Dataflow Analysis

Masters in Informatics and Computing Engineering
(MIEIC), 3rd Year

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Outline

- Dataflow Analysis
- Liveness Analysis
- Exercise
- Dataflow Analysis Issues
- Applications of Dataflow Analysis

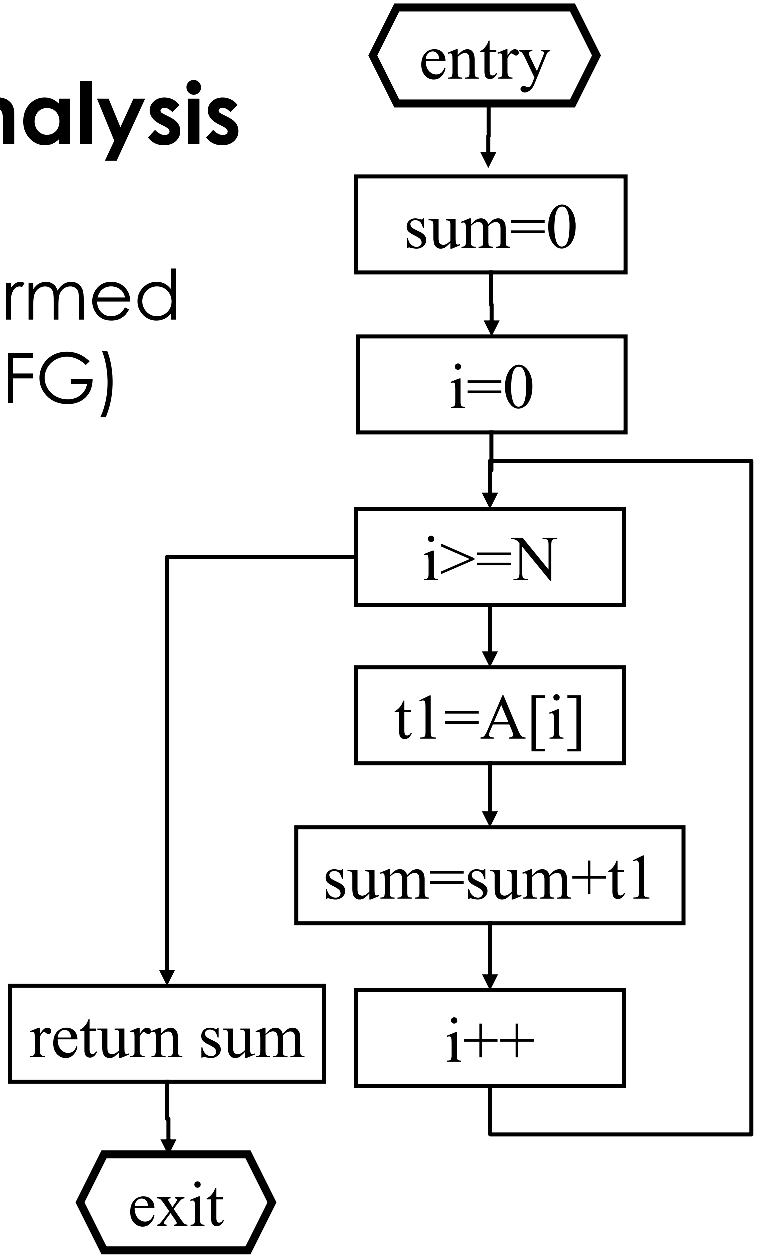
Dataflow Analysis

- Example of a dataflow problem
  - Two variables “a” and “b” can be stored in the same register if their lifetimes do not overlap, but how to determine their lifetimes?
  - We need to analyse the program flow in order to determine the lifetime of each variable
    - A problem known as *liveness analysis*
- *Liveness analysis* is performed using dataflow analysis
- There are many compiler optimizations using dataflow analysis

Dataflow Analysis

- Dataflow analysis is often performed using the control flow graph (CFG)

