Classical Dataflow Analysis

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Cs 6304

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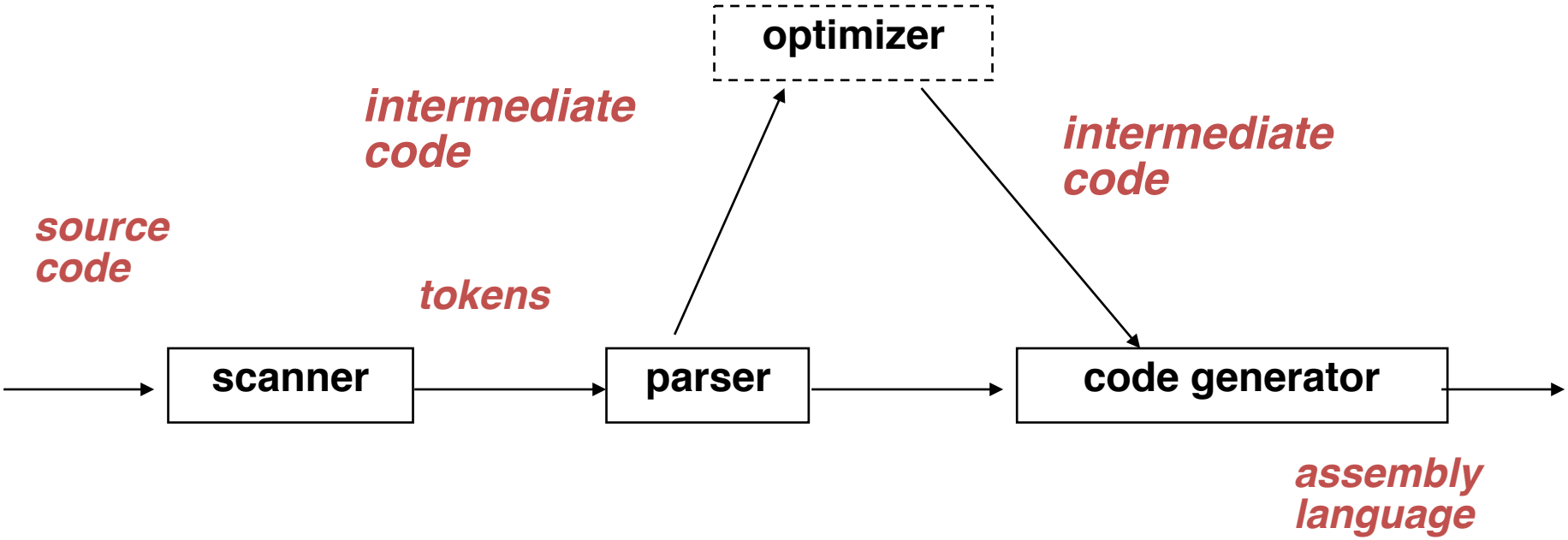
Lecture 1 – Outline

- Classical Dataflow Analysis
  - Control flow graphs, Reaching definitions, Live uses of variables, Available Expressions
  - Dataflow equations (transfer functions)
  - References: optimization chapter of compiler textbooks

Compilation Process



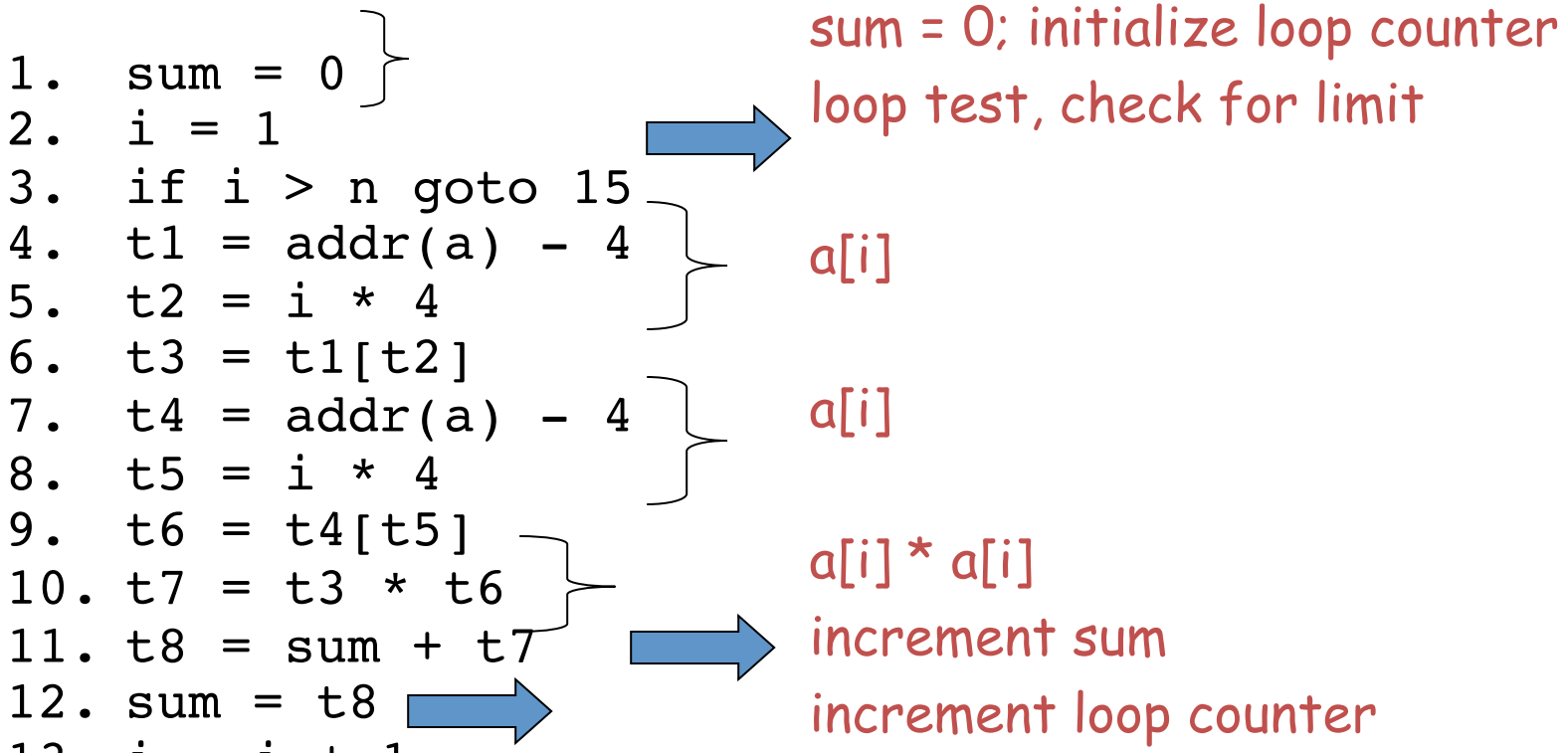
Optimization is a semantics-preserving transformation

