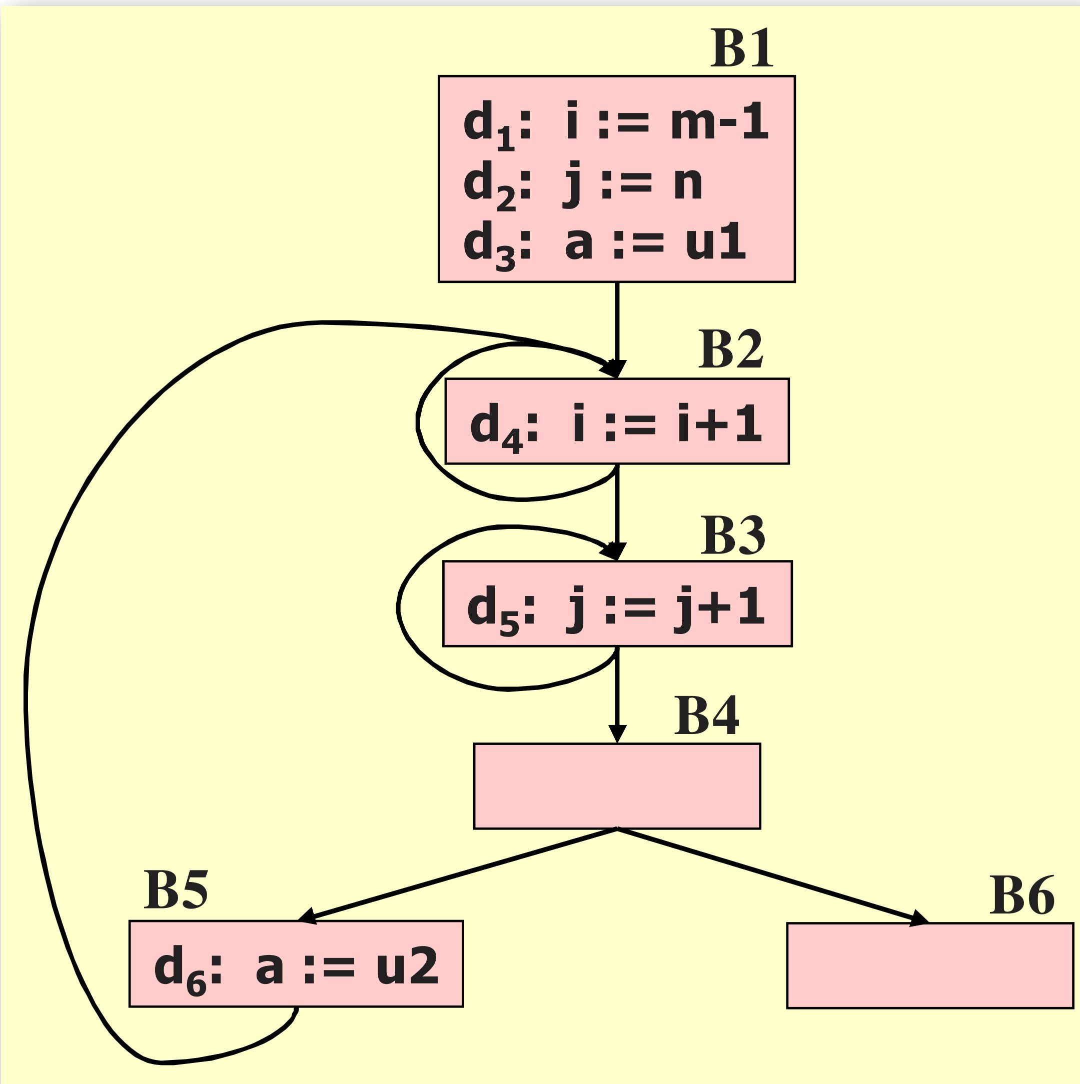


Points in a basic block:

- between statements
- before the first statement
- after the last statement

In the example, how many points do basic blocks B1, B2, B3, and B5 have?

