COM S/CPRE 513 x: Foundations and Applications of Program Analysis Spring 2018

Lecture 2: Control Flow Analysis

Instructor: Wei Le

2.1 What is Control Flow Analysis

Given program source code, control flow analysis aims to determine the order of program statements (or instructions), and predict and specify the set of execution traces. The topics of control flow analysis include:

1. representing the statically predicted execution traces: paths and control flow graphs
2. loops
3. infeasible paths
4. call graphs and interprocedural paths
5. exception
6. event-driven and framework based architecture like Android: callbacks, synchronous and asynchronous execution

2.1.1 Paths and control flow graphs (CFG, ICFG)

2.1.1.1 History

- 1970, Frances Allen's papers: "Control Flow Analysis" and "A Basis for Program Optimization" established "intervals" as the context for efficient and effective data flow analysis and optimization
- Turing award for pioneering contributions to the theory and practice of optimizing compiler techniques, awarded 2006

2.1.1.2 Definitions

- Dragon book, p529: basic block, flow graphs, predecessor, successor
- Evelyn Duesterwald et al., A practical framework for demand-driven interprocedural data flow analysis: ICFG, execution paths
- A summary:
  - *Basic block*: a linear sequence of program instructions having one entry point (the first instruction executed) and one exit point (the last instruction executed).
  - *Control flow graph (CFG)* is a directed graph in which the nodes represent basic blocks and the edges represent the transfer of the control flow between basic blocks

- a control flow graph specifies all possible execution paths. Control flow graph is an over-approximation of the execution traces. It includes the paths that are never possibly executed, namely *infeasible paths*.
- *Path*: a sequence of node on the CFG (static), including an entry node and an exit node; *path segment*: a subsequence of nodes along the path
- *Trace*: a sequence of instructions performed during execution (dynamic)
- CFG: representing control flow for a single procedure
- ICFG: representing control flow for a program

Example 2.1

2.1.1.3 Construction

Converting ast to cfg based on the types of statements, existing tools that construct a cfg

- Soot, LLVM
- Boa, Helium @ Iowa State

2.1.2 Loops

Most of the execution time is spent in loops - the 90/10 law, which states that 90% of the time is spent in 10% of the code, and only 10% of the time in the remaining 90% of the code.

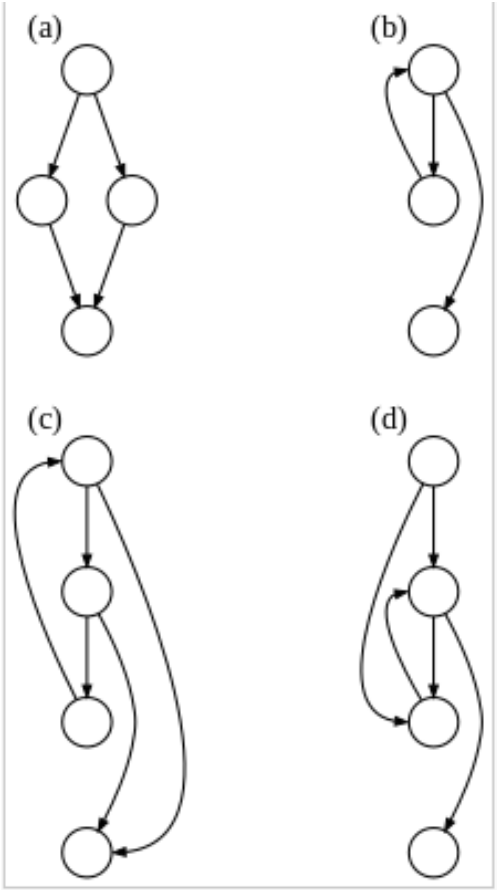
2.1.2.1 Dominance, Postdominance — what is a loop