Static (compile-time) Analysis

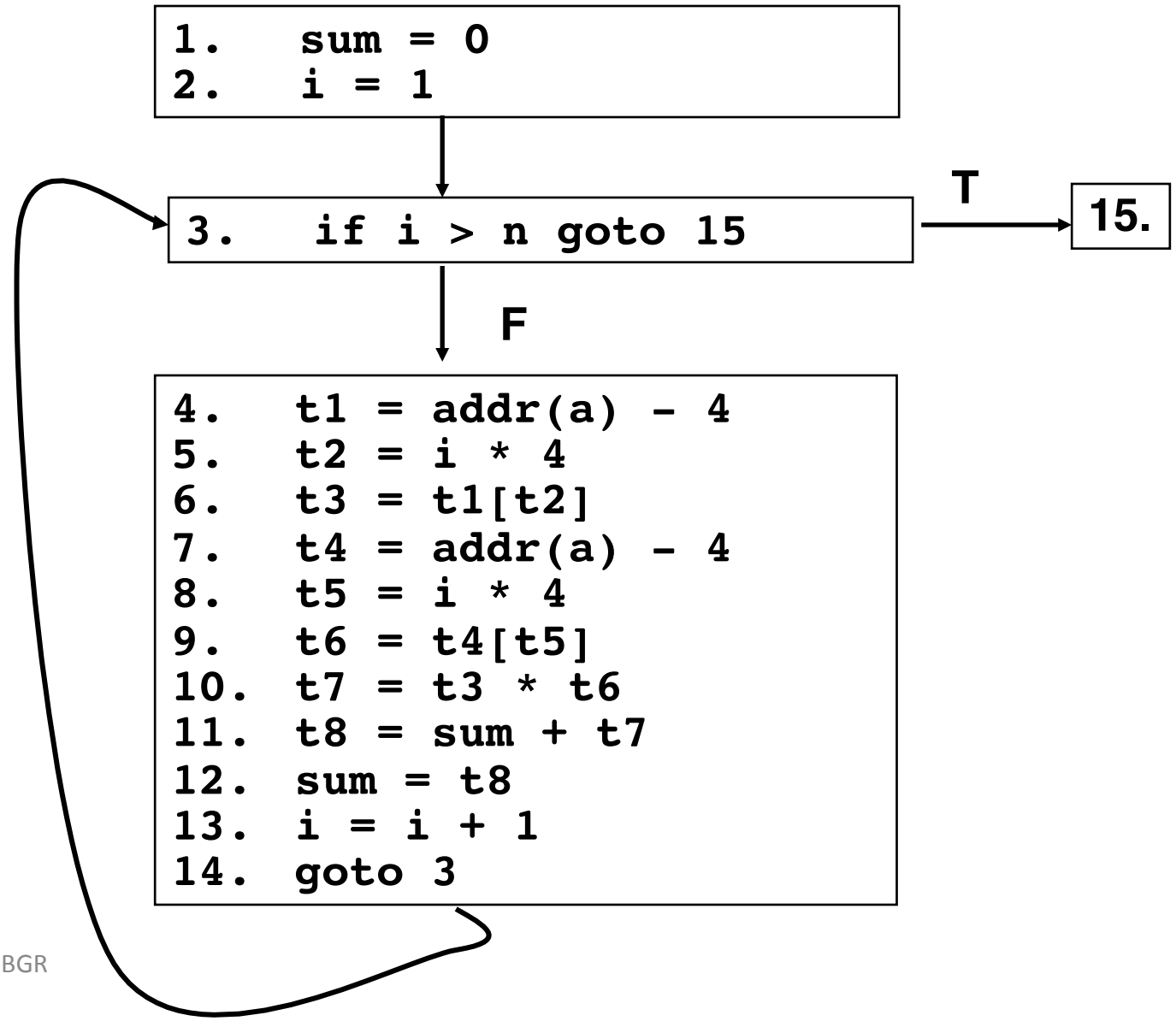
- Semantic analysis of code to ensure correctness of machine independent optimization
  - Optimizing Fortran compiler – IBM Backus late 1960's
- Classical dataflow problems defined on Fortran serve as simple examples of defining and solving dataflow problems
- Assume knowledge of internal program representations of code
  - Rooted, digraphs: control flow graph (of a function), call graph (program calling structure)

```
      sum = 0
      do 10 i = 1, n
10    sum = sum + a(i) * a(i)
      …
```