Points and Paths

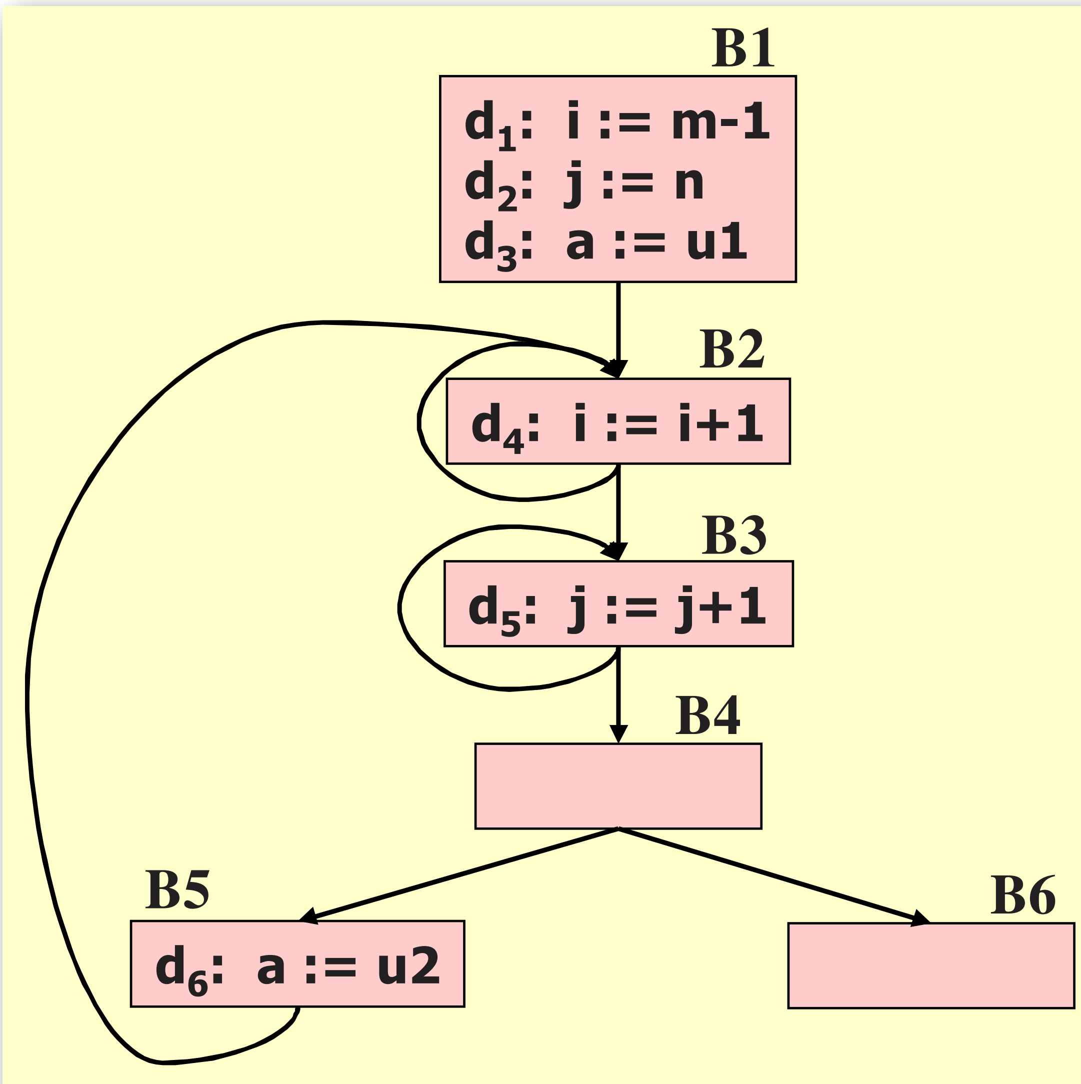


Points in a basic block:

- between statements
- before the first statement
- after the last statement

B1 has four, B2, B3, and B5 have two points each

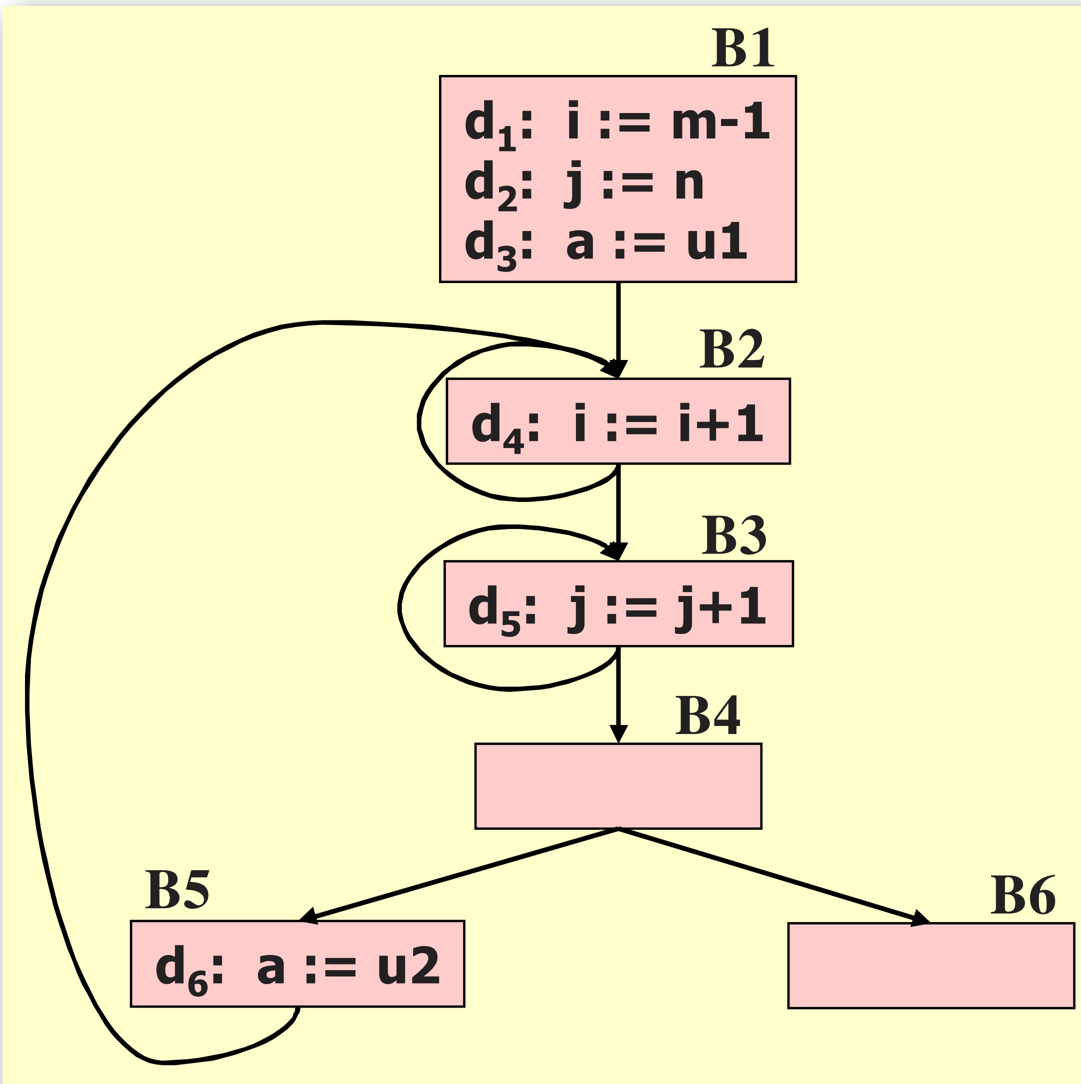
Points and Paths



A *path* is a sequence of points p_1, p_2, ..., p_n such that either:

1. if p_i immediately precedes *S*, then p_{i+1} immediately follows *S*
2. or p_i is the end of a basic block and p_{i+1} is the beginning of a successor block