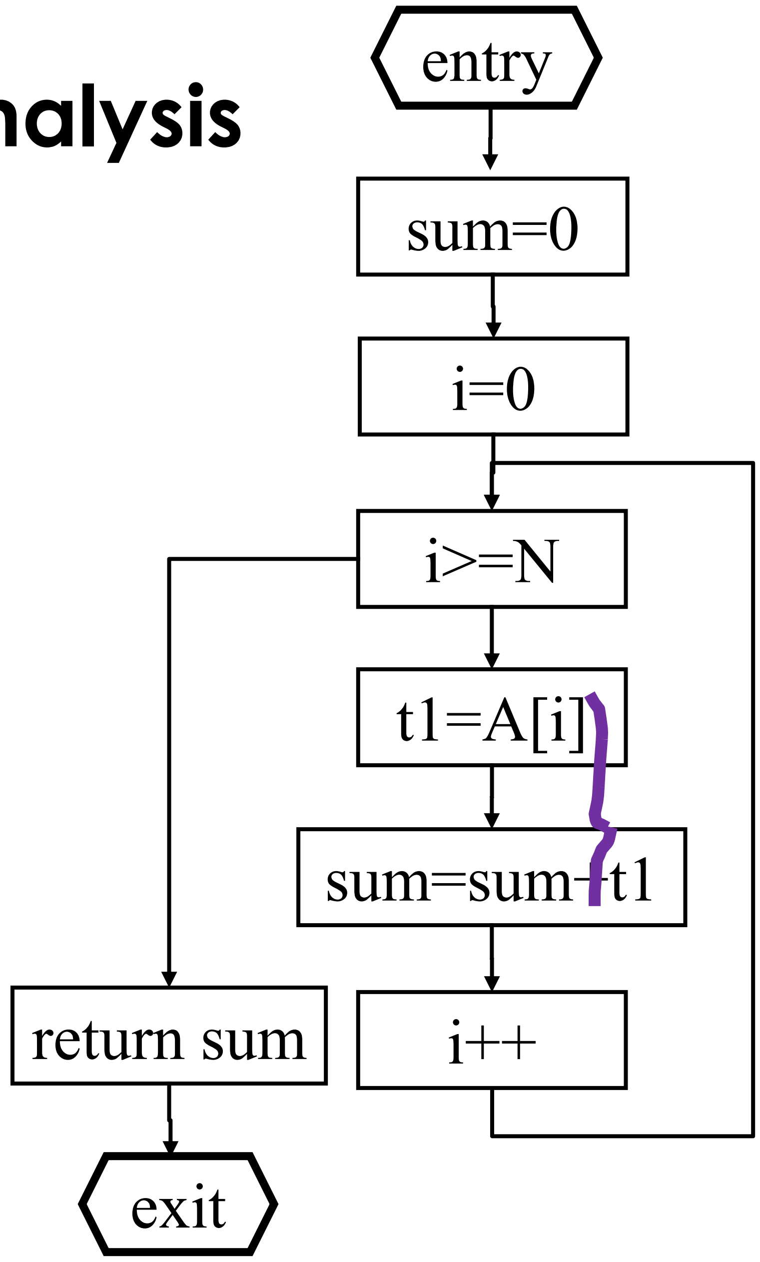
```
         sum = 0;
         i=0;
loop:    If(i>=N) goto end:
         t1=A[i];
         sum = sum + t1;
         i++;
         goto loop;
end:     return sum;
```



Dataflow Analysis

- Live range for variable t1?

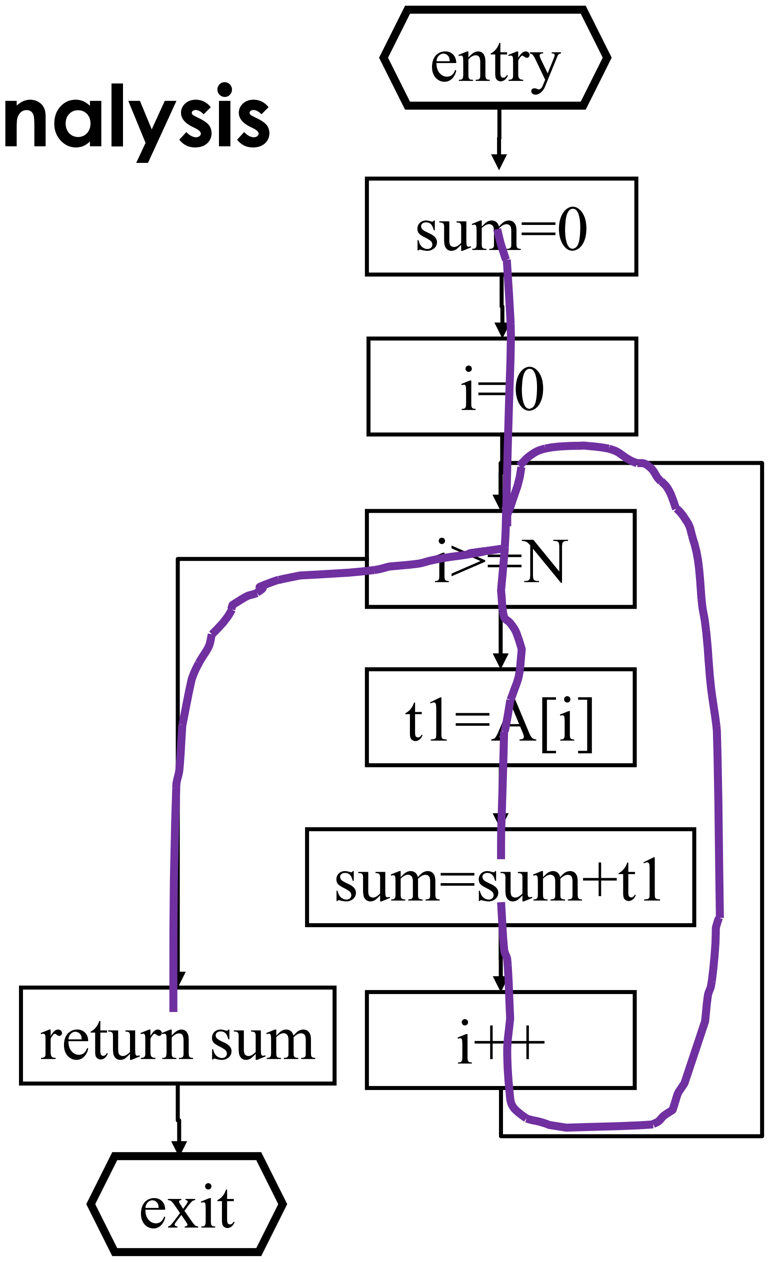
```
       sum = 0;
       i=0;
loop:  If(i>=N) goto end:
       t1=A[i];
       sum = sum + t1;
       i++;
       goto loop;
end:   return sum;
```