original Fortran

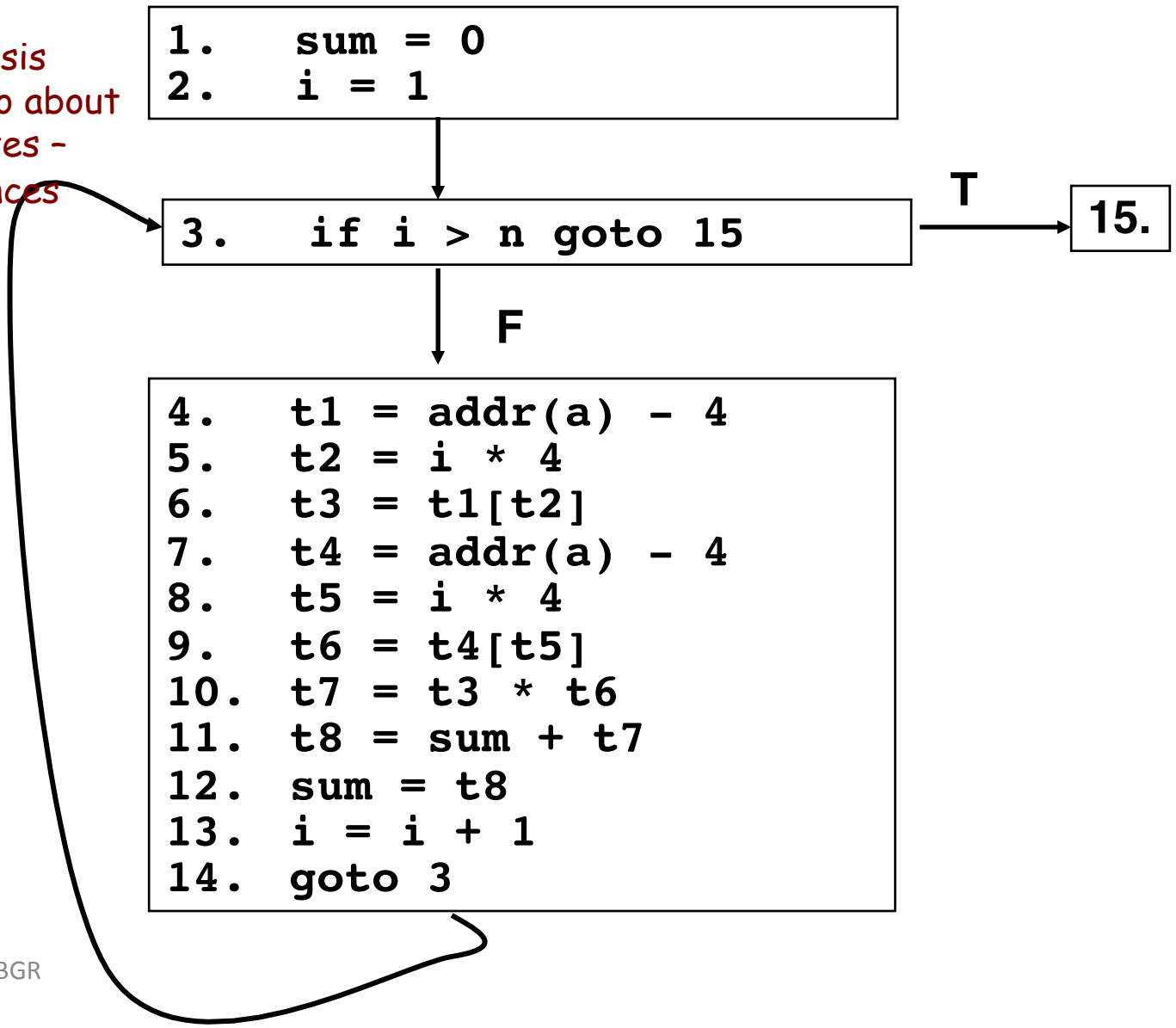


Control Flow Graph (CFG)



Optimized Control Flow Graph (CFG)

Optimizations enabled by dataflow analysis extracting info about reads and writes – data dependences

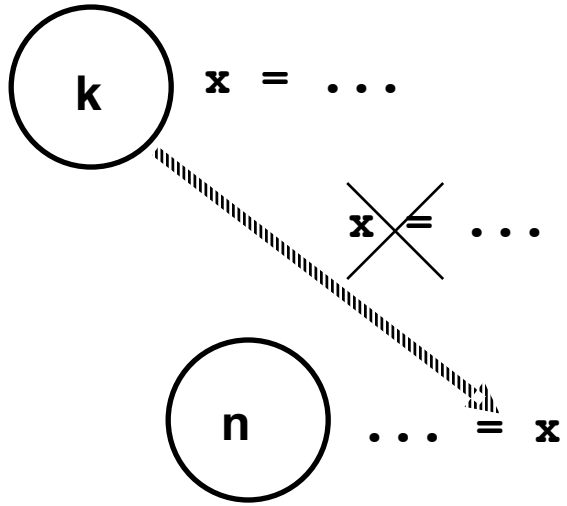


Some Classical Data Flow Problems

- Reaching definitions, Live uses of variables, Available expressions, used historically for low-level code optimizations
- Def-use and use-def chains, built from Reach and Live provide semantic basis for data dependence analysis
- Available expressions enable common subexpression elimination

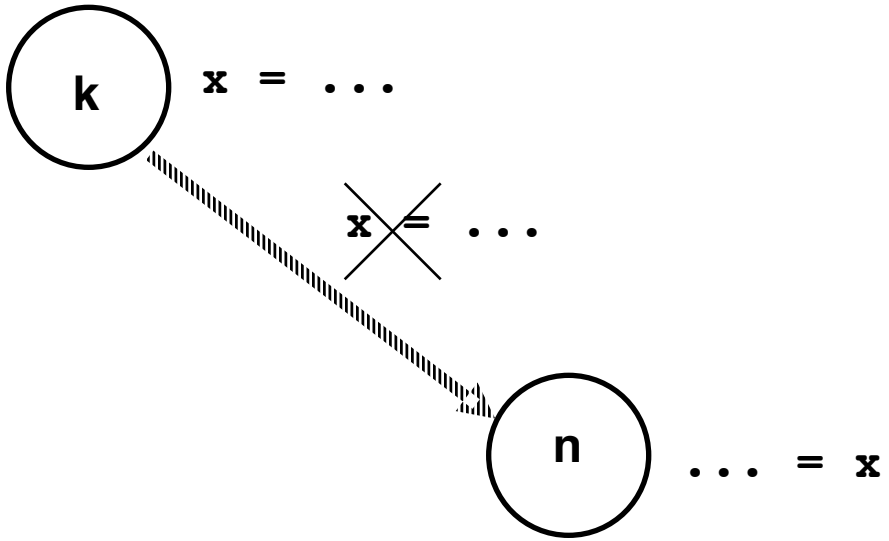
Reaching Definitions

- *Definition* A statement which may change the value of a variable
- A definition of a variable *x* at node *k* *reaches* node *n* if there is a definition-clear path from *k* to *n*.



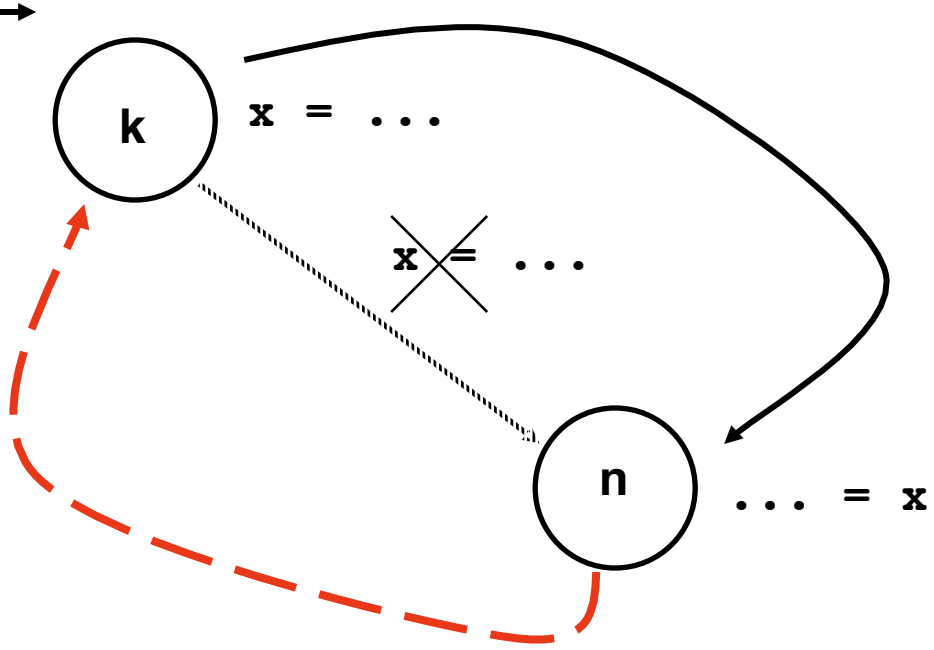
Live Uses of Variables

- *Use* Appearance of a variable as an operand of a 3 address statement
- A use of a variable *x* at node n is *live on exit* from node *k* if there is a definition-clear path for *x* from *k* to *n*.