- *dominance*, *dominator*, *dominator trees* and *postdominator* – relations between nodes on the CFG
  - Node d of a CFG *dominates* node n if every path from the entry node of the graph to n passes through d, noted as d *dom* n
  - Every node dominates itself: $n \in Dom(n)$, Reflexive: a dom a; Transitive: if a dom b and b dom c then a dom c; Antisymmetric: if a dom b and b dom a then b=a
  - Node d *strictly dominates* n if $d \in Dom(n)$ and $d \neq n$
  - Each node n (except the entry node) has a unique *immediate dominator* m which is the last dominator of n on any path from the entry to n (m *idom* n), $m \neq n$
  - The immediate dominator m of n is the strict dominator of n that is closest to n
  - Node d of a CFG *post dominates* node n if every path from n to the exit node passes through d (d *pdom* n)
  - Every node post dominates itself: $n \in Pdom(n)$
  - Each node n (except the exit node) has a unique *immediate post dominator*
- *head*, *back edge* – head (ancestor) dominates its tail (decedent), any edge from tail to head is a back edge

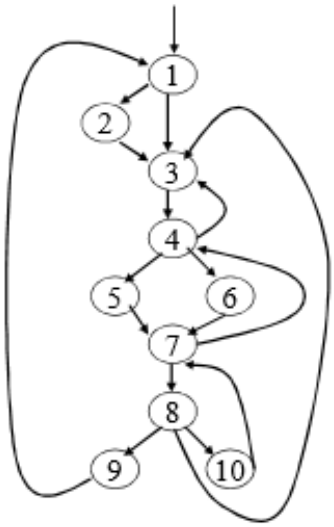
Example 2.2 *Dominance Figure 2.2*

Dominator Tree Figure 2.2

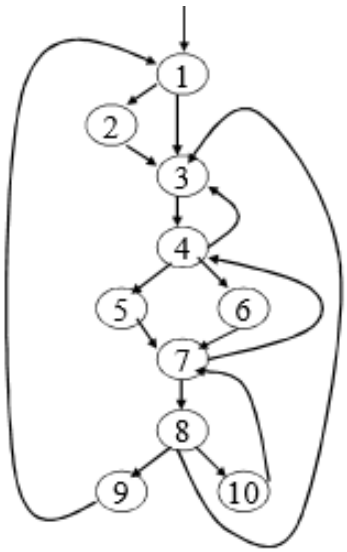
Post-dominance Figure 2.2

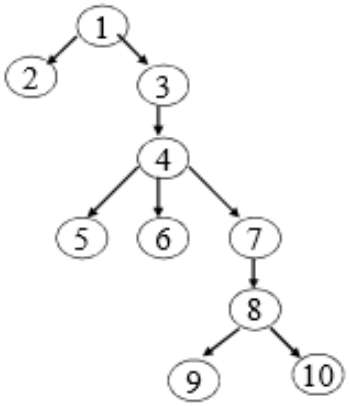


Some CFG examples:
(a) an if-then-else
(b) a while loop
(c) a natural loop with two exits, e.g. while with an if...break in the middle; non-structured but reducible
(d) an irreducible CFG: a loop with two entry points, e.g. goto into a while or for loop

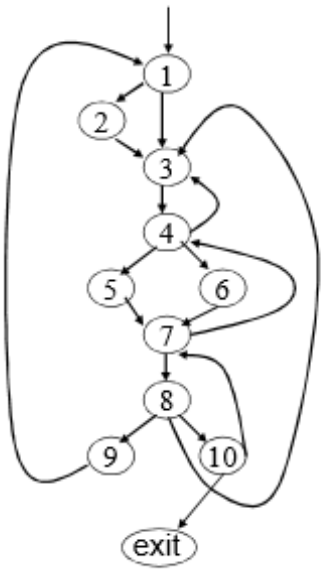


Block	Dom	IDom
1	{1}	—
2	{1,2}	1
3	{1,3}	1
4	{1,3,4}	3
5	{1,3,4,5}	4
6	{1,3,4,6}	4
7	{1,3,4,7}	4
8	{1,3,4,7,8}	7
9	{1,3,4,7,8,9}	8
10	{1,3,4,7,8,10}	8

