Program Analysis & Software Engineering

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Motivation

- Common Scenarios
  - No idea why the program fails for a certain input
  - No idea which modules implement function X
  - No time to achieve desired block coverage
  - No time to run even half of the regression tests

Outline

- Program Analysis
- Static v/s Dynamic
- Program Analysis in Software Engineering
  - Efficient Coverage Testing
  - Smart Debugging
  - Incremental Regression Testing
- A Short Demo
- Future Directions

Program Analysis

- Compiler Optimizations
  - Common Subexpression Elimination
  - Constant Folding
  - Code Motion
  - etc.

Static Program Analysis

- Control Flow Analysis
  - Basic Blocks
  - Dominator Trees
  - Natural Loops
  - etc.
- Data Flow Analysis
  - Def-Use Chains
  - Live Variables
  - Available Expressions
  - etc.

Dynamic Program Analysis

- Which paths were traversed?
- Which def-use associations were exercised?
- Which functions got invoked from where?
- Which statements were exercised?
- Which statement should I try to cover next?
- etc.

Static v/s Dynamic

Static	Dynamic
What *could* happen?	What *did* happen?
Foresight	Hindsight
Conservative	Precise

Program Analysis & Software Engineering

- Traditional Applications
  - Software Metrics
  - Coverage Testing
  - Execution Profiling
- Newer Applications
  - Efficient Coverage Testing
  - Incremental Regression Testing
  - Smart Debugging
  - Program Understanding
  - White Box Reliability Engineering
  - Probabilistic Optimizations

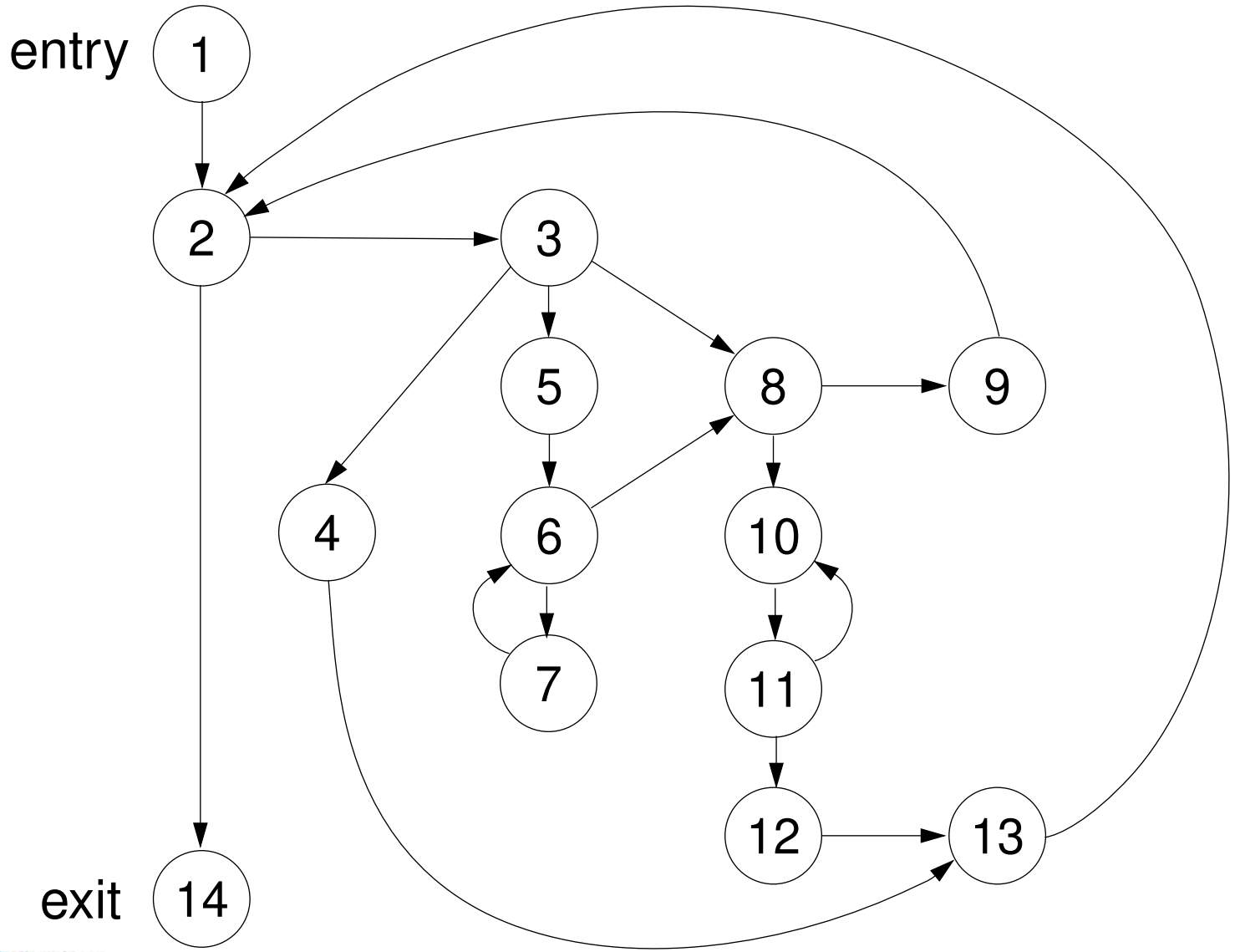
An Example

```
exp1;
while (exp2) {
    switch (exp3) {
        case 1: exp4;
                break;
        case 2: exp5;
                while (exp6) exp7;
        default:
            if (exp8) {
                exp9;
                continue;
            }
            do exp10; while (exp11);
            exp12;
    }
    exp13;
}
exp14;
```

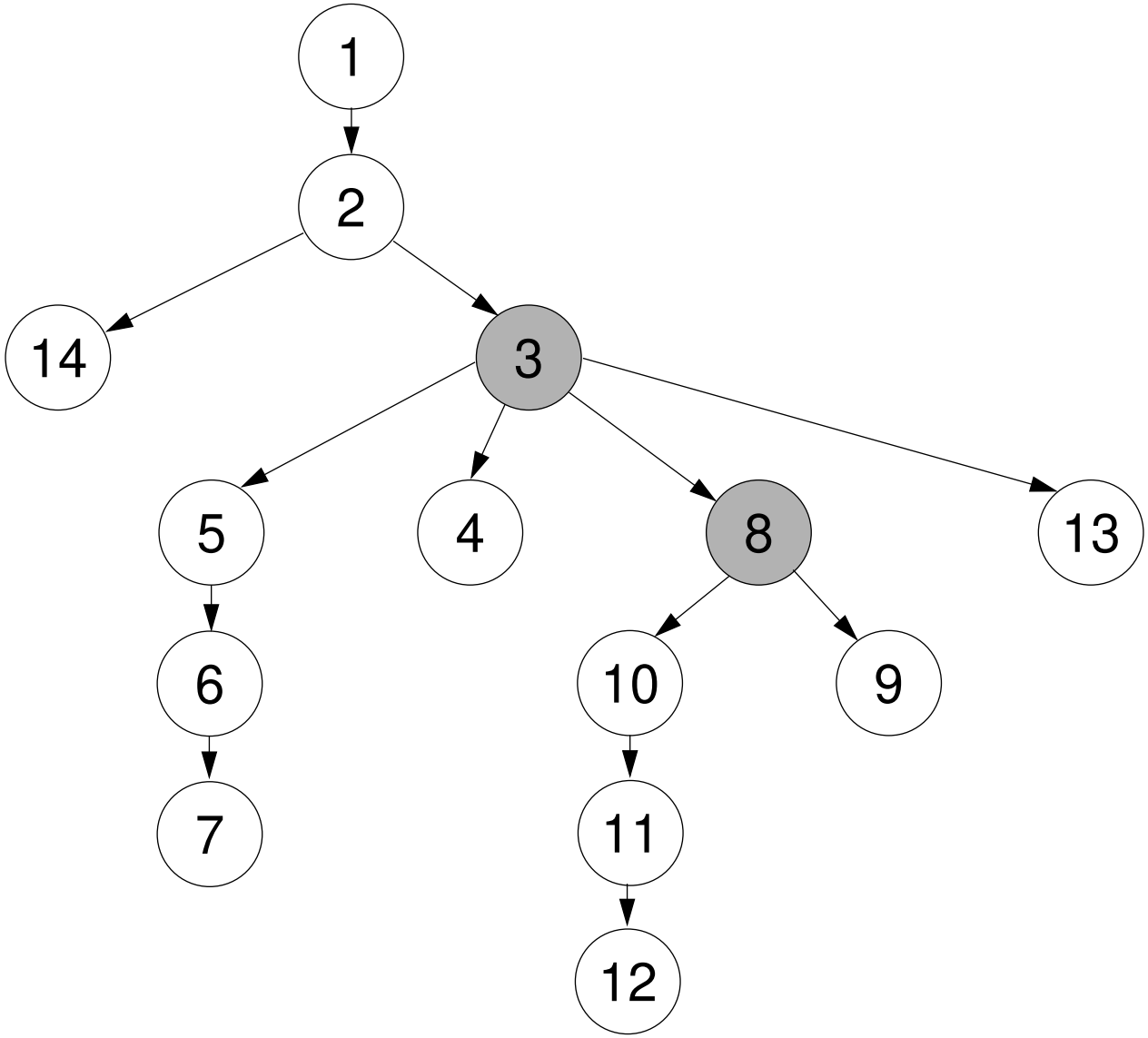
Efficient Coverage Testing

```
exp1;
while (exp2) {
    switch (exp3) {
        case 1: exp4;
                break;
        case 2: exp5;
                while (exp6) exp7;
        default:
            if (exp8) {
                exp9;
                continue;
            }
            do exp10; while (exp11);
            exp12;
    }
    exp13;
}
exp14;
```