Data Flow Analysis

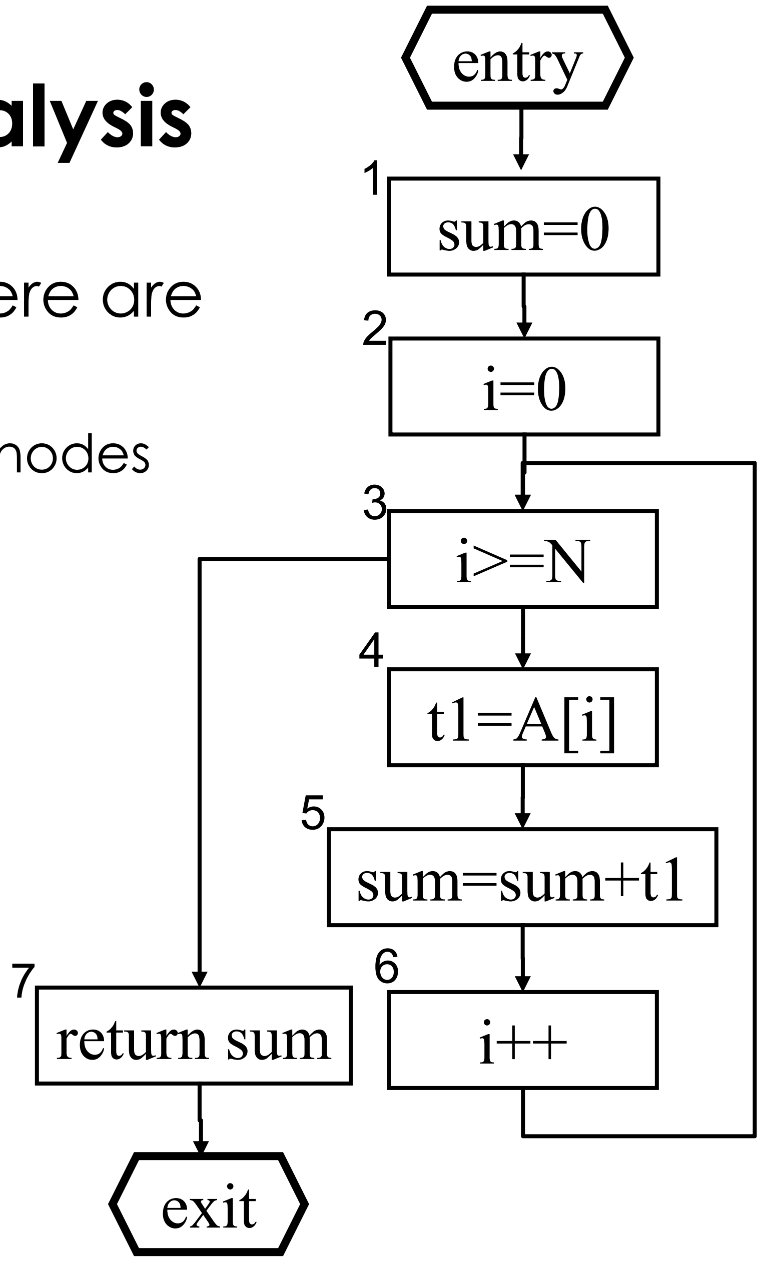
- Live range for variable sum?

```
       sum = 0;
       i=0;
loop:  If(i>=N) goto end:
       t1=A[i];
       sum = sum + t1;
       i++;
       goto loop;
end:   return sum;
```