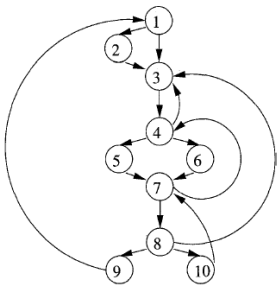


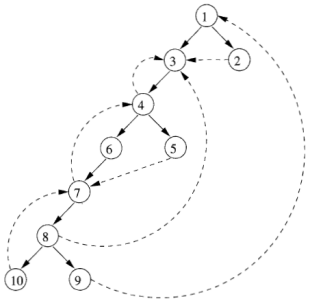


- In a dominator tree, a node's parent is its immediate dominator



Block	Pdom	IPdom
1	{3,4,7,8,10,exit}	3
2	{2,3,4,7,8,10,exit}	3
3	{3,4,7,8,10,exit}	4
4	{4,7,8,10,exit}	7
5	{5,7,8,10,exit}	7
6	{6,7,8,10,exit}	7
7	{7,8,10,exit}	8
8	{8,10,exit}	10
9	{1,3,4,7,8,10,exit}	1
10	{10,exit}	exit



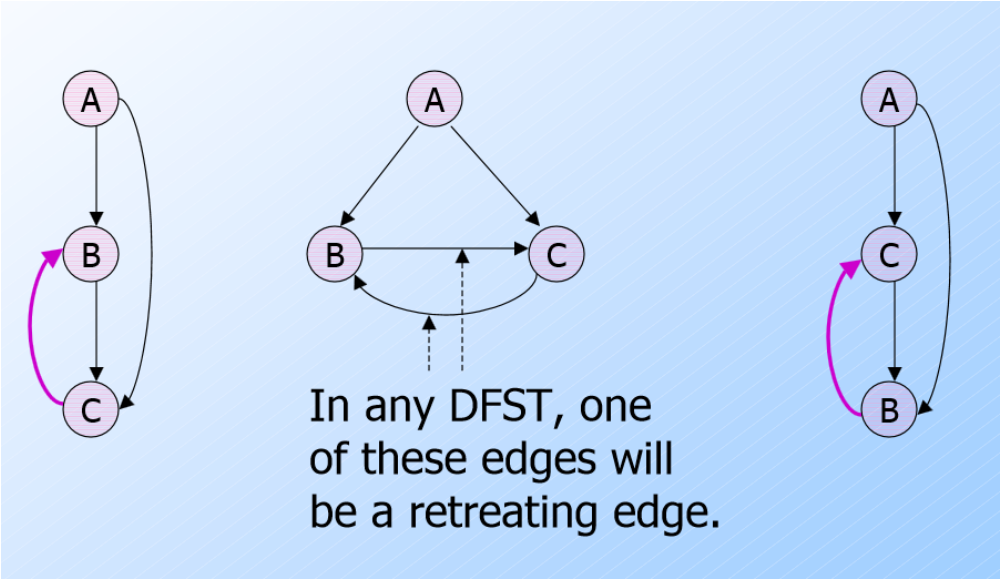


2.1.2.2 Reducibility — a special type of loops

- A graph traversal visits each node via edges
- A *depth-first traversal* of a graph visits all the nodes in the graph once, by starting at the entry node and visiting the nodes as far away from the entry node as quickly as possible. In a depth-first presentation of the flow graph, the parent is the ancestor and the children is the decedent
- *Retreating edge*: in a depth first traversal of a graph, the retreating edge $m \to n$ connects a decedent m to its ancestor n ($dfn[m] \geq dfn[n]$) [dragon book p.662]
- A flow graph is *reducible* if every retreating edge in a flow graph is a back edge: take any DFST for the flow graph, remove the back edges, the result should be acyclic — intuitively, there are multiple "heads"

Example 2.3 *Depth-first traversal*

Example 2.4 *Irreducible Graph:*



Natural Loops (Reducible Loops):

- Flowgraph is reducible iff all loops in it *natural*
- Single entry node (d)
  - no jumps into middle of loop
  - d dominates all nodes in loop
- Requires back edge into loop header ($n \rightarrow d$)