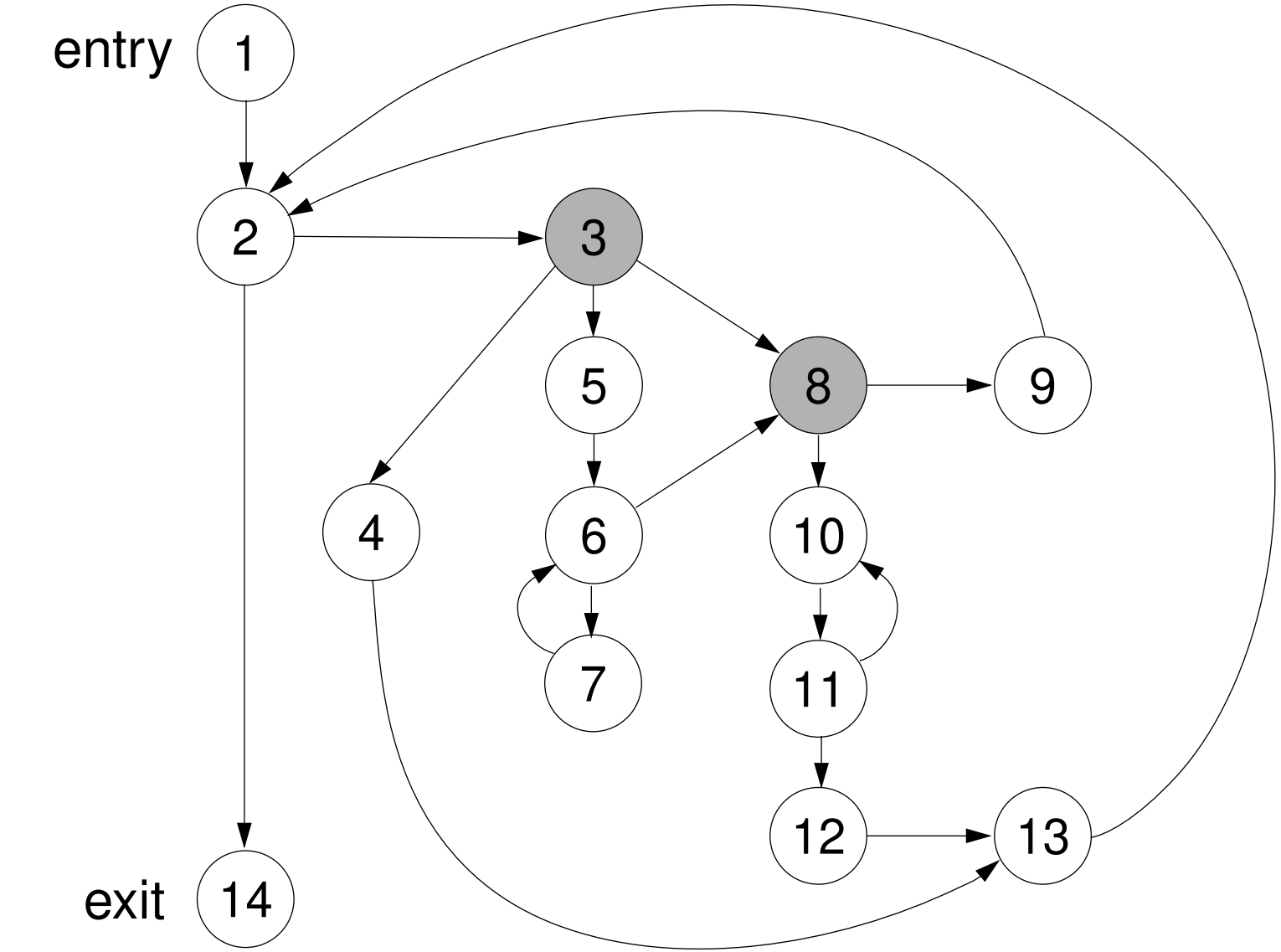
Control Flow Graph



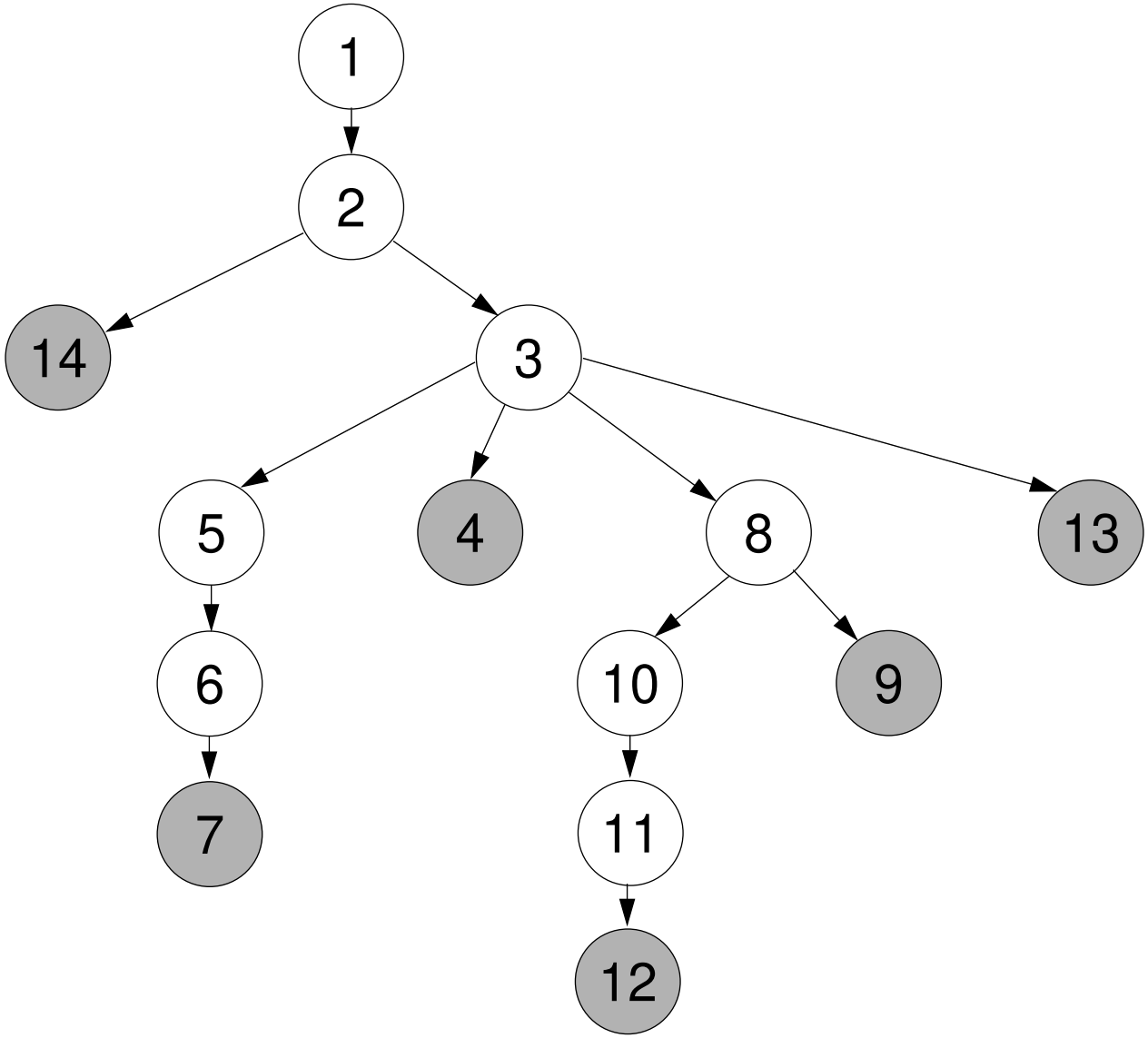
Predominator Tree



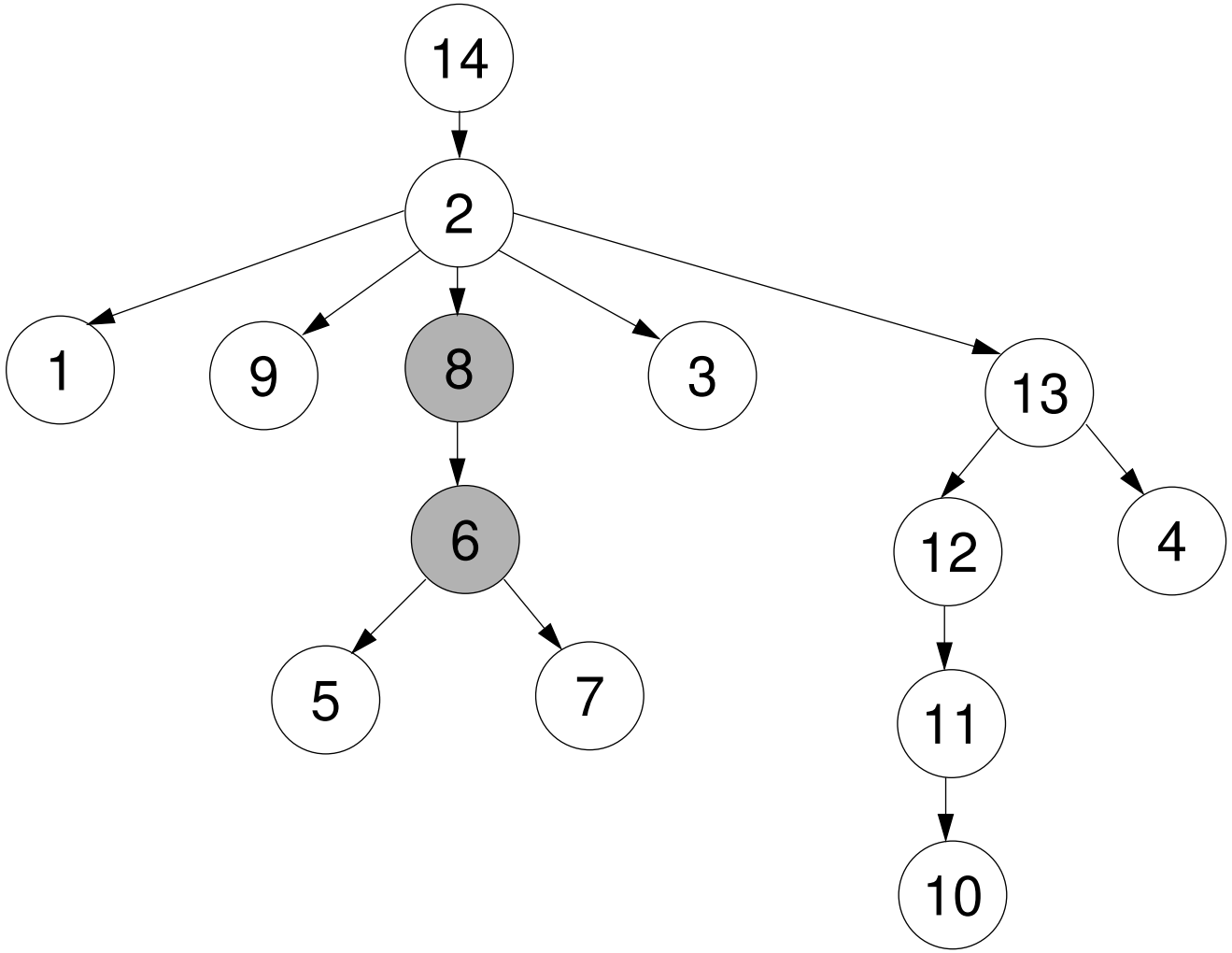
Control Flow Graph