Points and Paths

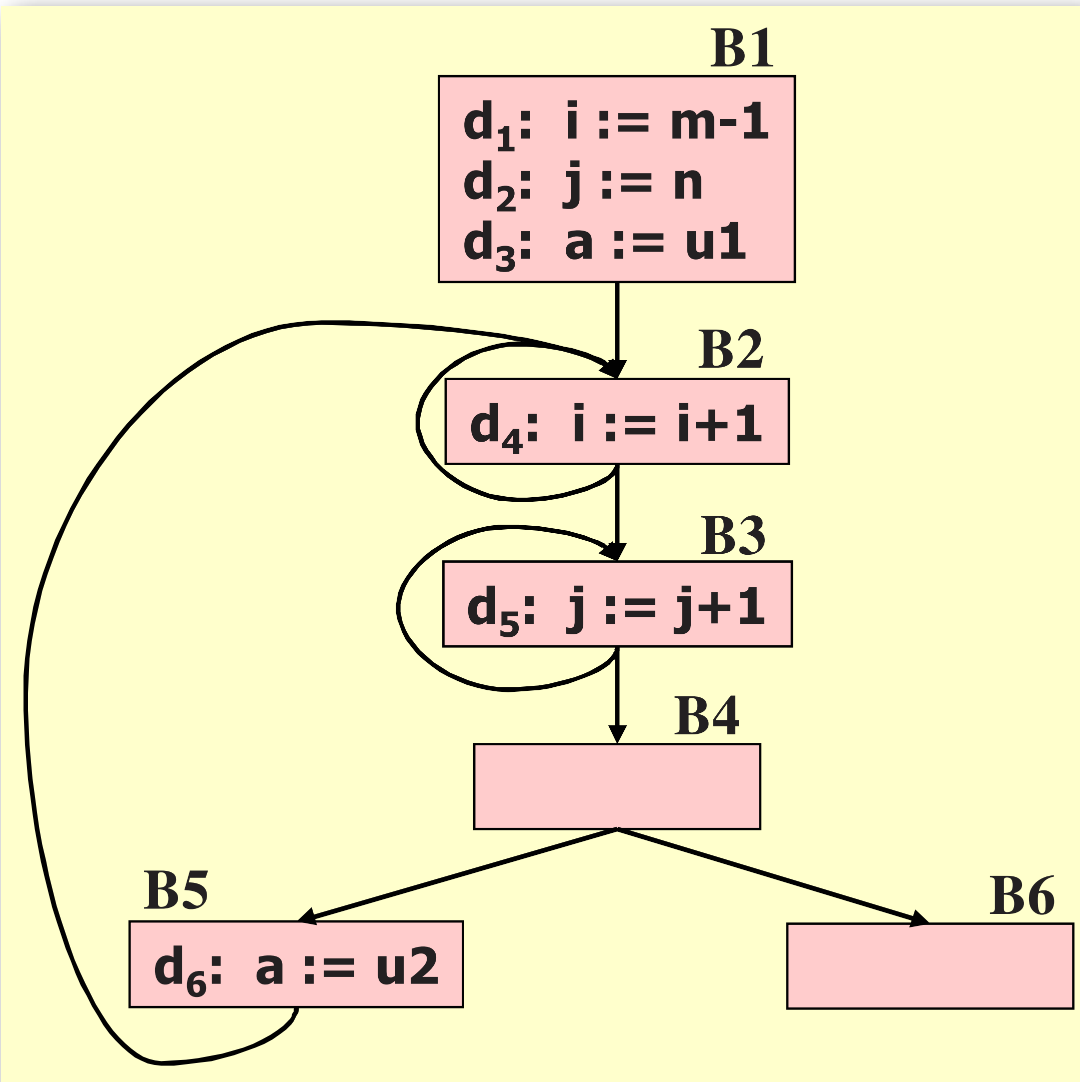


A *path* is a sequence of points p_1, p_2, ..., p_n such that either:

1. if p_i immediately precedes *S*, then p_{i+1} immediately follows *S*
2. or p_i is the end of a basic block and p_{i+1} is the beginning of a successor block

In the example, is there a path from the beginning of block B5 to the beginning of block B6?

Points and Paths



A *path* is a sequence of points p_1, p_2, ..., p_n such that either:

1. if p_i immediately precedes *S*, then p_{i+1} immediately follows *S*
2. or p_i is the end of a basic block and p_{i+1} is the beginning of a successor block

There is a path through the end point of B5 and then through all the points in B2, B3, and B4

Global Dataflow Analysis

- We need to know variable **def** and **use** information between basic blocks for:
  - constant folding
  - dead-code elimination
  - redundant computation elimination
  - code motion
  - induction variable elimination
  - build data dependence graph (DDG)

Definition and Use

S_k: $V_1 = V_2 + V_3$

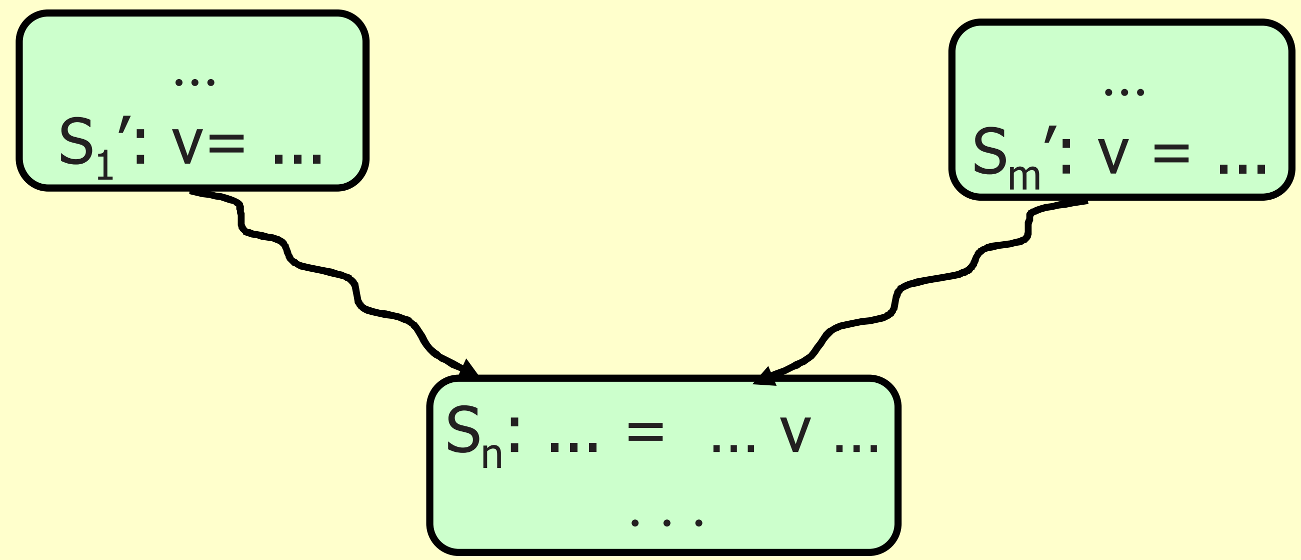
S_k is a *definition* of V_1
S_k is an *use* of V_2 and V_3