Example 2.5 *Natural Loops:*

Reducibility in Practice:

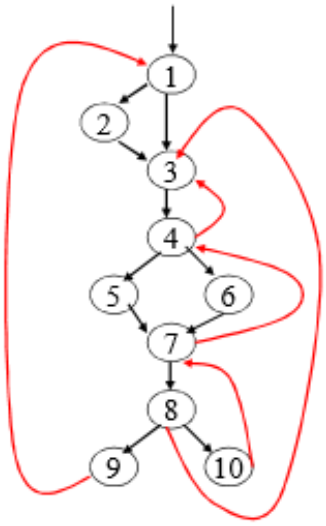
- If you use only while-loops, for-loops, repeat-loops, if-then(-else), break, and continue, then your flow graph is reducible.
- Some languages only permit procedures with reducible flowgraphs (e.g., Java)
- GOTO Considered Harmful: can introduce irreducibility
  - FORTRAN
  - C
  - C++

2.1.2.3 Single Loops, Nested Loops, Inner Loops and Outer Loops

single loops, *nested loops* and *inner loops*

Single loop: loops that do not contain other loops inside

Nested loop:



Back edge	Natural loop
10→7	{7,10,8}
7→4	{4,7,5,6 10,8}
4→3	{3,4,7,5,6,10,8}
8→3	
9→1	{1,9,8,7,5,6, 10,4,3,2}

- Why neither {3,4} nor {4,5,6,7} is a natural loop?

- If two loops do not have the same header, disjoint
- one is entirely contained (nested within) the other

An *inner loop* is a loop that contains no other loops

- Good optimization candidate
- The inner loop of the previous example: 7,8,10

2.1.2.4 Goals of Loop Analysis: Useful information about a loop

1. Loop bound: loop iteration count
2. Loop termination problems
3. Loop invariant: the properties hold during loop execution
4. Loop summary: the output variables represented using the input variables
5. Loop induction variable:

Example 2.6 *Loop invariant, loop summary*

Loop features (Syntactic):

- Single or multi-paths
- Data structure: integer, string, array, containers ...
- Library calls

- Environment: user interactive, networking
- Nested loop

Semantic:

- What a loop computes: test a membership, sort a list of numbers, calculate a mean, traverse a data structure ...
- Loop invariants
- Pre- and post-conditions
- The relations of output variables and input variables are linear

Runtime Characteristics:

- Cache misses
- Performance

2.1.2.5 Loop Algorithms

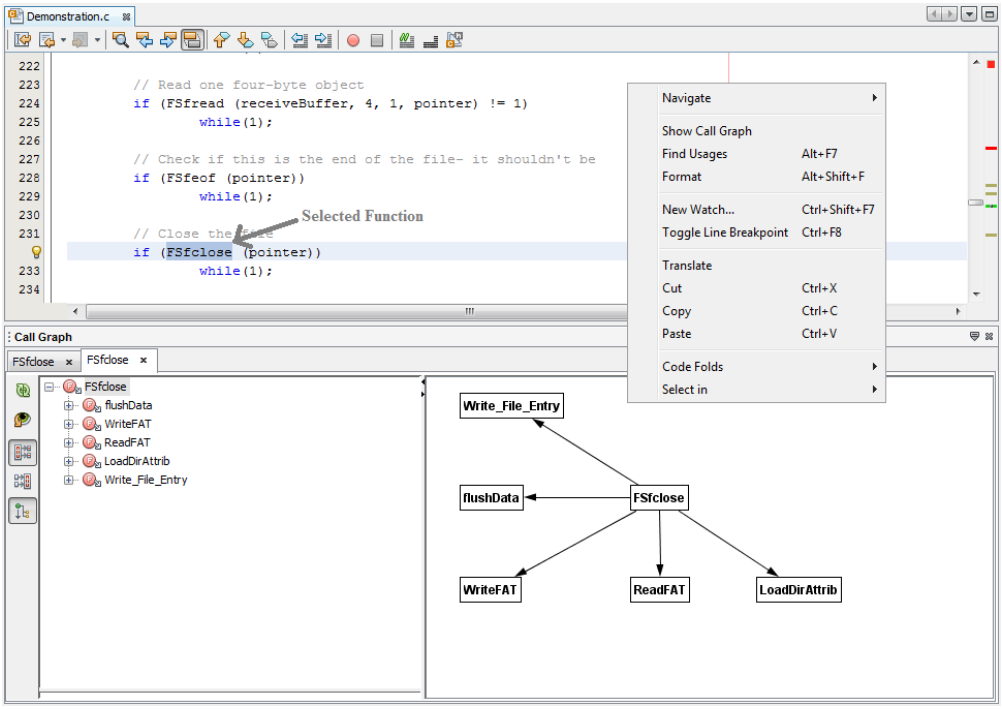
- Construct loops for CFG: Convert AST to CFG based on the types of statements
- Detect loops in CFG: Dominance' based loop recognition: entry of a loop dominates all nodes in the loop
- Detect natural loops in CFG
- Applications:
  - determine loop bound and worst case execution time
  - determine termination of the program
  - determine loop invariant for verifying the code
  - determine loop summary