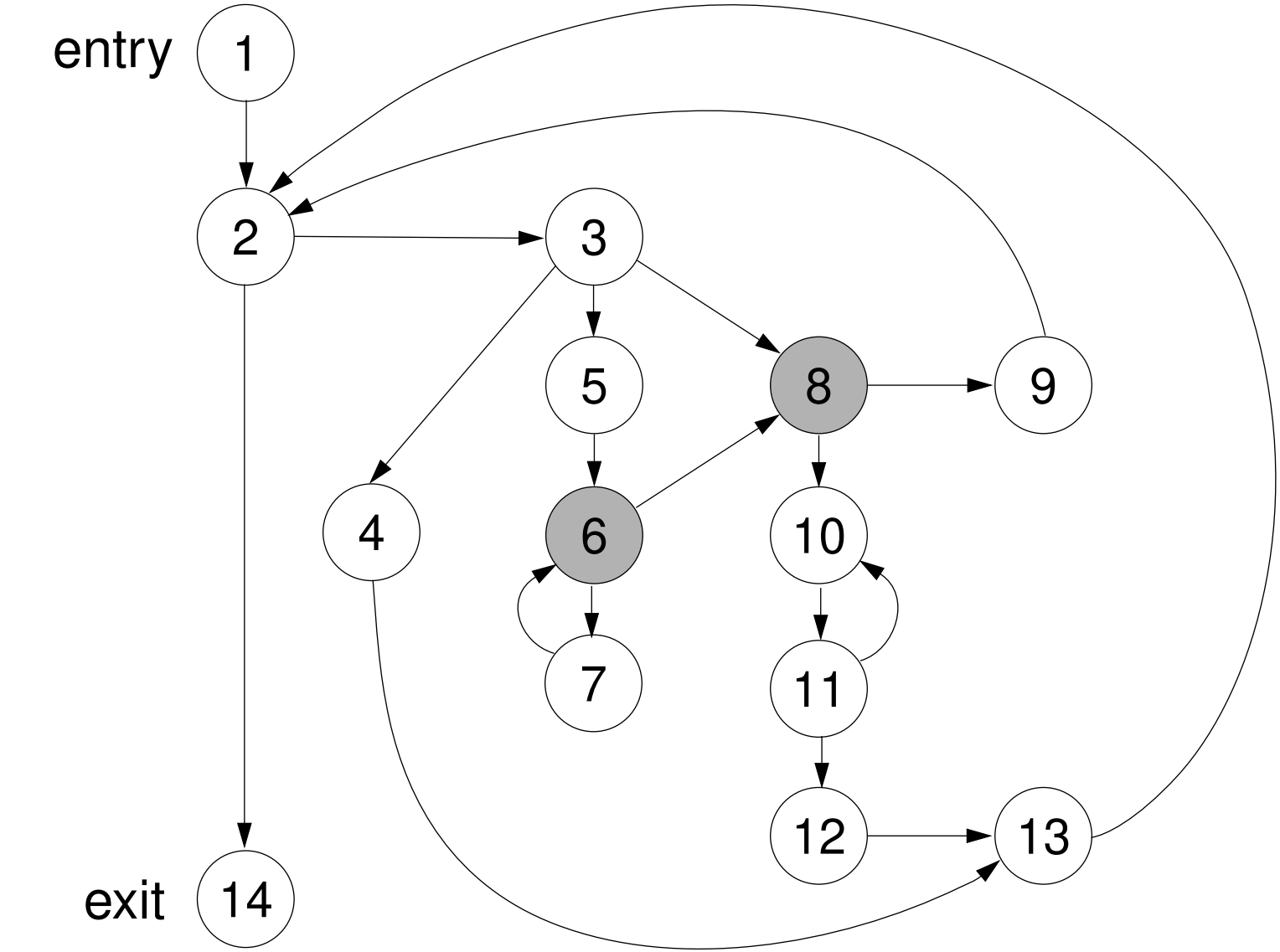
Predominator Tree (cont'd)



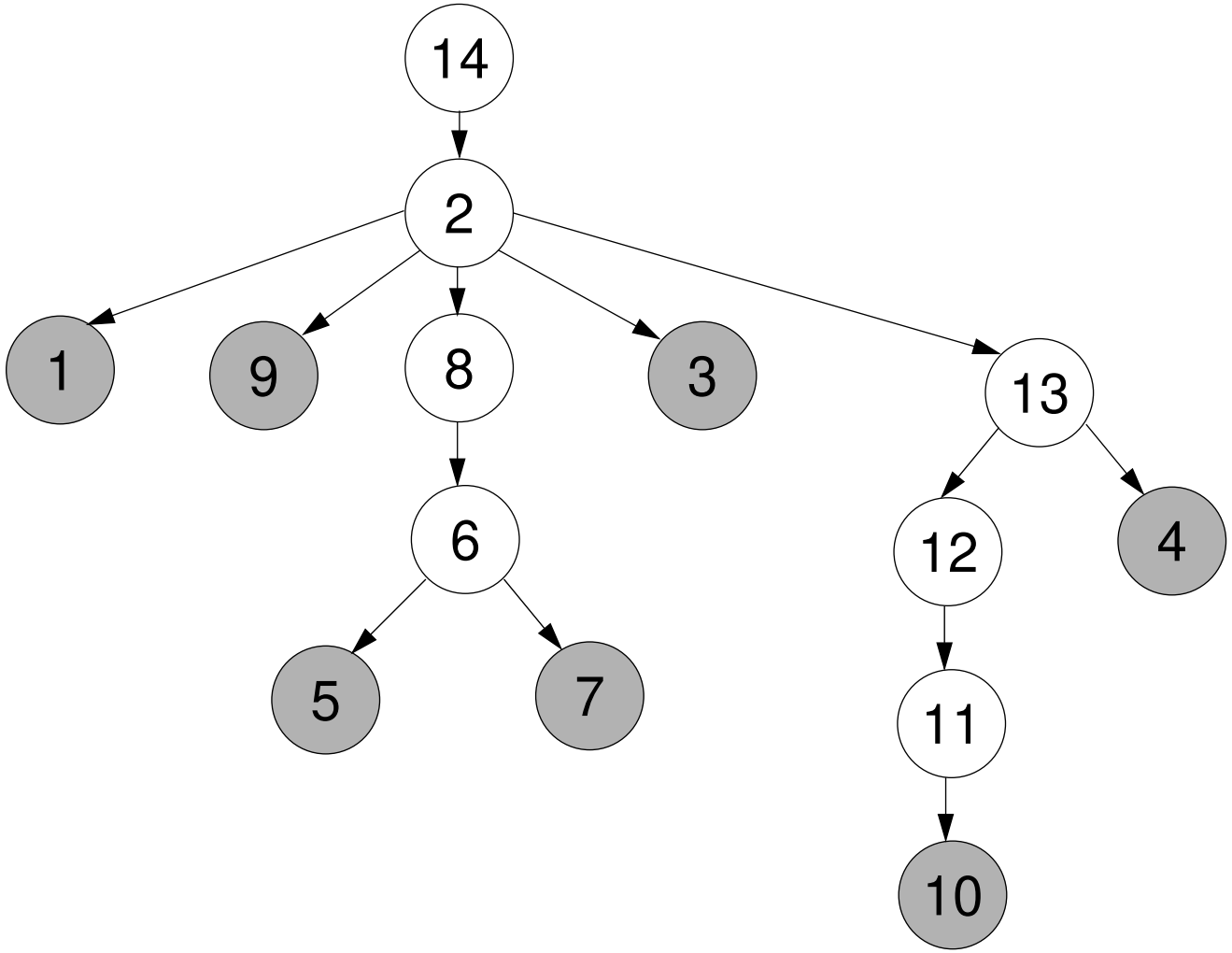
Postdominator Tree



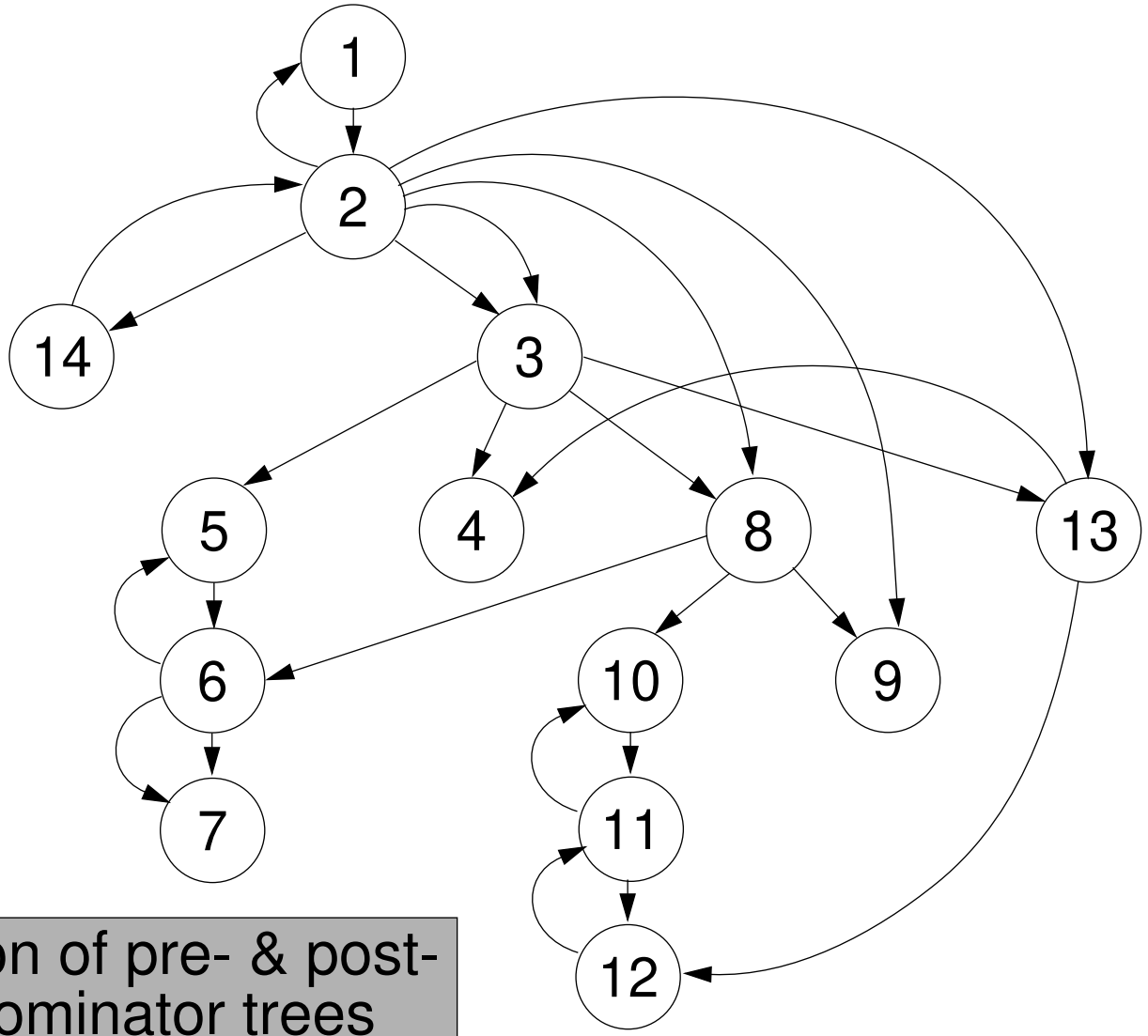
Control Flow Graph



Postdominator Tree (cont'd)