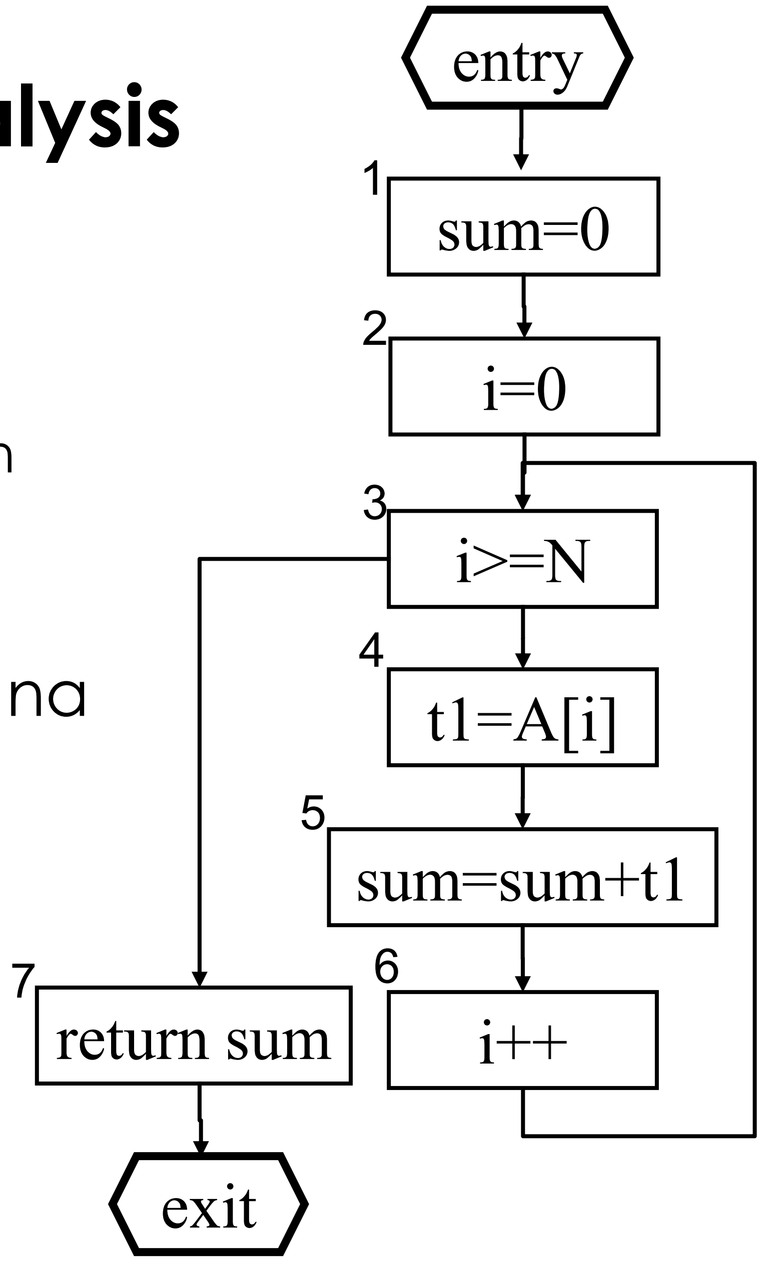
Dataflow Analysis

- Given a node n in a flow graph, there are
  - Out-edges that lead to sucessor nodes
  - In-edges that come from predecessor nodes
- Sets:
  - ***succ[n]*** is the set of sucessors
    - ***succ[3]*** = {4, 7}
  - ***pred[n]*** is the set of predecessors
    - ***pred[3]*** = {2, 6}