Challenges of loop analysis:

- multipath
- loop exit conditions
- nested loops

Traditional Loop Analysis: Very small state space is covered

- Iterate once [Cadar, Dunbar, Engler 08] [Chipounov, Kuznetsov, Candea 12]
- Report unknown [Xie, Chou, Engler 03]
- Pattern matching [Saxena, Poosankam, McCamant, Song 00]



- ...

New research 2013: Goal: Loop effects on variables Solution: Segmented Symbolic Analysis (dynamic)

New research 2017: Analyzing multiple path loops using pushing down automata Performance Diagnosis for Inefficient Loops

2.1.2.6 Infeasible Paths

Refining data flow information using infeasible paths:

SPEC 95 benchmarks, 2% are infeasible

9–40% branch manifest correlations

2.1.3 Call graphs and interprocedural analysis

Call graph is a directed graph that represents the calling relationships between program procedures

Example 2.7

Challenges of call graph construction: Dynamic dispatch

- Which implementation of the function will be invoked at the callsite?
- The binding is determined at runtime, based on the input of the program and execution paths.

```
class A {
public:
   virtual void f();
   ...
};
```

```
class B: public A {
public:
   virtual void f();
...
};
```

```
int main()
{
   A *pa = new B();

   pa->f();
   ...
}
```

```
int main()
{
  A a; // An A instance is created on the stack
  B b; // A B instance, also on the stack

  a = b;  // Only the A part of 'b' is copied into a.

  a.f();  // Static dispatch. This determines the binding
          // of f to A's f and this is done at compile time.
```

Example 2.8 *Dynamic Dispatch: To which implementation the call* **f** *bound to?*

Compared to Static Dispatch: Static dispatch: the binding is determined at the compiler time.

Programming language constructs that support dynamic dispatch:

- Function pointers
- Class hierarchy in object oriented languages
- Functional languages