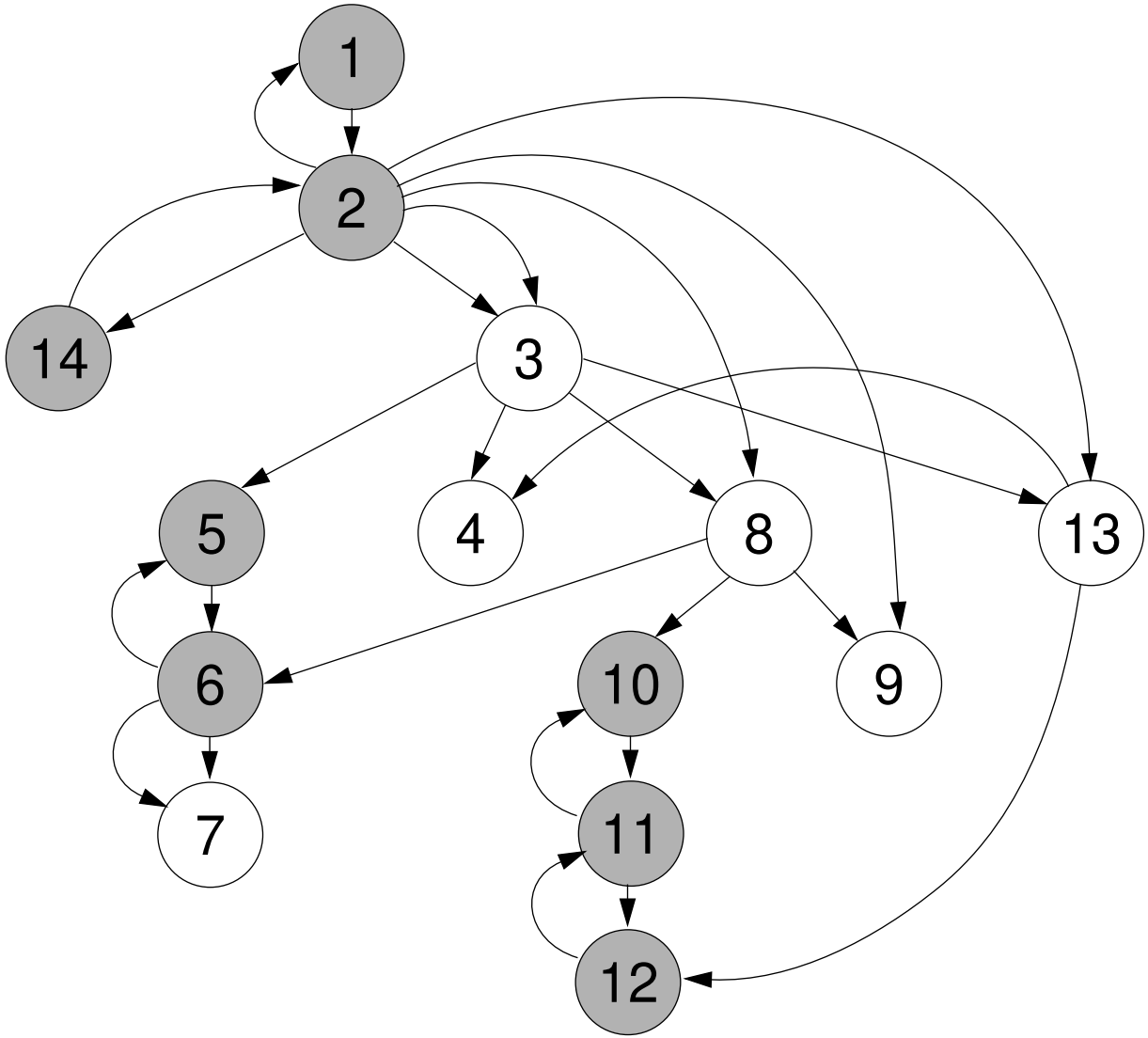


Dominator Graph

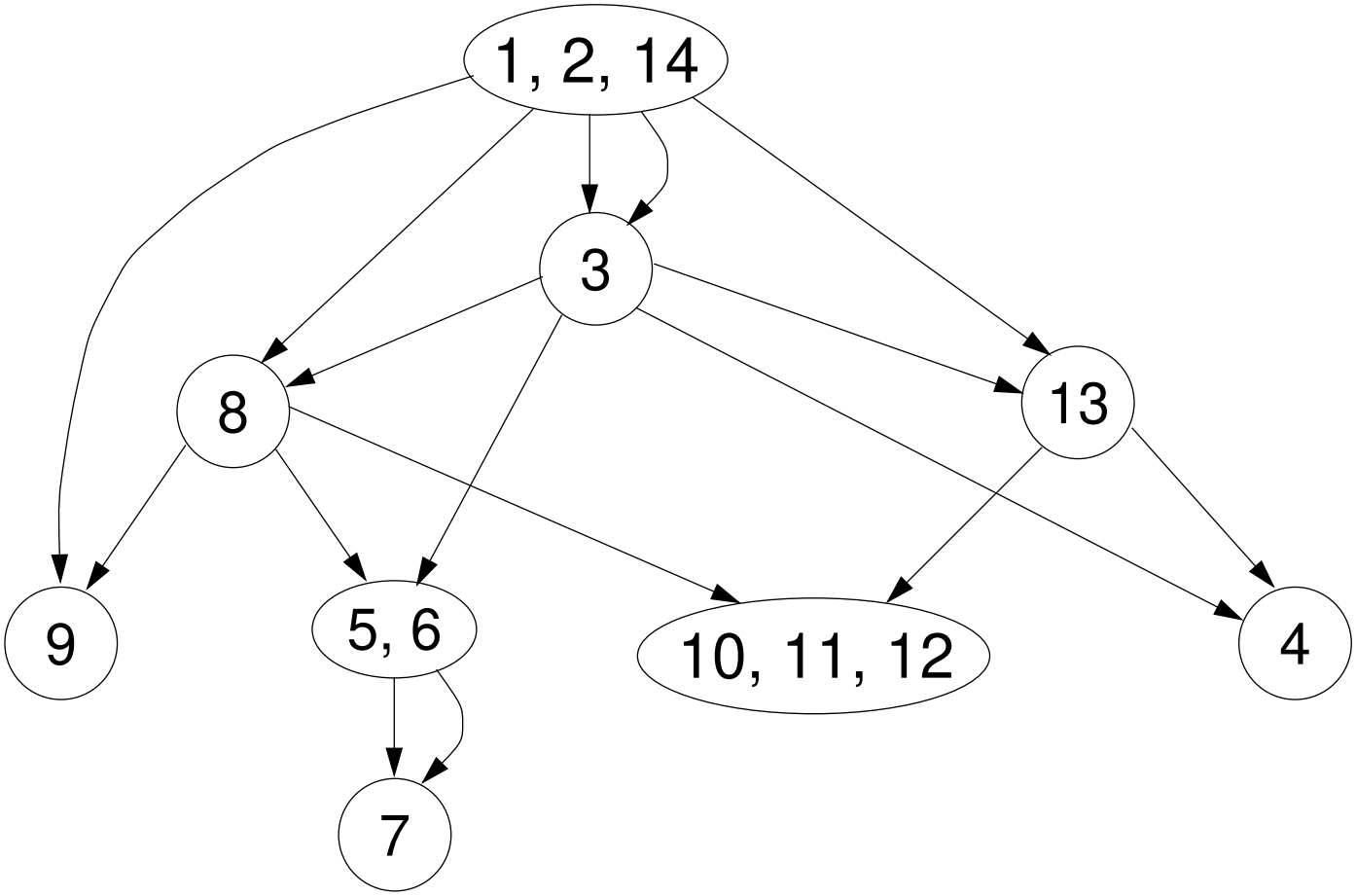


union of pre- & post-dominator trees

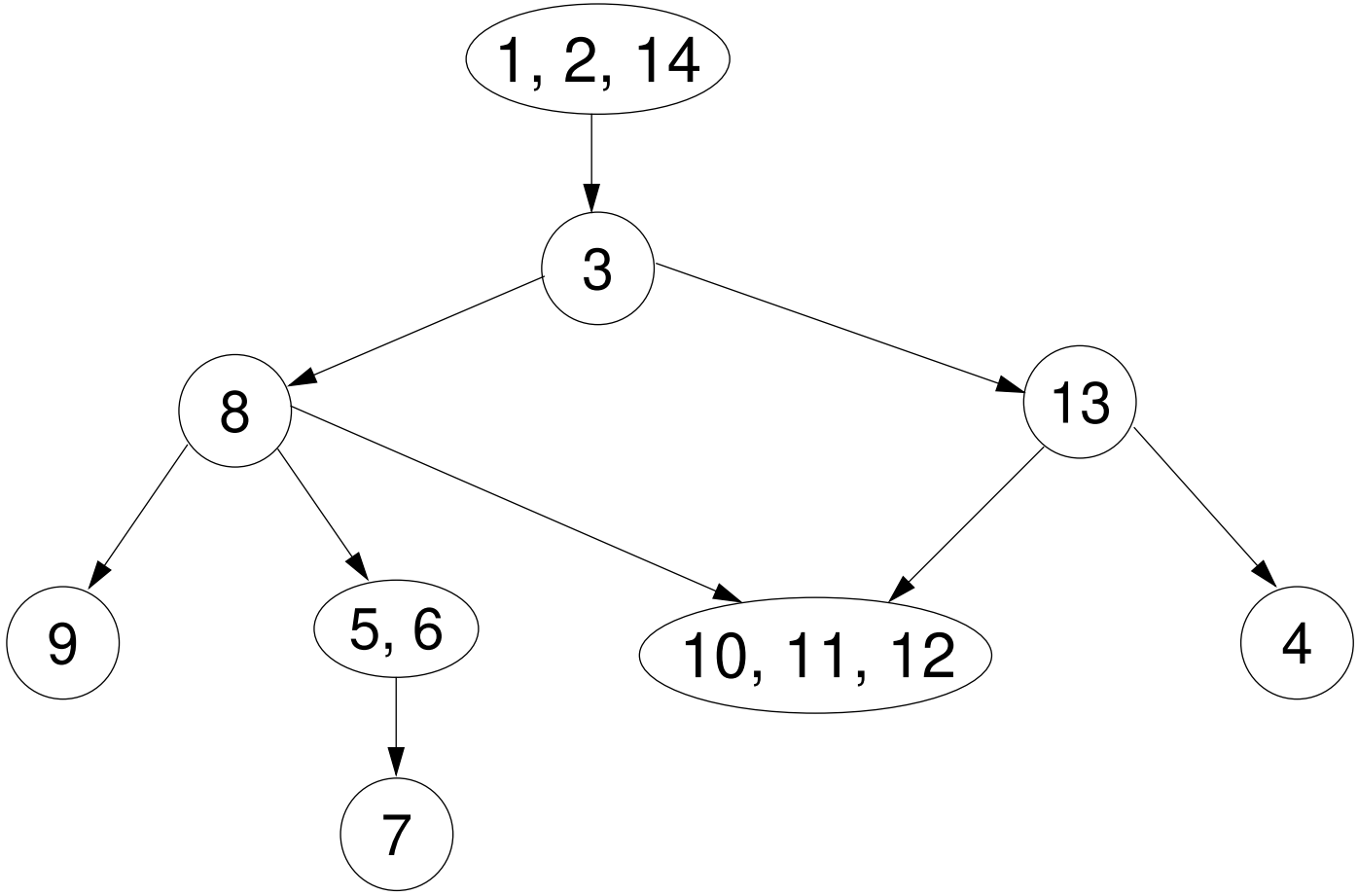
Dominator Graph (cont'd)