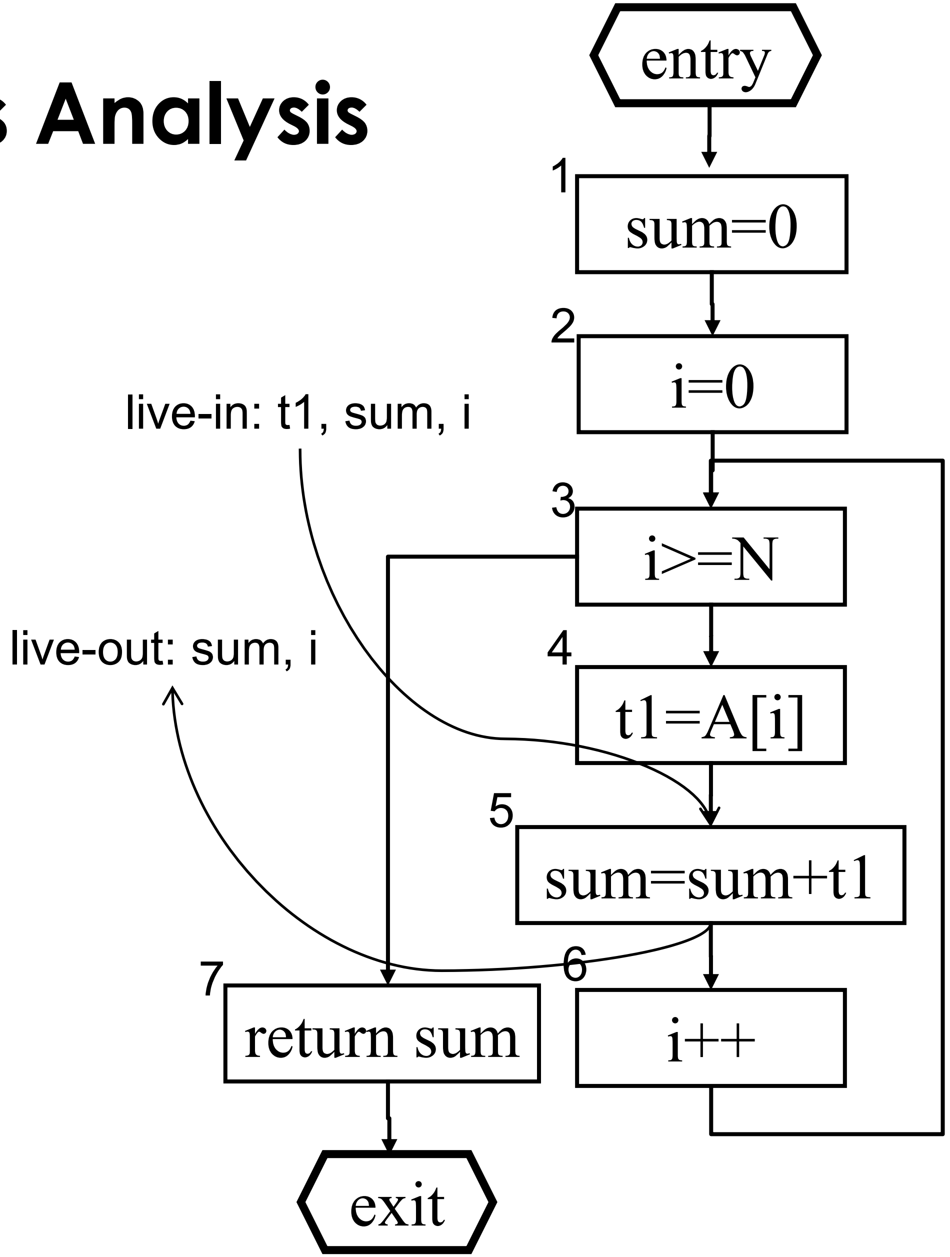
Liveness Analysis

- An assignment to a variable or temporary <u>defines</u> the variable
  - ***def[n]*** is the set of variables defined in n
  - ***def[5]*** = {sum}
- Na occurence of a variable or temporary in the right-hand side of na assignment (or in other expressions) <u>uses</u> the variable
  - ***use[n]*** is the set variables used in n
  - ***use[5]*** = {sum, t1}



Liveness Analysis

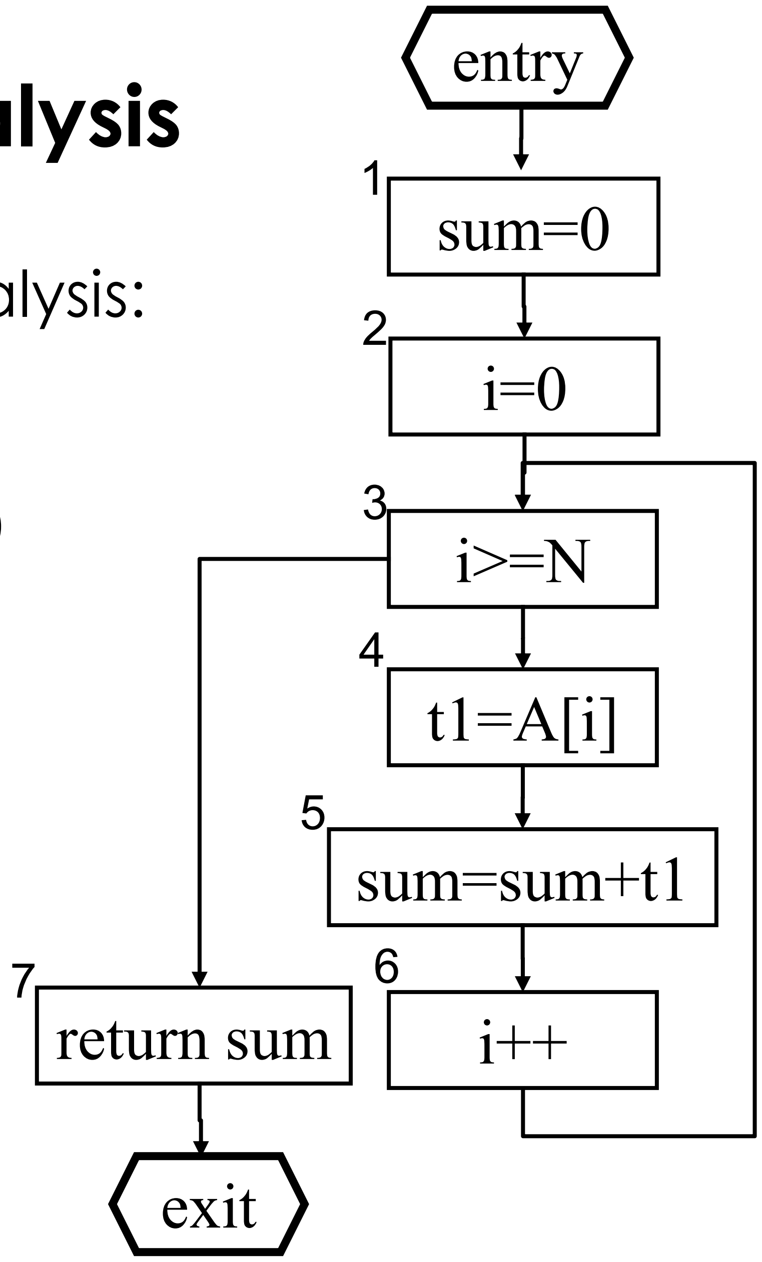
- A variable is live on an edge if there is a forward path from that edge to a *use* that does not go through any *def* of the same variable
- A variable is *live-in* at a node if it is live in any of the *in-edges* of the node
- A variable is *live-out* at a node if it is live on any of the *out-edges* of the node



Liveness Analysis

- Dataflow equations for liveness analysis:

$$in[n] = use[n] \cup (out[n] - def[n])$$
$$out[n] = \bigcup_{s \in succ[n]} in[s]$$