- We often need to study *def-use chains* to track how data propagates within a program
- Useful for other purposes as well

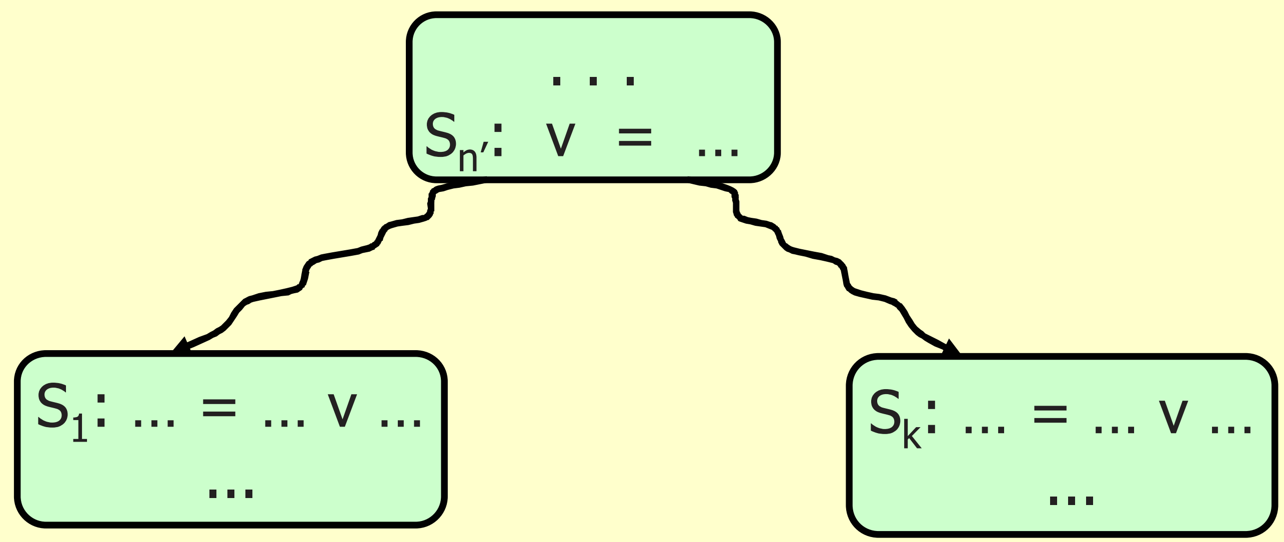
DU and UD Chains

- Many dataflow analyses need to find the use-sites of each defined variable or the definition-sites of each variable used in an expression
- *Def-Use* (D-U) and *Use-Def* (U-D) chains are efficient data structures that keep this information
  - An UD chain is a list of all definitions that can reach a given use of a variable
  - A DU chain is a list of all uses that can be reached by a given definition of a variable

Example



A **UD chain**: $UD(S_n, v) = (S_1', \ldots, S_m')$.



A **DU chain**: $DU(S_{n'}, v) = (S_1, \ldots, S_k)$.

Questions?

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Sources

- Lecture *Software Reverse Engineering* at University of Mannheim, spring term 2010 (Ralf Hund, Carsten Willems and Felix Freiling)
- Lecture *Compiler Design and Optimization* at University of Alberta by José Nelson Amaral
  - http://webdocs.cs.ualberta.ca/~amaral/courses/680/index.html