Condensed Dominator Graph



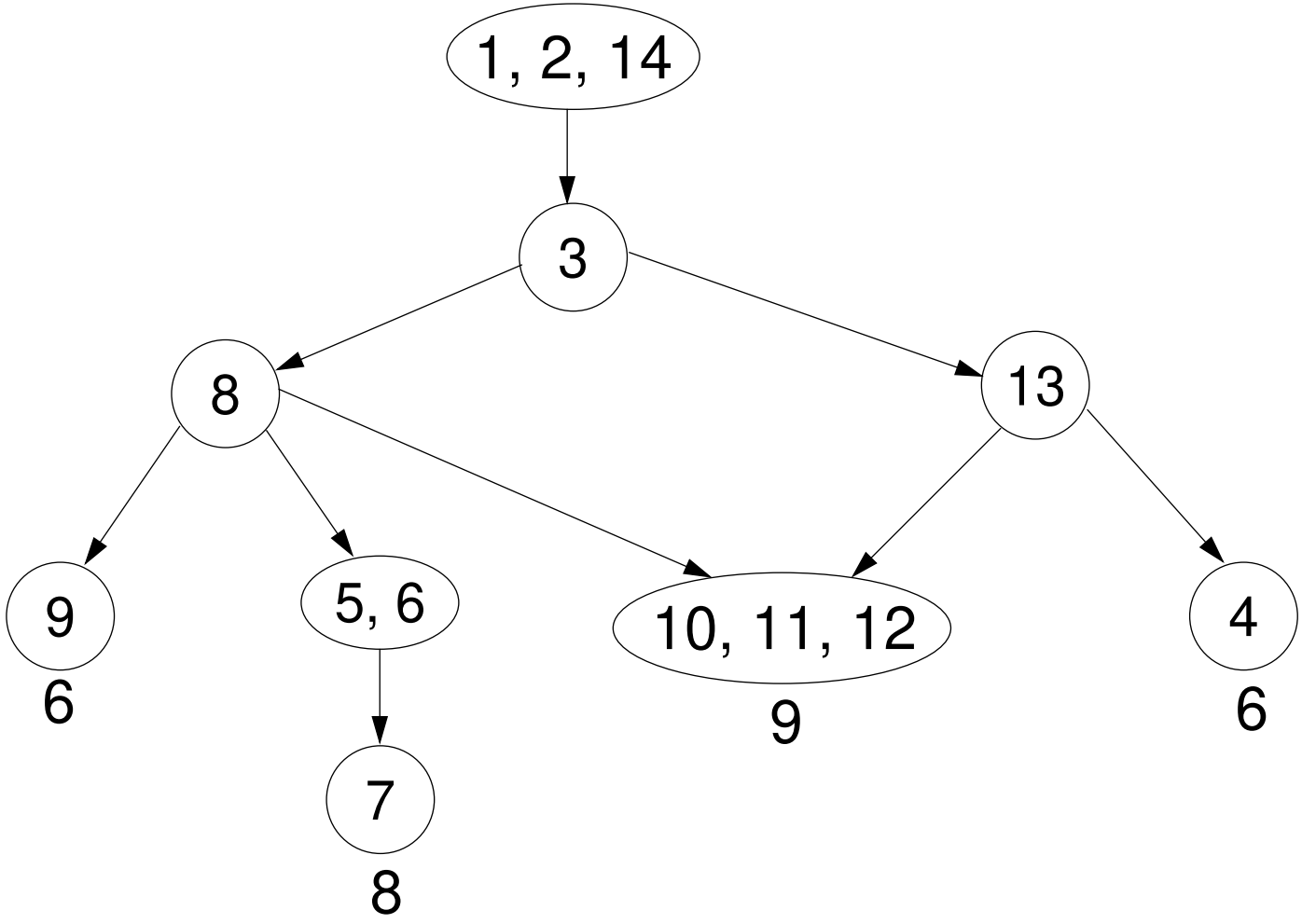
Super Block Dominator Graph



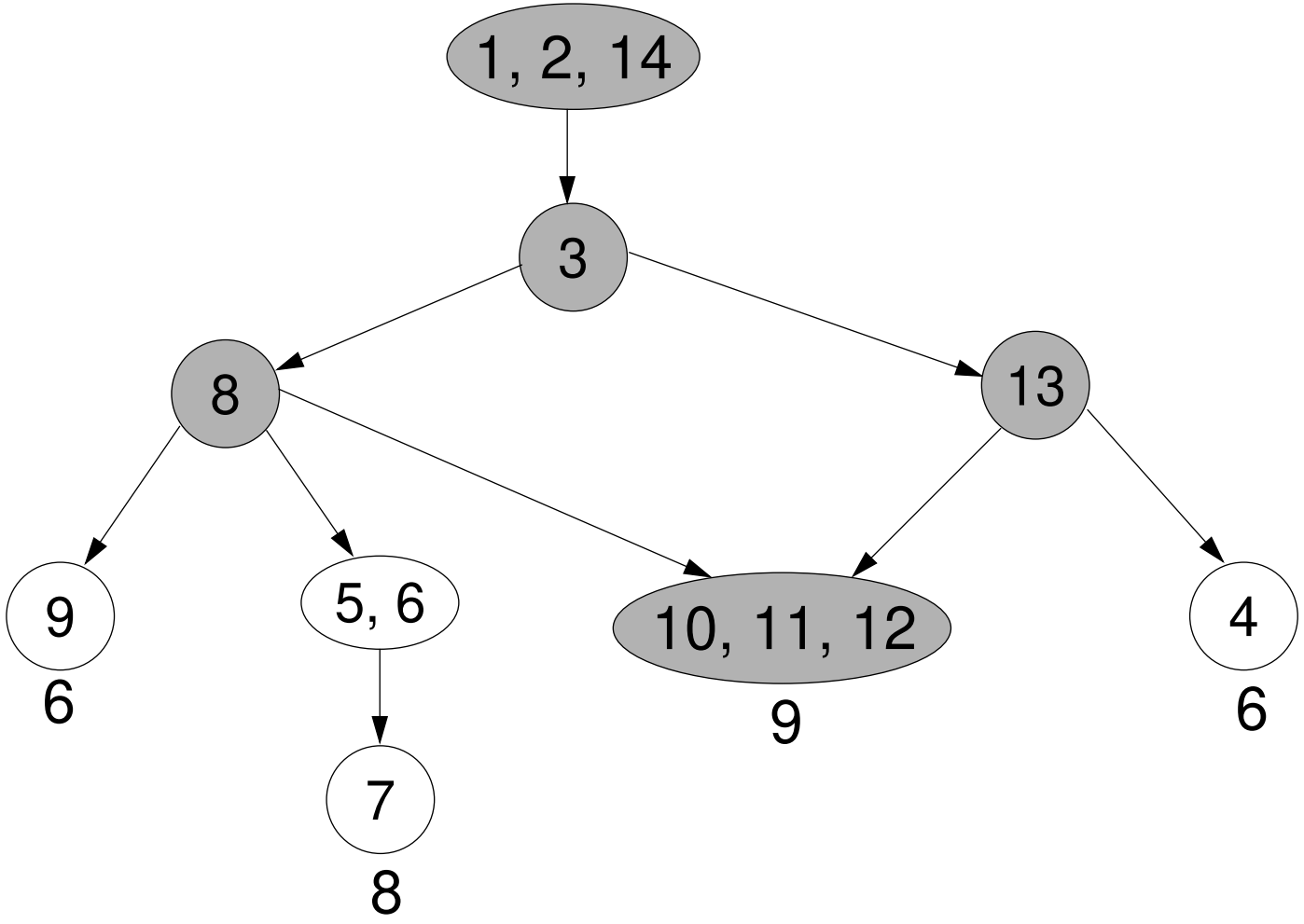
Super Blocks v/s Basic Blocks

- A super block contains one or more basic blocks.
- A super block need not be contiguous.
- If any statement in a super block is visited, then all statements in it must be visited, *provided the execution terminates on that input*.
- We only need one instrument per super block.