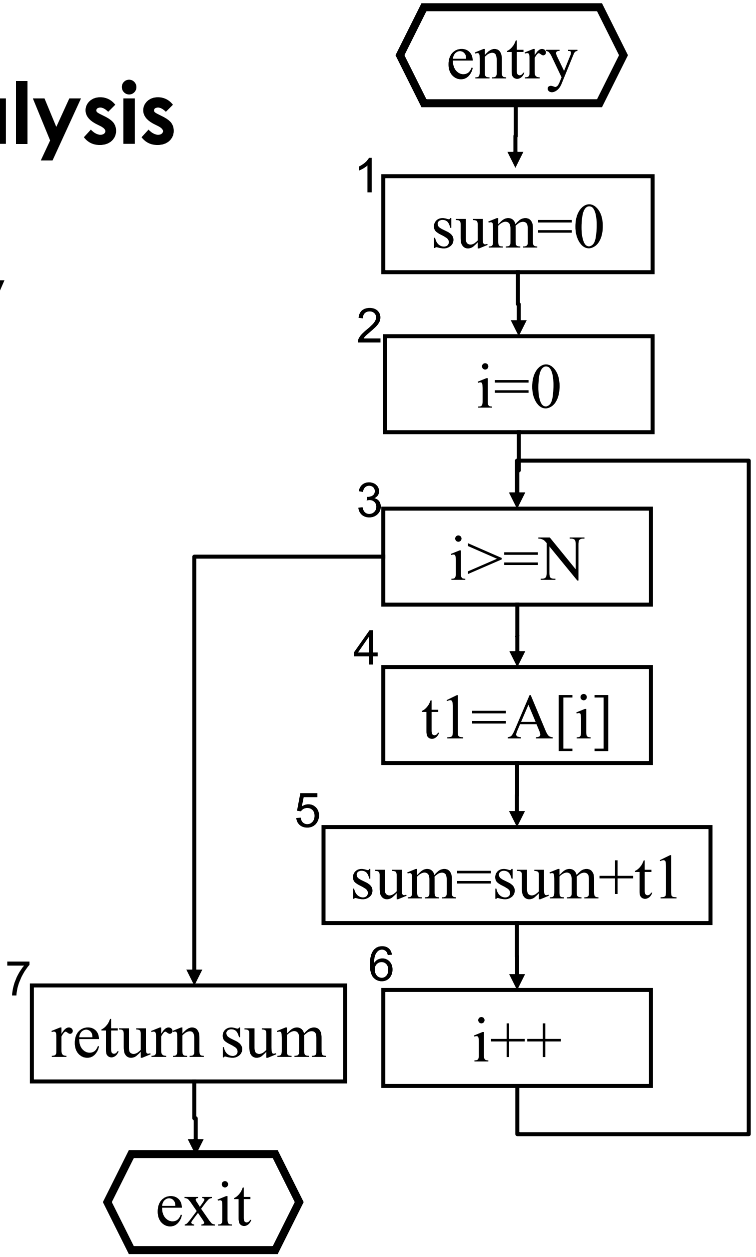


Liveness Analysis

- Computation of liveness analysis by iterative algorithm:

for each n
    in[n] ← {}; out[n] ← {}
repeat
    for each n
        in'[n] ← in[n]; out'[n] ← out[n]
        in[n] ← use[n] ∪ (out[n] – def [n])
        out[n] ← $\bigcup_{s \in succ[n]}$ in[s]

until in'[n] = in[n] and out'[n] = out[n] for all n



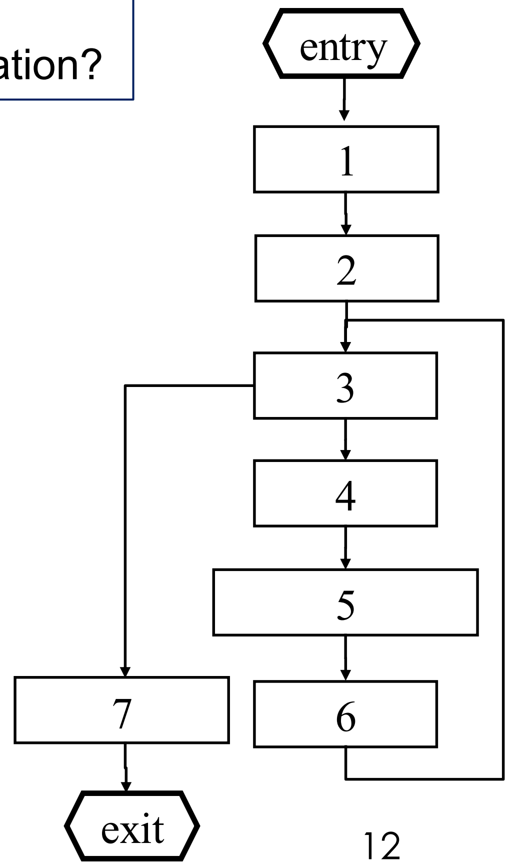
Liveness Analysis

- Computation of liveness analysis (forward):

$$in[n] \leftarrow use[n] \cup (out[n] - def\,[n])$$
$$out[n] \leftarrow \bigcup_{s \in succ[n]} in[s]$$

last iteration?