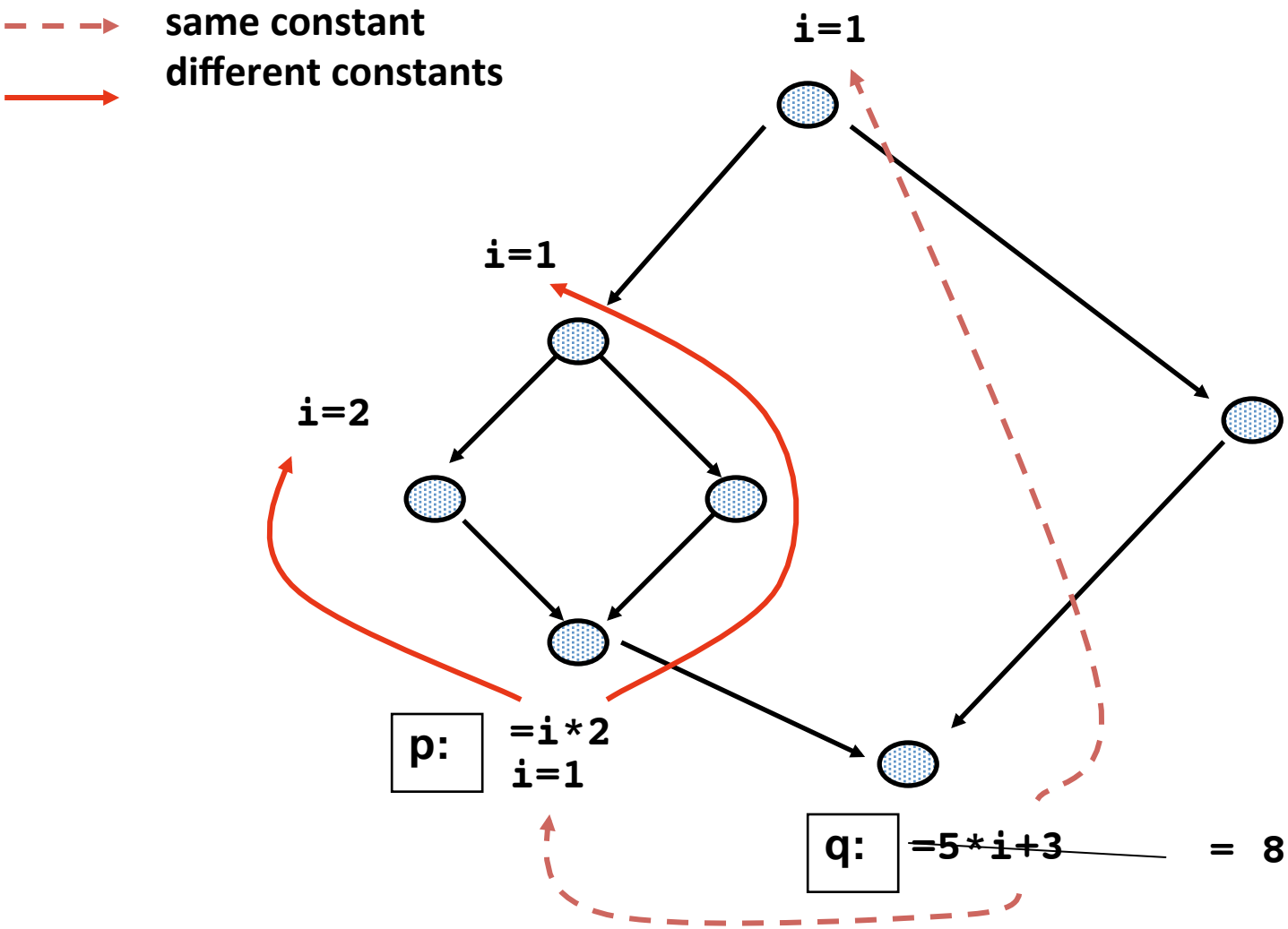


Def-use Relations

- Use-def chain links an use to a definition that reaches that use ⇢
- Def-use chain links a definition to an use that it reaches ⟶



Constant Propagation



Reaching Definitions Equations

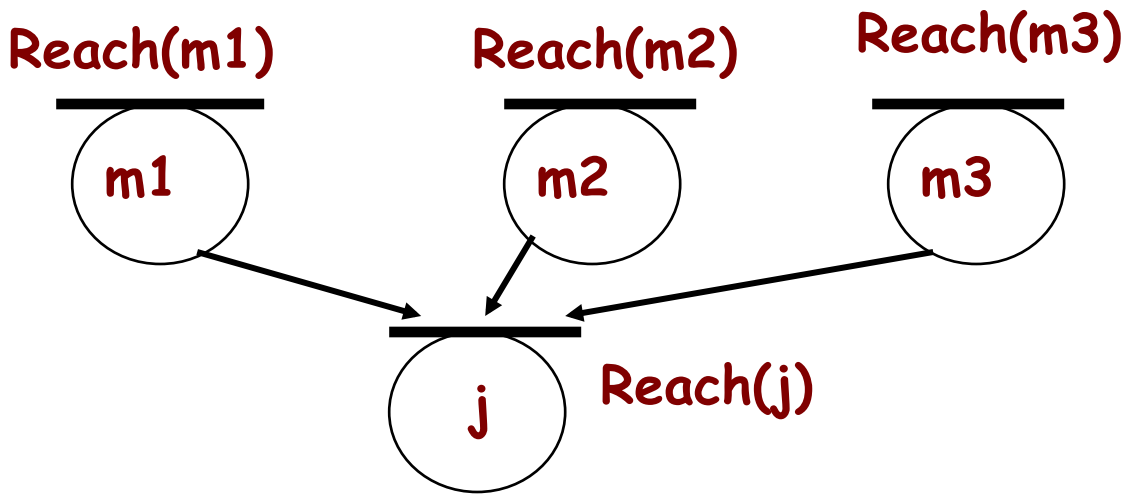
$$Reach(j) = \bigcup_{m \in Pred(j)} \{ Reach(m) \cap pres(m) \cup dgen(m) \}$$