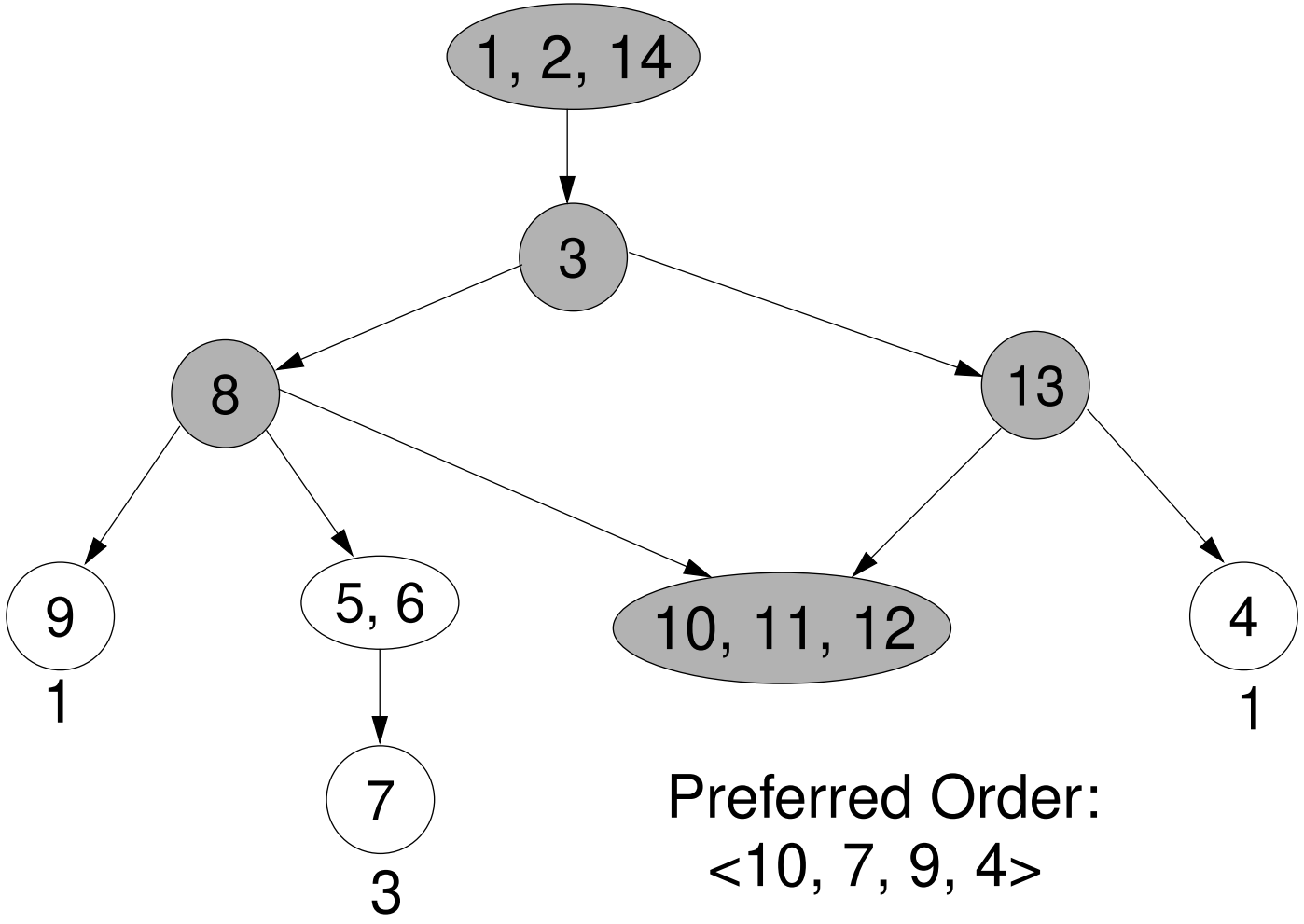
Weighted Super Block Dominator Graph



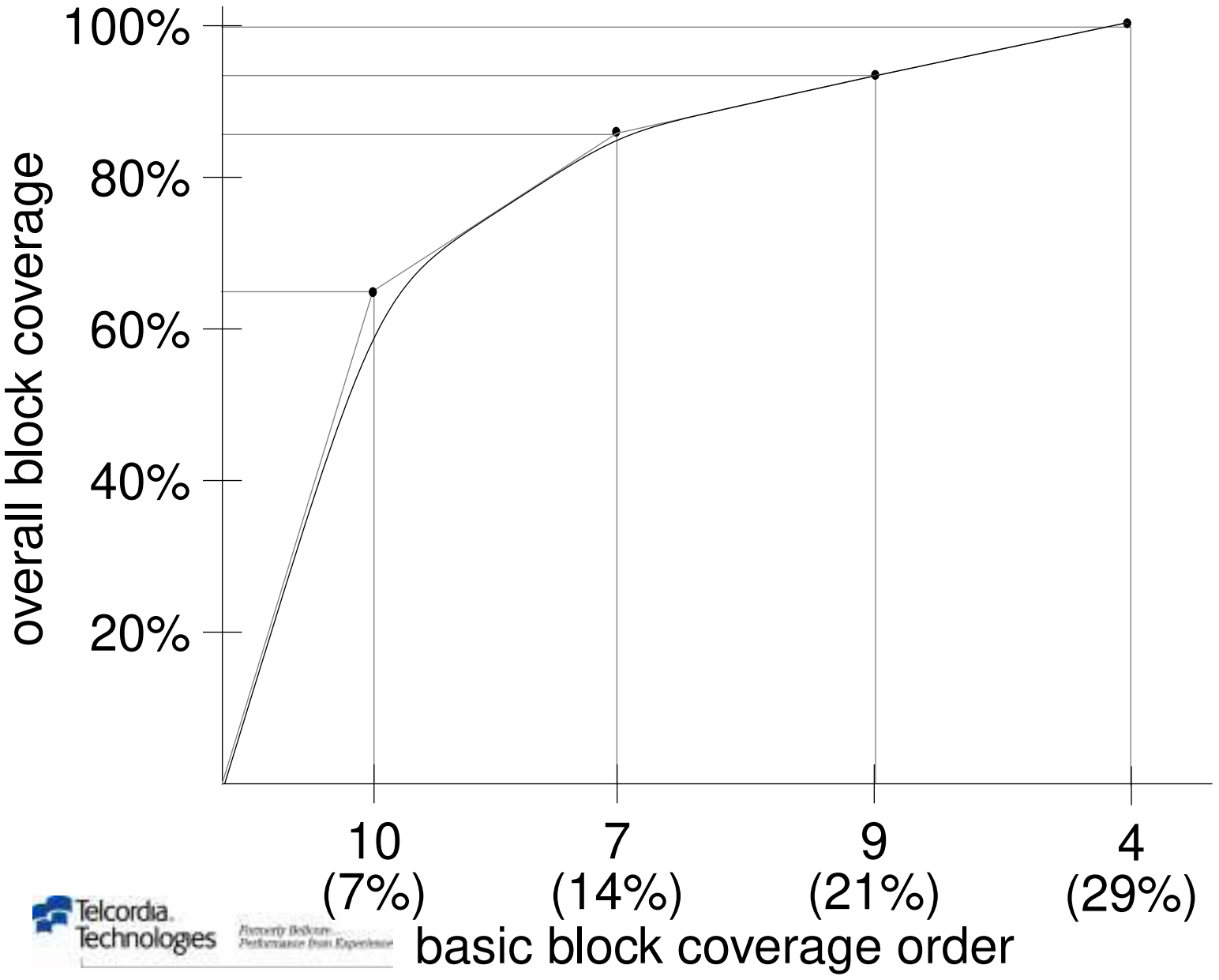
Cover the Heaviest Leaf First



Recompute Weights



Coverage Rate



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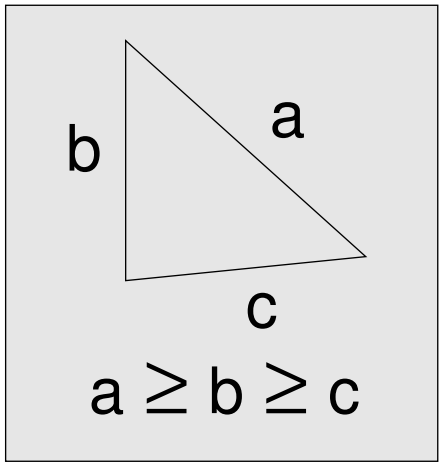
Experimental Results

program	basic blocks	blocks that need to be covered		probes required	
sort	455	138	30%	152	33%
spiff	1266	361	29%	404	32%
mgr	3848	1043	27%	1233	32%
ion	4886	1280	26%	1507	31%
atac	8737	2574	29%	2971	34%
odin	9870	2344	24%	2944	30%
xlib	15580	5111	33%	6016	39%
tvo	17680	6267	35%	8150	46%

Smart Debugging

```
read (a, b, c);
class := scalene;
if a = b || b = a
    class := isosceles;
if a*a = b*b + c*c
    class := right;
if a = b && b = c
    class := equilateral;
case class of
    right       :  area := b*c / 2;
    equilateral :  area := a*a * sqrt(3)/4;
    otherwise   :  s := (a+b+c)/2;
                   area := sqrt(s*(s-a)*(s-b)*(s-c));
end;
write(class, area);
```



Test Suite

Test case	Input			Output	
	a	b	c	class	area
T_1	2	2	2	equilateral	1.73
T_2	4	4	3	isosceles	5.56
T_3	5	4	3	right	6.00
T_4	6	5	4	scalene	9.92
T_5	3	3	3	equilateral	3.90

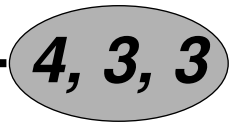
Failure Detected!

Test case	Input			Output	
	a	b	c	class	area
T_1	2	2	2	equilateral	1.73
T_2	4	4	3	isosceles	5.56
T_3	5	4	3	right	6.00
T_4	6	5	4	scalene	9.92
T_5	3	3	3	equilateral	3.90
T_6	4	3	3	scalene	4.47

Failure!

Where's the Bug?

```
read (a, b, c);
class := scalene;
if a = b || b = a
    class := isosceles;
if a*a = b*b + c*c
    class := right;
if a = b && b = c
    class := equilateral;
case class of
    right          :  area := b*c / 2;
    equilateral    :  area := a*a * sqrt(3)/4;
    otherwise      :  s := (a+b+c)/2;
                      area := sqrt(s*(s-a)*(s-b)*(s-c));
end;
write(class, area);
```



Execution Slice w.r.t. T_6 = (4 3 3)

```
read (a, b, c);
class := scalene;
if a = b || b = a
    class := isosceles;
if a*a = b*b + c*c
    class := right;
if a = b && b = c
    class := equilateral;
case class of
    right       :  area := b*c / 2;
    equilateral :  area := a*a * sqrt(3)/4;
    otherwise   :  s := (a+b+c)/2;
                   area := sqrt(s*(s-a)*(s-b)*(s-c));
end;
write(class, area);
```

Failure Detected!

Test case	Input			Output	
	a	b	c	class	area
T_1	2	2	2	equilateral	1.73
T_2	4	4	3	isosceles	5.56
T_3	5	4	3	right	6.00
T_4	6	5	4	scalene	9.92
T_5	3	3	3	equilateral	3.90
T_6	4	3	3	scalene	4.47

Failure!

Execution Slice w.r.t. Failed Test (T_6)

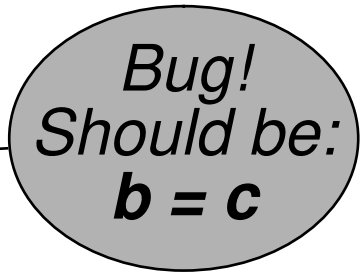
```
read (a, b, c);
class := scalene;
if a = b || b = a
    class := isosceles;
if a*a = b*b + c*c
    class := right;
if a = b && b = c
    class := equilateral;
case class of
    right      :  area := b*c / 2;
    equilateral :  area := a*a * sqrt(3)/4;
    otherwise  :  s := (a+b+c)/2;
                  area := sqrt(s*(s-a)*(s-b)*(s-c));
end;
write(class, area);
```

Execution Slice w.r.t. Passed Test, (T_2)

```
read (a, b, c);
class := scalene;
if a = b || b = c
    class := isosceles;
if a*a = b*b + c*c
    class := right;
if a = b && b = c
    class := equilateral;
case class of
    right      :  area := b*c / 2;
    equilateral :  area := a*a * sqrt(3)/4;
    otherwise  :  s := (a+b+c)/2;
                  area := sqrt(s*(s-a)*(s-b)*(s-c));
end;
write(class, area);
```

Resulting Dice [Slice (4 3 3) – Slice (4 4 3)]

```
read (a, b, c);
class := scalene;
if a = b || b = a
    class := isosceles;
if a*a = b*b + c*c
    class := right;
if a = b && b = c
    class := equilateral;
case class of
    right       :  area := b*c / 2;
    equilateral :  area := a*a * sqrt(3)/4;
    otherwise   :  s := (a+b+c)/2;
                   area := sqrt(s*(s-a)*(s-b)*(s-c));
end;
write(class, area);
```



Slicing Experiment

- Unix Sort Program
- 508 Basic Blocks
- 25 Independently Seeded Faults
- 56 Tests
- 96% Block Coverage, 89% Branch Coverage
- 6 Faults Not Detected By Any Test

Slicing Experiment Results

fault id	# of dices	# good	avg. size
F117	159	84%	26%
F206	55	93%	11%
F336	783	100%	24%
F414	55	100%	22%
F439	208	94%	18%
F442	495	100%	14%
F507	684	50%	6%
F608	55	100%	31%
F631	423	100%	19%
F634	300	100%	23%

fault id	# of dices	# good	avg. size
F691	735	100%	16%
F772	55	98%	19%
F782	384	79%	11%
F783	384	100%	11%
F806	55	96%	29%
F811	159	85%	23%
F851	768	100%	15%
F882	423	100%	14%
F910	255	86%	15%
Avg.	**338**	**93%**	**18%**

Incremental Regression Testing

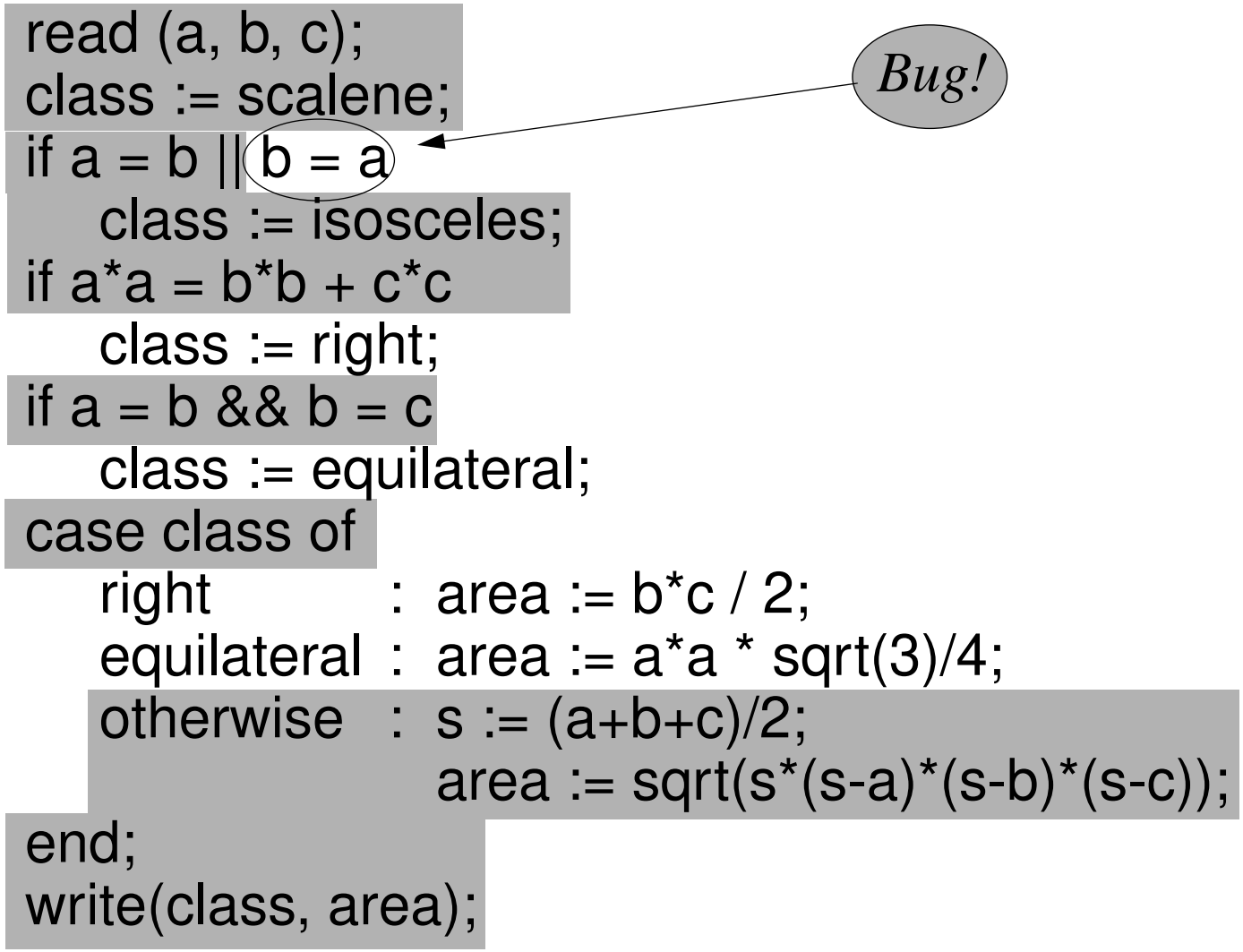
```
read (a, b, c);
class := scalene;
if a = b || b = c
    class := isosceles;
if a*a = b*b + c*c
    class := right;
if a = b && b = c
    class := equilateral;
case class of
    right          :  area := b*c / 2;
    equilateral    :  area := a*a * sqrt(3)/4;
    otherwise      :  s := (a+b+c)/2;
                      area := sqrt(s*(s-a)*(s-b)*(s-c));
end;
write(class, area);
```