				1st iteration		2nd iteration		3rd iteration		4th iteration		6th iteration	
node	use	def	succ	in	out	in	out	in	out	in	out	in	out
1		s	2										s
2		i	3				i		i		s,i	s	s,i
3	i		4,7	i		i	s,i	s,i	s,i	s,i	s,i	s,i	s,i
4	i	t	5	i		i	s,t	s,i	s,t	s,i	s,t,i	s,i	s,t,i
5	s,t	s	6	s,t		s,t	i	s,t,i	i	s,t,i	i	s,t,i	s,i
6	i	i	3	i	i	i	i	i	s,i	s,i	s,i	s,i	s,i
7	s			s		s		s		s		s	

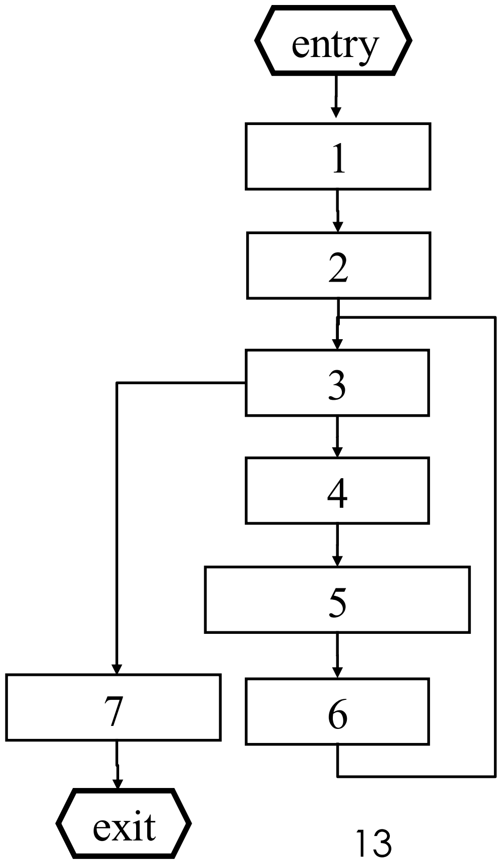


Liveness Analysis

- Computation of liveness analysis (backward):

$$out[n] \leftarrow \bigcup_{s \in succ[n]} in[s]$$
$$in[n] \leftarrow use[n] \cup (out[n] - def[n])$$

beginning				1st iteration		2nd iteration		3rd iteration	
node	use	def	succ	out	in	out	in	out	in
7	s								
6	i	i	3						
5	s,t	s	6						
4	i	t	5						
3	i		4						
2		i	3						
1		s	2						



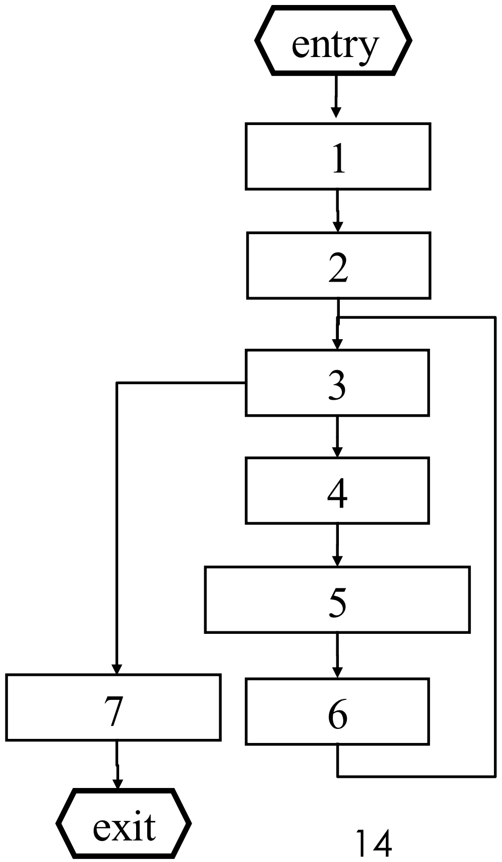
Liveness Analysis

- Computation of liveness analysis (backward):

$$out[n] \leftarrow \bigcup_{s \in succ[n]} in[s]$$
$$in[n] \leftarrow use[n] \cup (out[n] - def[n])$$

3 iterations

beginning				1st iteration		2nd iteration		3rd iteration	
node	use	def	succ	out	in	out	in	out	in
7	s				s		s		s
6	i	i	3		i	s,i	s,i	s,i	s,i
5	s,t	s	6	i	s,t,i	s,i	s,t,i	s,i	s,t,i
4	i	t	5	s,t,i	s,i	s,t,i	s,i	s,t,i	s,i
3	i		4	s,i	s,i	s,i	s,i	s,i	s,i
2		i	3	s,i	s	s,i	s	s,i	s
1		s	2	s		s		s	



Liveness Analysis

- It is a backward problem
- Thus we should use a backward dataflow analysis formulation
  - Note that the use of

$$out[n] = \bigcup_{s \in succ[n]} in[s]$$

$$in[n] = use[n] \cup (out[n] - def[n])$$

  - Instead of:

$$in[n] = use[n] \cup (out[n] - def[n])$$

$$out[n] = \bigcup_{s \in succ[n]} in[s]$$

  - Saves iterations

Liveness Analysis

- It is a backward problem
- ***Depth-first search*** can be used for ordering the nodes of the CFG
- What would be the order of nodes for the CFG of the previous example?

https://en.wikipedia.org/wiki/Depth-first_search

Exercise 1

- Computation of liveness analysis (backward):

			1st iteration		2nd iteration		3rd iteration	
stmt	use	def	out	in	out	in	out	in
6								
5								
4								
3								
2								
1								

Example:

1: t1=x*x;

2: t2=a*t1;

3: t3=b*x;

4: t4=t3+c;

5: t5=t4+t2;

6: y=t5;

Exercise 2

- Computation of liveness analysis
- Do we need an iterative algorithm for computing liveness analysis in straightline code (as in the example below)?