where:

pres(m) is the set of defs preserved through node *m*

dgen(m) is the set of defs generated at node *m*

Pred(j) is the set of immediate predecessors of node *j*



Live Uses Equations

$$Live(j) = \bigcup_{m \in Succ(j)} \{ Live(m) \cap pres(m) \cup ugen(m) \}$$

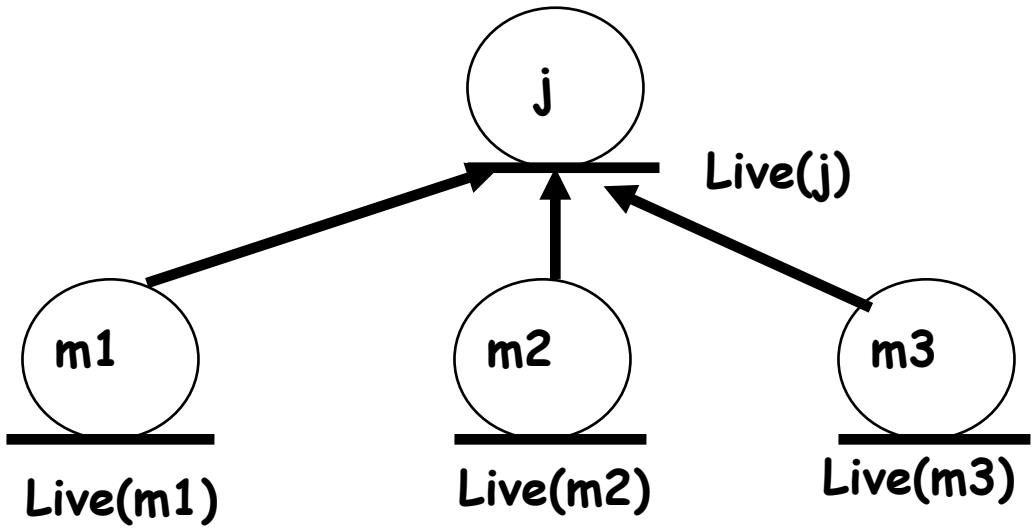
where

pres(m) is the set of uses preserved through node *m*

(these will correspond to variables whose defs are preserved)

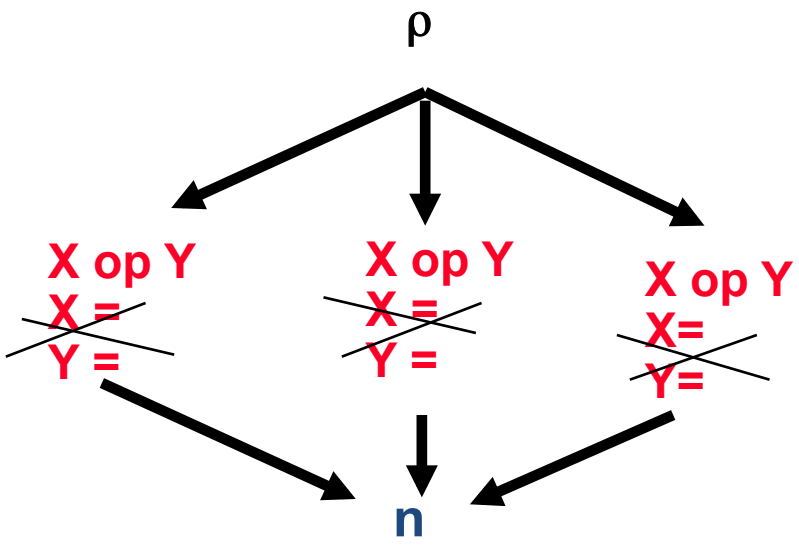
ugen(m) is the set of uses generated at node *m*