Which Tests Should We Rerun?

Test case	Input			Output	
	a	b	c	class	area
T_1	2	2	2	equilateral	1.73
T_2	4	4	3	isosceles	5.56
T_3	5	4	3	right	6.00
T_4	6	5	4	scalene	9.92
T_5	3	3	3	equilateral	3.90
T_6	4	3	3	scalene	4.47

Failure!

Execution Slice w.r.t. T_2 = (4 4 3)



Execution Slice w.r.t. T_4 = (6 5 4)

```
read (a, b, c);
class := scalene;
if a = b || b = a
    class := isosceles;
if a*a = b*b + c*c
    class := right;
if a = b && b = c
    class := equilateral;
case class of
    right       :  area := b*c / 2;
    equilateral :  area := a*a * sqrt(3)/4;
    otherwise   :  s := (a+b+c)/2;
                   area := sqrt(s*(s-a)*(s-b)*(s-c));
end;
write(class, area);
```

Which Test Cases Should We Rerun?

Test case	Input			Output	
	a	b	c	class	area
T_1	2	2	2	equilateral	1.73
T_2	4	4	3	isosceles	5.56
T_3	5	4	3	right	6.00
T_4	6	5	4	scalene	9.92
T_5	3	3	3	equilateral	3.90
T_6	4	3	3	scalene	4.47

Failure!

Execution Slice w.r.t. T_3 = (5 4 3)

```
read (a, b, c);
class := scalene;
if a = b || b = a
    class := isosceles;
if a*a = b*b + c*c
    class := right;
if a = b && b = c
    class := equilateral;
case class of
    right          :  area := b*c / 2;
    equilateral    :  area := a*a * sqrt(3)/4;
    otherwise      :  s := (a+b+c)/2;
                      area := sqrt(s*(s-a)*(s-b)*(s-c));
end;
write(class, area);
```

Bug!

scalene *Failure!*

Which Test Cases Should We Rerun?

Test case	Input			Output	
	a	b	c	class	area
T_1	2	2	2	equilateral	1.73
T_2	4	4	3	isosceles	5.56
T_3	5	4	3	right	6.00
T_4	6	5	4	scalene	9.92
T_5	3	3	3	equilateral	3.90
T_6	4	3	3	scalene	4.47

Failure!

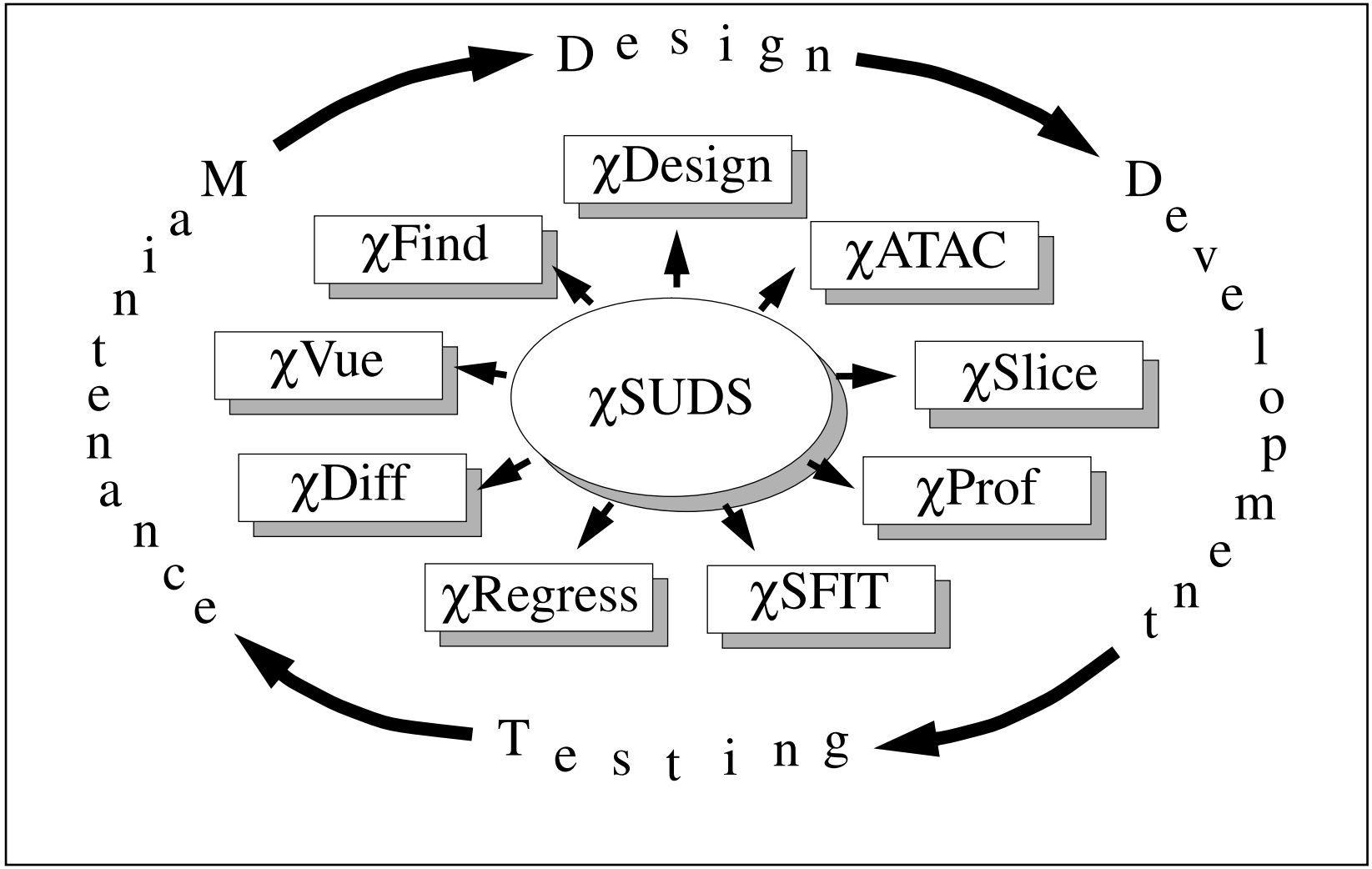
Regression Testing Experiment

- A Space Program from European Space Agency
- About 10,000 lines of C code
- 10 Actual Faults Obtained from Its Error Logs
- 1,000 Regression Tests With Operational Profile

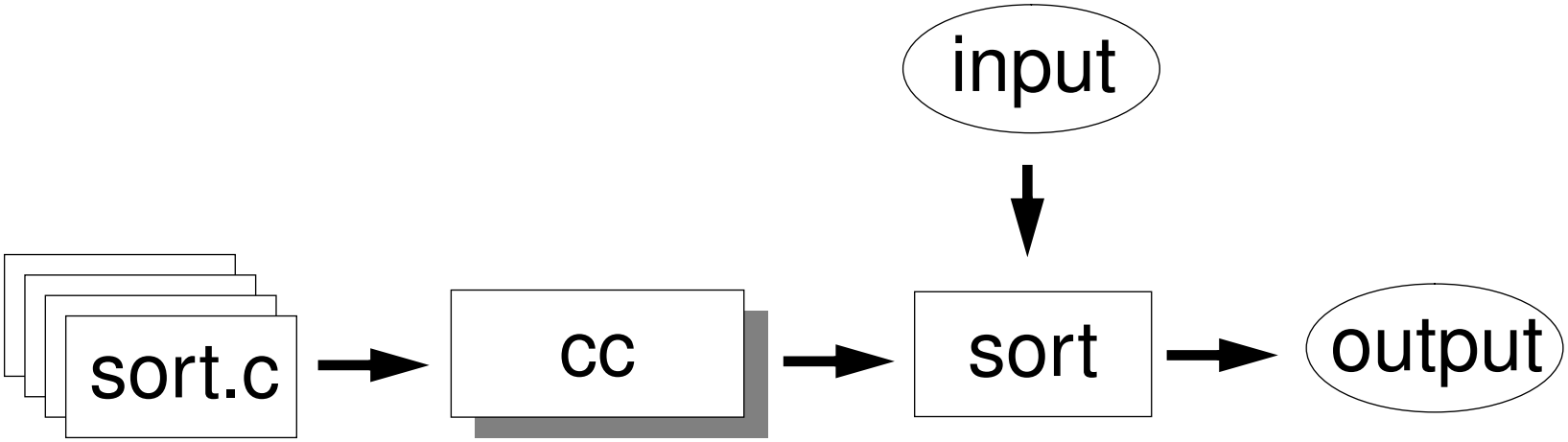
Regression Testing Experiment Results

fault id	# tests rerun	% tests rerun	minimum # tests
F1	38	3.8%	26
F2	22	2.2%	16
F3	84	8.4%	36
F4	4	0.4%	4
F5	4	0.4%	4
F6	38	3.8%	32
F7	38	3.8%	32
F8	34	3.4%	6
F9	71	7.1%	46
F10	470	47%	320