Example:

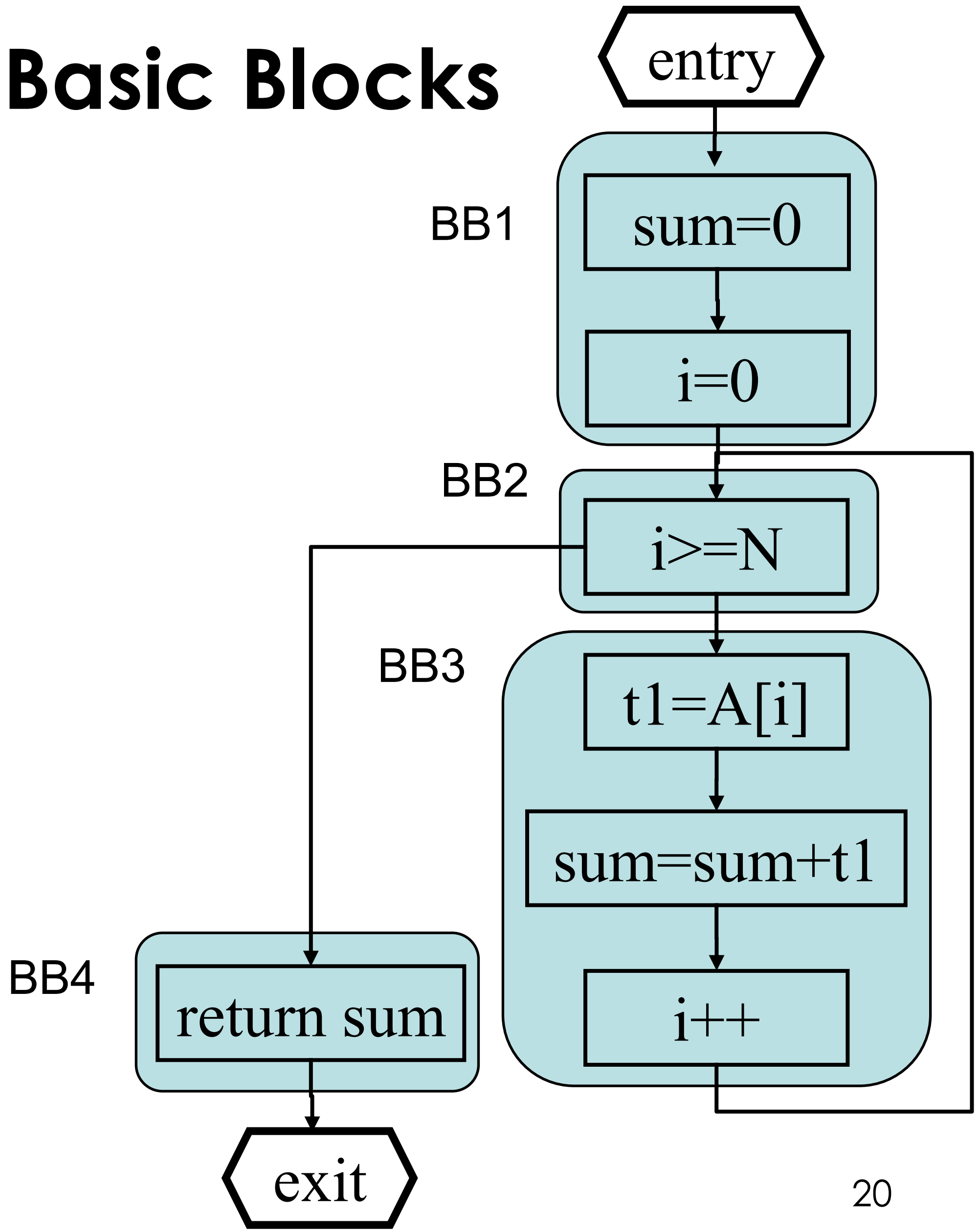
```
1: t1=x*x;
2: t2=a*t1;
3: t3=b*x;
4: t4=t3+c;
5: t5=t4+t2;
6: y=t5;
```

Dataflow Analysis Issues

- Speed of the iterative algorithm depends
  - on the number of nodes of the CFG (control flow graph) and
  - on the visiting order of the nodes of the CFG
- It is common to use CFGs consisting of basic blocks (see next slide) instead of one node per instruction
- Order of visiting should be according to the flow direction of the problem (e.g., liveness analysis is a backward problem)

Control Flow Graphs of Basic Blocks

- CFGs consisting of basic blocks (BBs)
- Basic blocks are the largest groups of instructions where
  - the control flow begins at the first instruction and only exit in the last one
  - Once in a basic block, all its Instructions are executed



Complementary Information

Applications of Dataflow Analysis

- Used for many optimizations
  - liveness analysis
  - def-use and use-def computations
  - constant propagation
  - copy propagation
  - dead-code elimination
  - common subexpression elimination
  - etc.
- Example:
  - How to determine the definitions of a variable that reach a certain use of the variable?