succ(j) is the set of immediate successors of node *j*

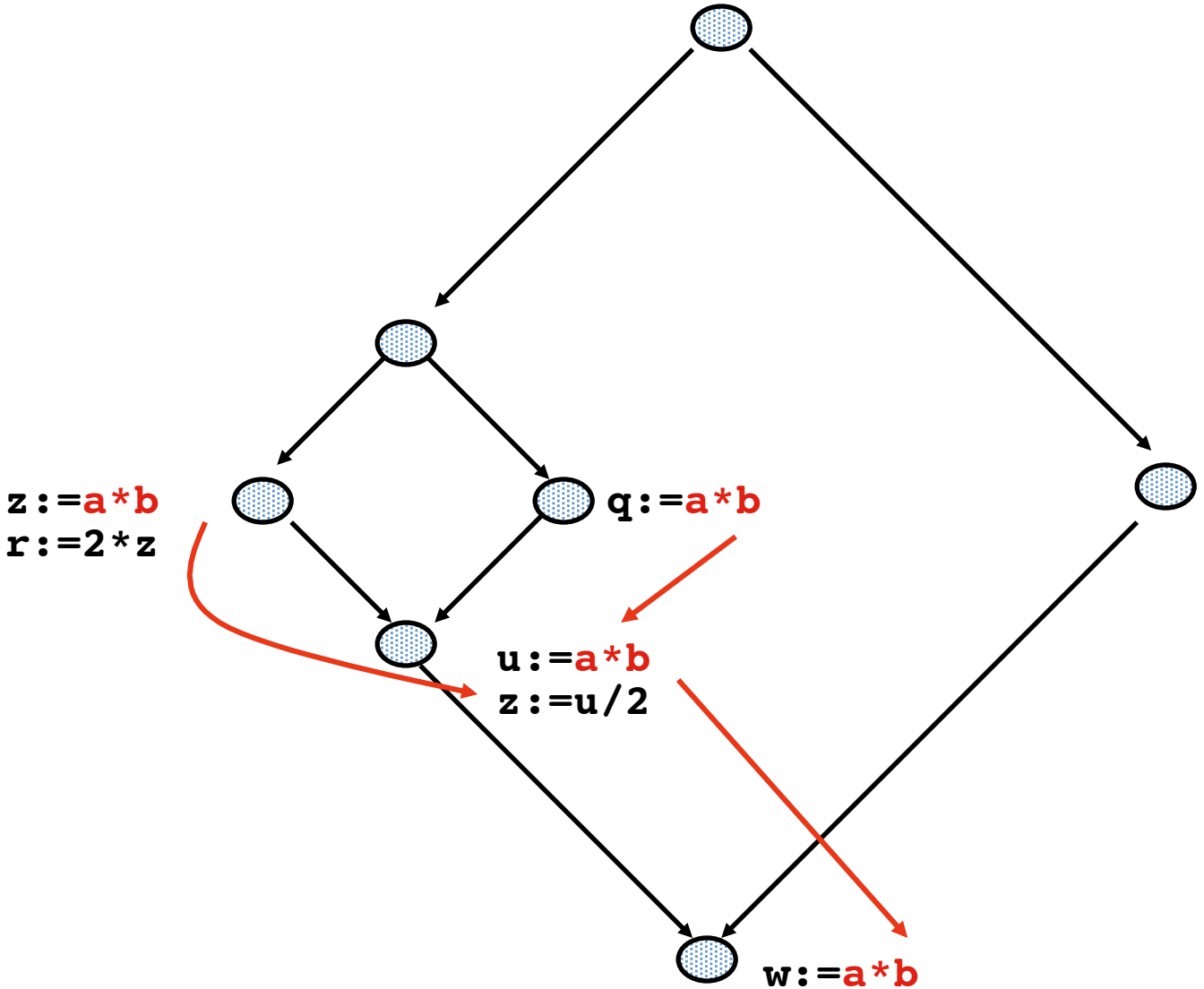


Available Expressions

- An expression X op Y is *available* at program point *n* if EVERY path from program entry to *n* evaluates X op Y, and after every evaluation prior to reaching *n*, there are NO subsequent assignments to X or Y.



Global Common Subexpressions



Available Expressions Equations

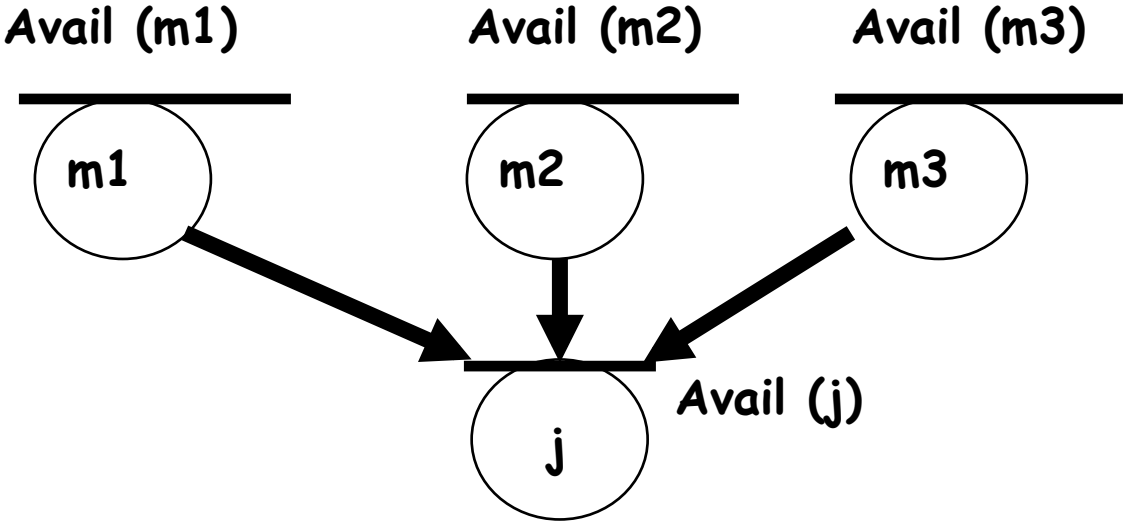
$$Avail(j) = \bigcap_{m \in Pred(j)} \{ Avail(m) \cap epres(m) \cup egen(m) \}$$

where:

epres(m) is the set of expressions preserved through node *m*

egen(m) is the set of (downwards exposed) expressions generated at node *m*

pred(j) is the set of immediate predecessors of node *j*



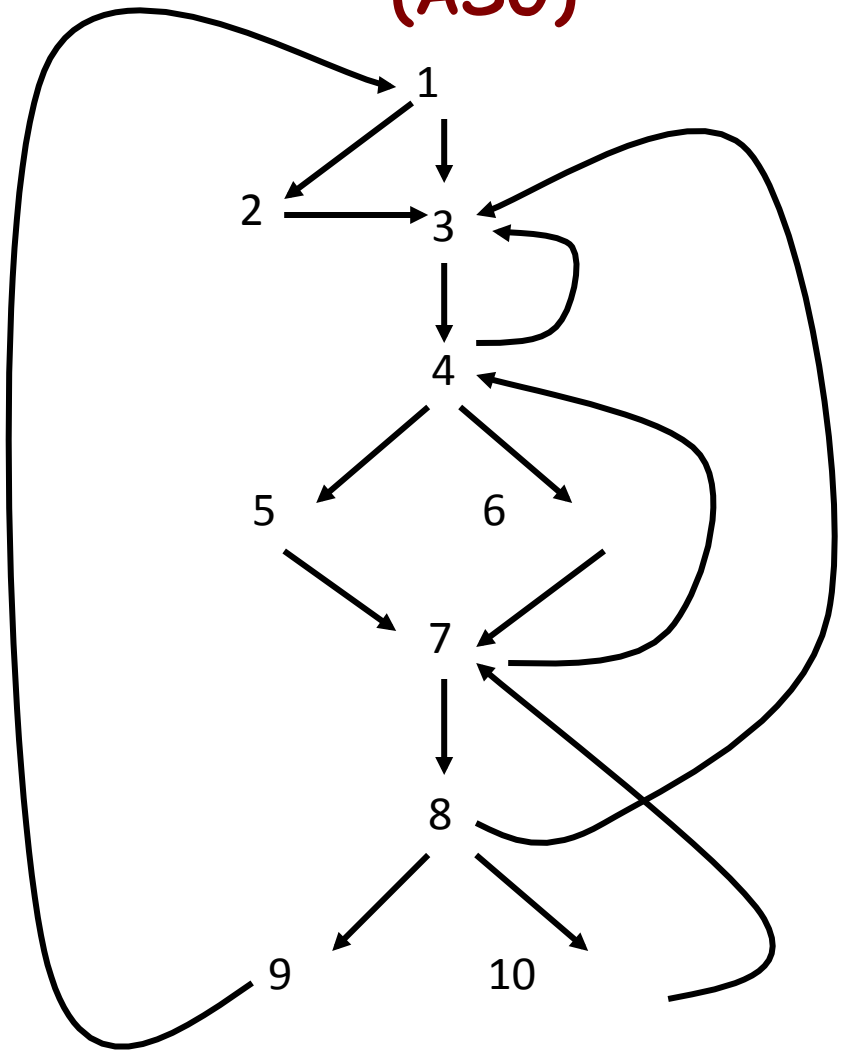
Classical Dataflow Problems

	May Problems	Must Problems
Forward Problems	Reaching Defs	Available Exprs
Backward Problems	Live Uses of Variables	Very Busy Expressions

Dominators and Natural Loops

- A dominator of a node x in a rooted digraph is a node y such that all paths from the root to x must pass through y
- A node x can have many dominators. There is one dominator y such that there are no other dominators on a path from y to x. Then y is x's immediate dominators.
- Dominators and spanning trees can define natural loops on a rooted digraph.