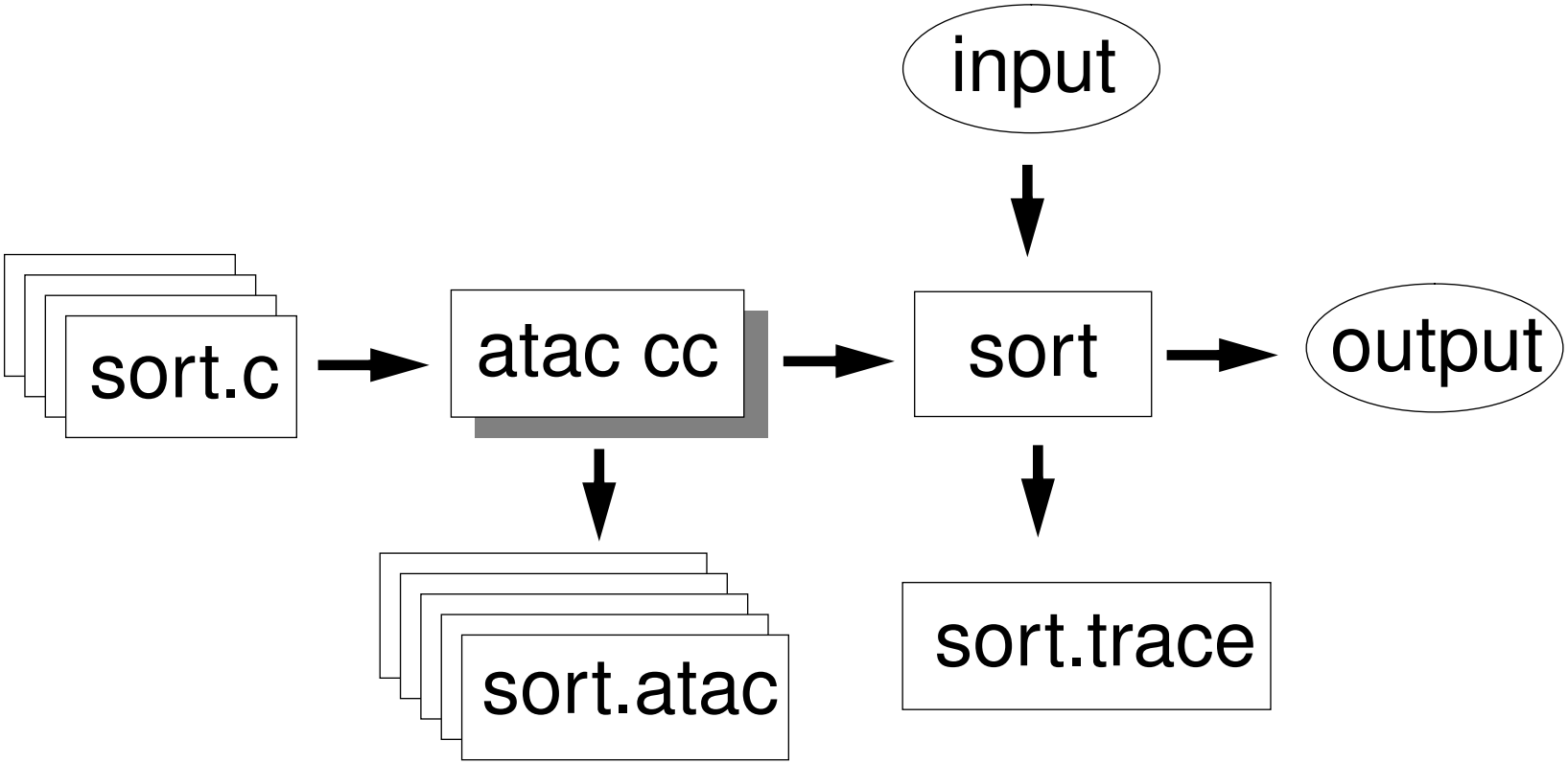
χSuds ToolSuite



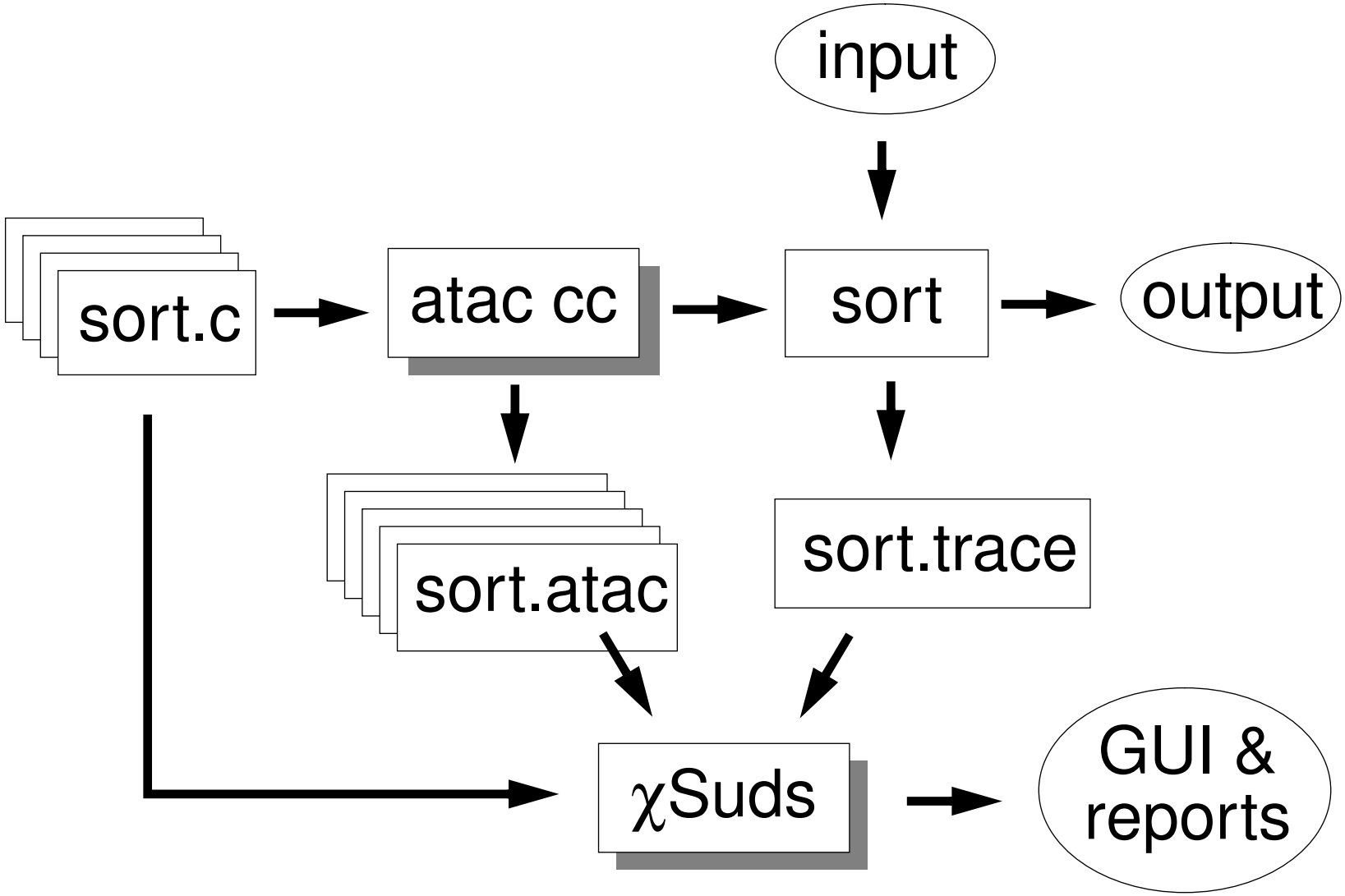
Program Instrumentation



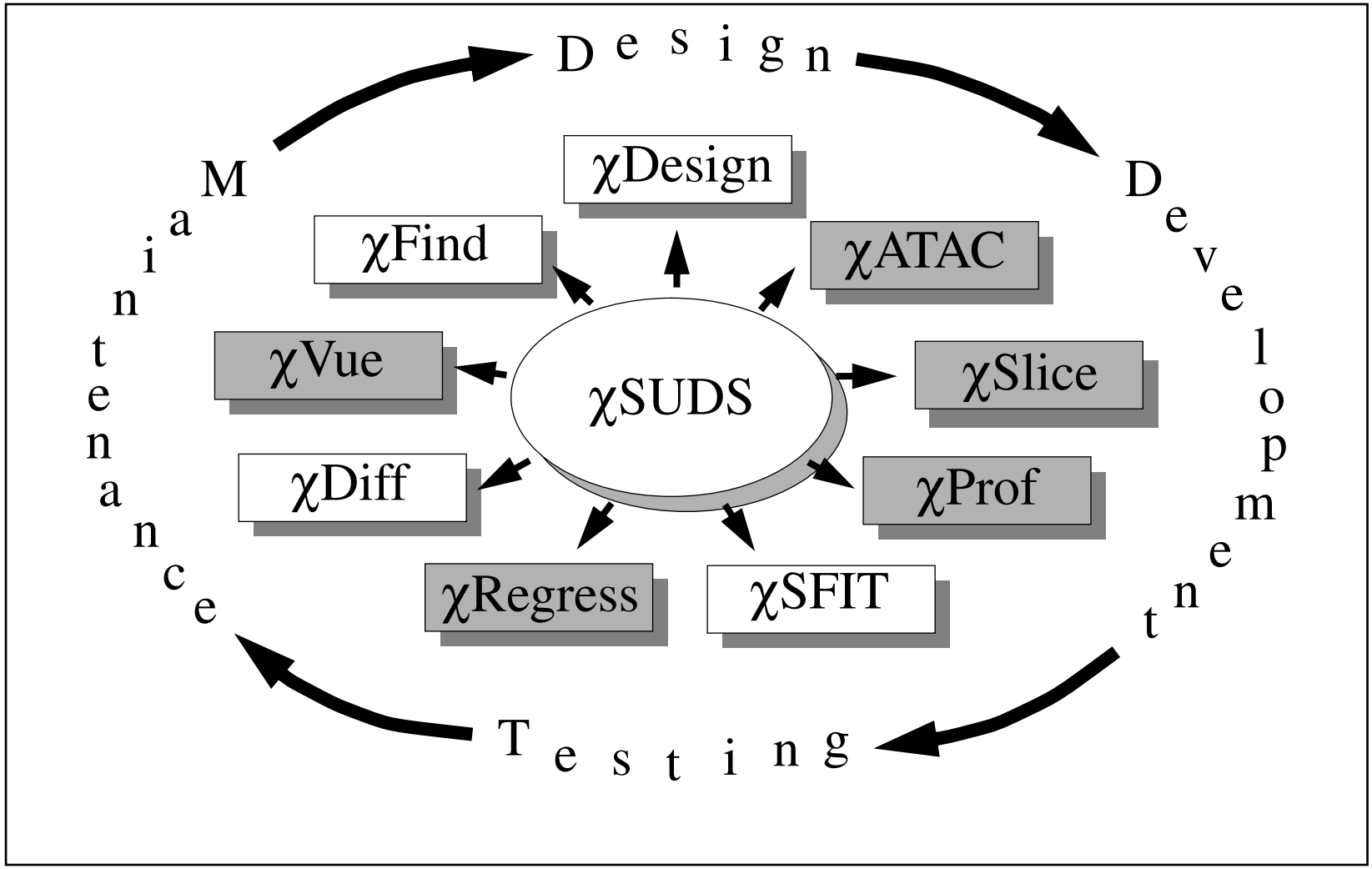
Program Instrumentation (cont'd)



Program Instrumentation (cont'd)



A Short Demo


Design
Development
Testing
Maintenance
χDesign
χATAC
χSlice
χProf
χSFIT
χRegress
χDiff
χVue
χFind
χSUDS

For More Information:

- www.research.telcordia.com/demos/#xsuds
- xsuds.argreenhouse.com
- www.research.telcordia.com/papers/hira

Future Directions

- Smart Program Diffs and Incremental Analysis
- More Empirical Studies
- More Advanced Heuristics
- High Level User Interfaces
- Automatic Test Case Generation