2.1.3.1 Call graph construction for Function Pointers

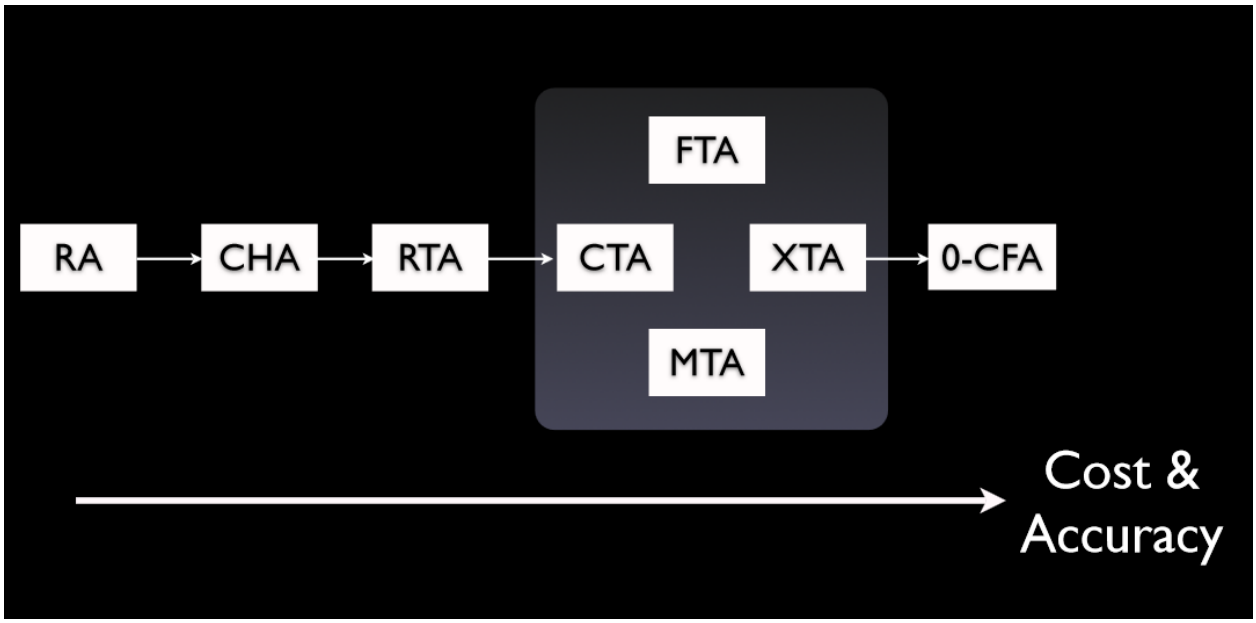
Example 2.9 *Function Pointers*

- Determining dataflow or values of variables
- Call-target resolution depend on the flow of values
- data-flow depends on control-flow, yet control-flow depends on data-flow

2.1.3.2 Call graph construction for Object-oriented languages

Relations of Type Inference, Alias Analysis, Call Graph Construction:

```c
#include <math.h>
#include <stdio.h>

// Function taking a function pointer as an argument
double compute_sum(double (*funcp)(double), double lo, double hi)
{
    double  sum = 0.0;

    // Add values returned by the pointed-to function '*funcp'
    for (int i = 0;  i <= 100;  i++)
    {
        double  x, y;

        // Use the function pointer 'funcp' to invoke the function
        x = i/100.0 * (hi - lo) + lo;
        y = (*funcp)(x);
        sum += y;
    }
    return (sum/100.0);
}

int main(void)
{
    double  (*fp)(double);      // Function pointer
    double  sum;

    // Use 'sin()' as the pointed-to function
    fp = sin;
    sum = compute_sum(fp, 0.0, 1.0);
    printf("sum(sin): %f\n", sum);

    // Use 'cos()' as the pointed-to function
    fp = cos;
    sum = compute_sum(fp, 0.0, 1.0);
    printf("sum(cos): %f\n", sum);
    return 0;
}
```



- Call graph construction needs to know the type of the object receivers for the virtual functions
- Object receivers may alias to a set of reference variables so we need to perform alias analysis
- Determine types of the set of relevant variables: type inferences – infer types of program variables

Scalable Propagation-Based Call Graph Construction Algorithms by Frank Tip and Jens Palsberg

Class Hierarchy Analysis: CHA

Rapid Type Analysis: RTA

Variable Type Analysis: VTA

Call Graph Construction for Object-Oriented Programs Between 1990-2000:

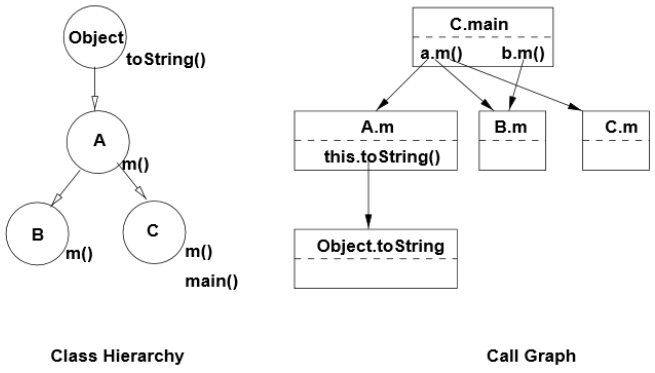
- *Class hierarchy analysis* (newly defined types) and *rapid type analysis* (RTA) (analyzing instantiation of the object) – resolve 71% virtual function calls [1996:Bacon]
- Theoretical framework for call graph constructions for object-oriented programs [1997:Grove]
- Pointer target tracking [1991:Loeliger]
- Callgraph analysis [1992:Hall]
- Variable type and declared type analysis [2000:Sundaresan]
- Scaling Java Points-To Analysis using SPARK [2003:Lhotak]

2.1.3.3 Context-Sensitivity for Building Call Graphs

In a context-insensitive call graph, each procedure is represented by a single node in the graph. Each node has an indexed set of call sites, and each call site is the source of zero or more edges to other nodes, representing

```
class A extends Object {
  String m() {
    return(this.toString());
  }
}

class B extends A {
  String m() { ... }
}

class C extends A {
  String m() { ... }
  public static void main(...) {
   A a = new A();
   B b = new B();
   String s;

   ...
   s = a.m();
   s = b.m();
  }
}
```

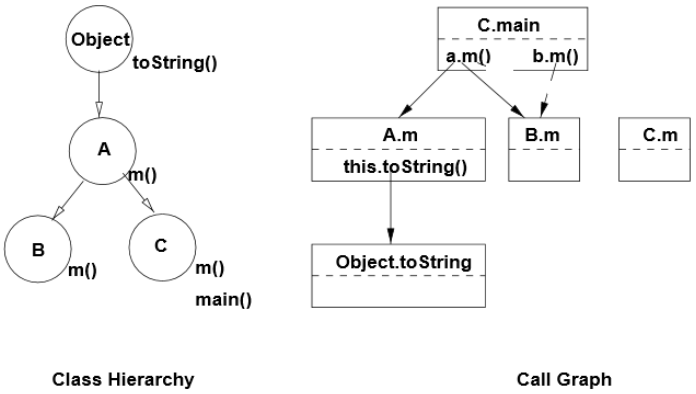
(a) Example Program



(b) Class Hierarchy and Call Graph


```
class A extends Object {
  String m() {
    return(this.toString());
  }
}

class B extends A {
  String m() { ... }
}

class C extends A {
  String m() { ... }
  public static void main(...) {
   A a = new A();
   B b = new B();
   String s;

   ...
   s = a.m();
   s = b.m();
  }
}
```

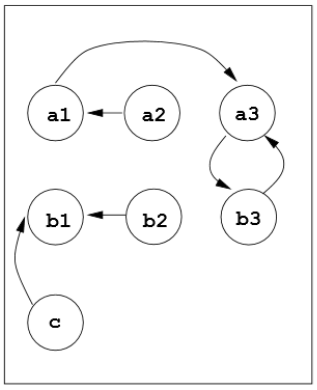
(a) Example Program



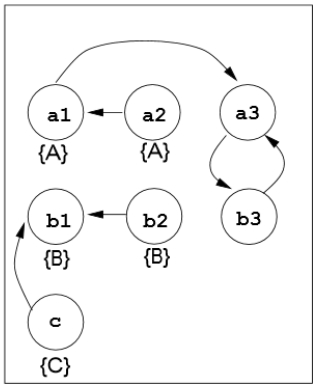
(b) Class Hierarchy and Call Graph

```
A a1, a2, a3;
B b1, b2, b3;
C c;

a1 = new A();
a2 = new A();
b1 = new B();
b2 = new B();
c = new C();

a1 = a2;
a3 = a1;
a3 = b3;
b3 = (B) a3;
b1 = b2;
b1 = c;
```