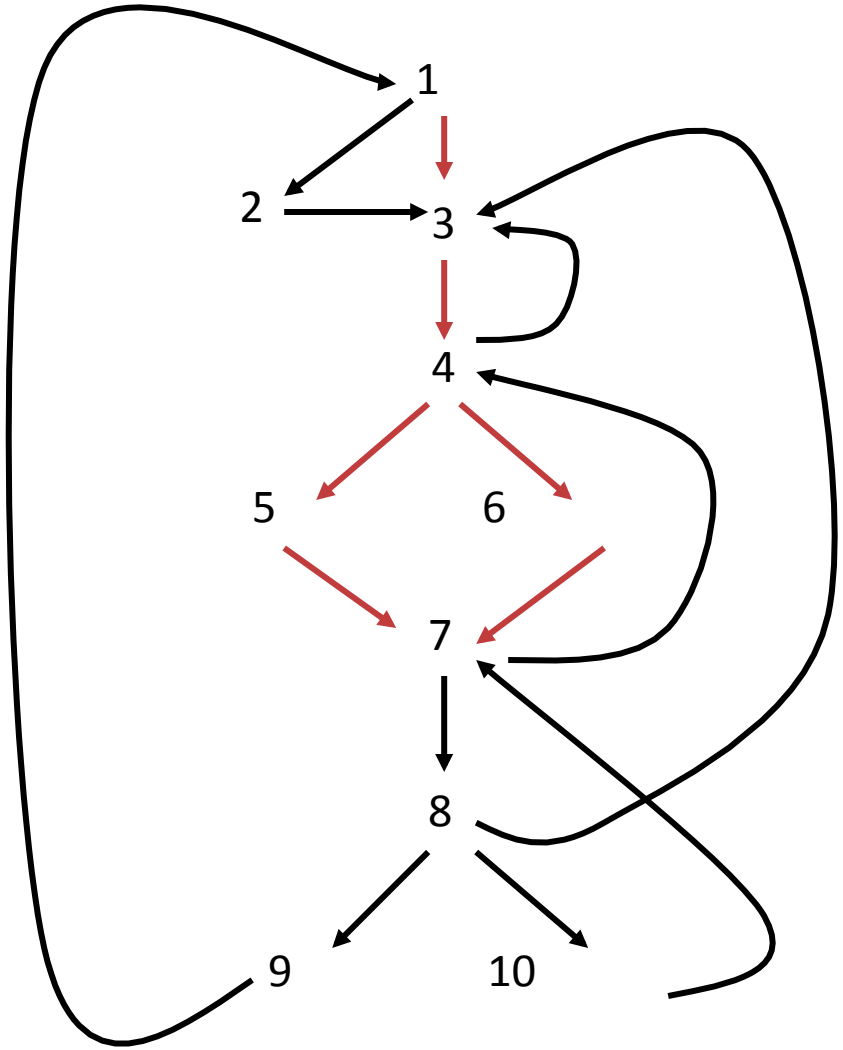
Loops Example from Aho,Sethi,Ullman (ASU)

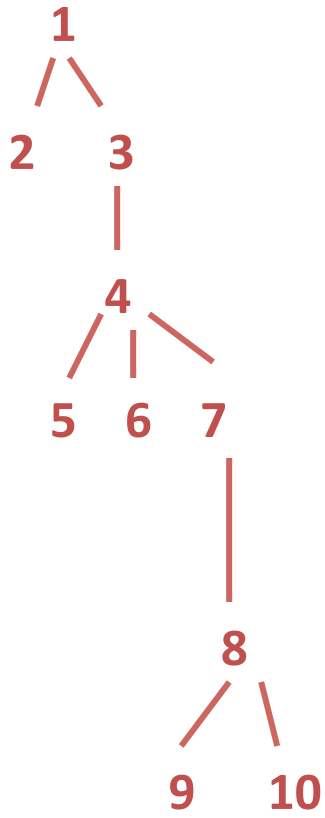


How to find the loops on this graph?

node 1 dominates node 7

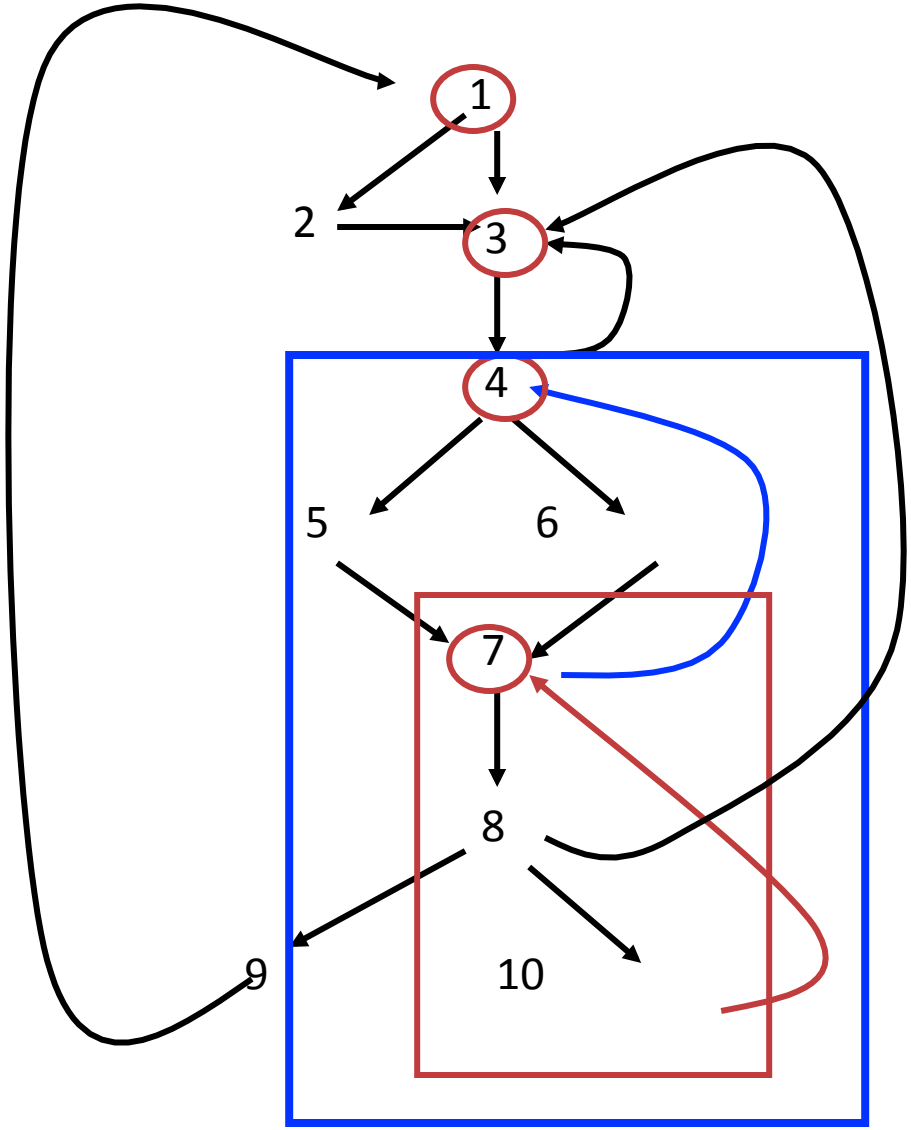
Example

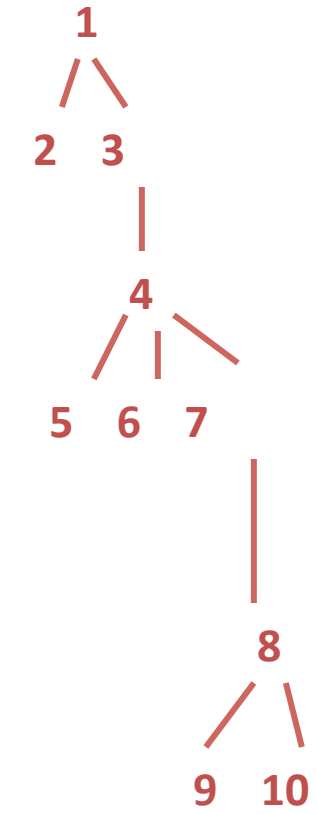




Dominator Tree

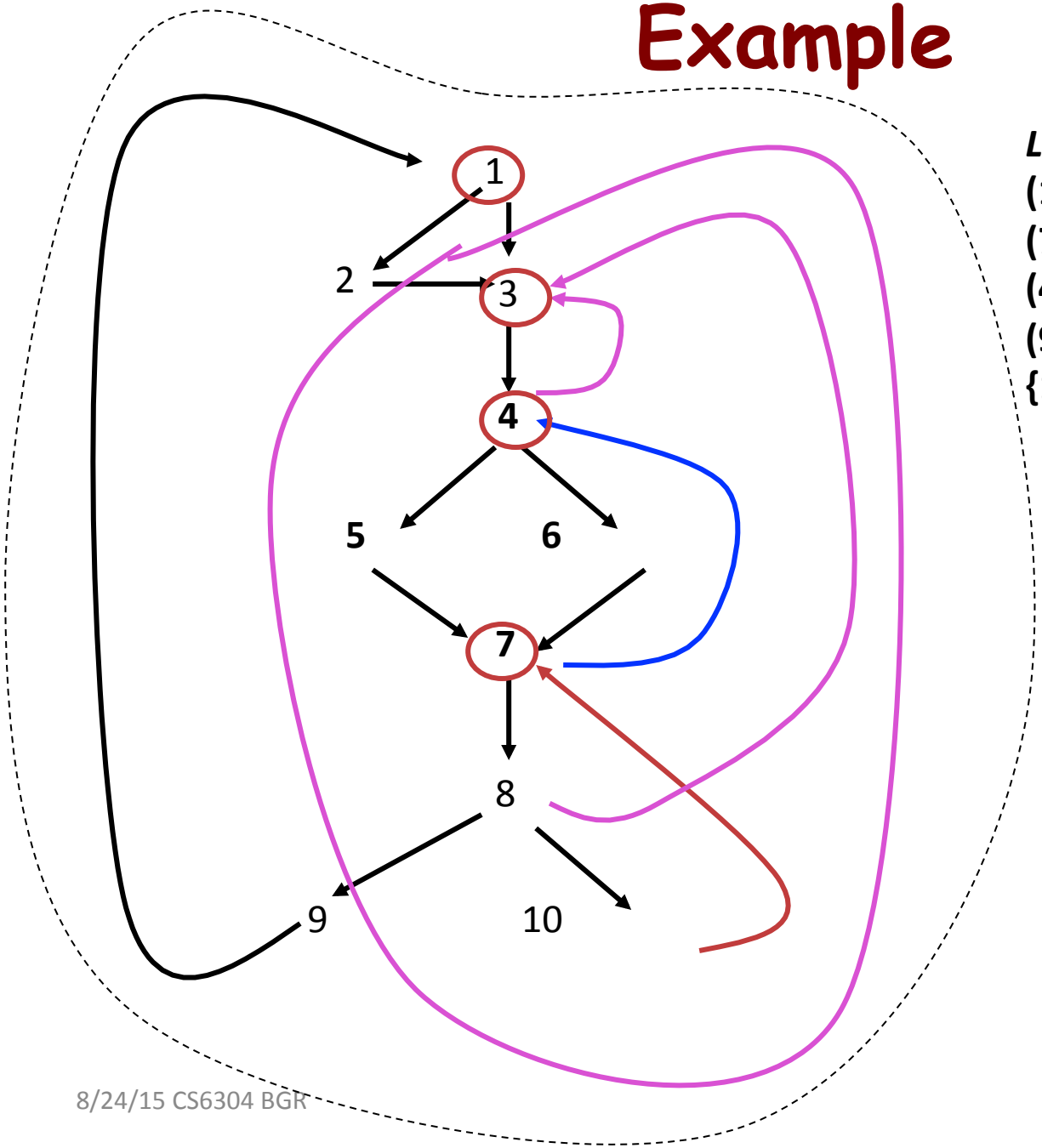
Example





Dominator Tree

Example



Loops

(10,7): {7,8,10}

(7,4): {4,5,6,7,8,10}

(4,3)(8,3): {3,4,5,6,7,8,10}

(9,1):

{1,2,3,4,5,6,7,8,9,10}

Dominators, ASU

- How to find dominators of CFG, G=(N,E,ρ)? Use fixed point iteration (justification later)

$D(\rho) = \{\rho\}$

for $n \in N-\{\rho\}$ do

{ $D(n) = N;$}

while changes to any D(n) occur do

{ for $n \in N-\{\rho\}$ do

$$D(n) = \{n\} \cup \bigcap_{p \in pred(n)} D(p)$$

}

Dominators

- Algorithm terminates since at every step some set D(k) becomes smaller; this cannot occur indefinitely, so loop terminates
- Invariant: Node *k* is parent of node *n* in the dominator tree, if node *k* is the *immediate dominator* of *n*