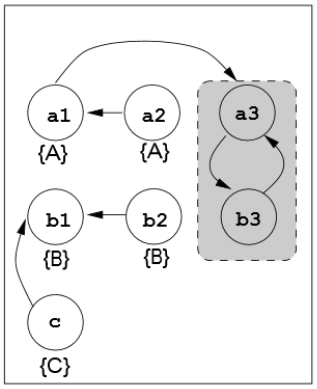
(a) Program



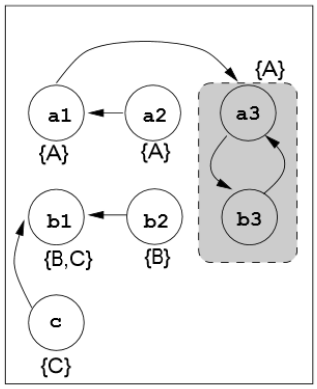
(b) Nodes and Edges



(c) Initial Types



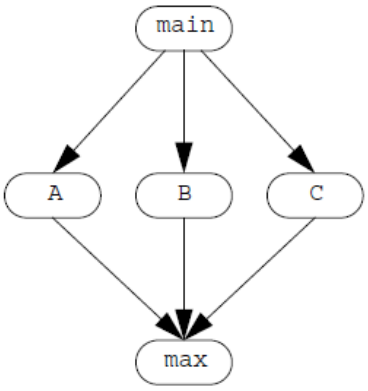
(d) Strongly-connected components



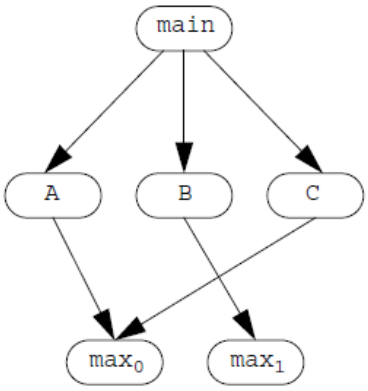
(e) final solution

```
procedure main() {
  return A() + B() + C();
}

procedure A() {
  return max(4, 7);
}
procedure B() {
  return max(4.5, 2.5);
}
procedure C() {
  return max(3, 1);
}
```

(a) Example Program



(b) Context-Insensitive



(c) Context-Sensitive

possible callees of that site; multiple callees at a single site are possible for a dynamically dispatched message send or an application of a computed function.

k-CFA [1988:Shivers]

- 0-CFA: context-insensitive
- *k-CFA*: k number of calls are considered
- k-CFA for functional language: EXPTIME-complete (non-polynomial)
- k-CFA for OO programs: polynomial

2.1.4 Exception

Exception Handling: C++

Exception Handling: Java

Frequency of Occurrence of Exception Handling Statements in Java [Sinha:2000]

2.1.4.1 Modeling Exception Handling Constructs in ICFGs [Sinha:2000]

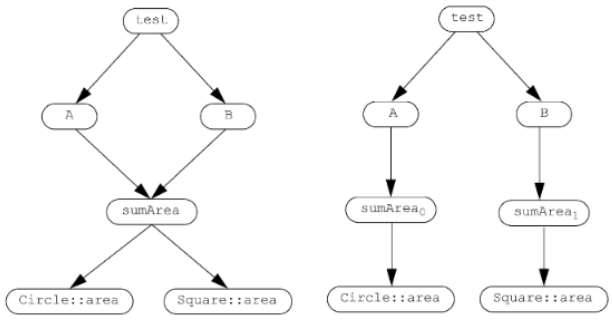
Analysis and Testing Program With Exception Handling Constructs[Sinha:2000]

2.1.5 Callbacks, synchronous and asynchronous execution

```
class Shape {
   abstract float area();
}

class Square extends Shape {
   float size;
   Square(float s) {
      size = s;
   }
   float area() {
      return size * size;
   }
}

class Circle extends Shape {
   float radius;
   Circle(float r) {
      radius = r;
   }
   float area() {
      return PI*radius*radius;
   }
}

class SPair {
   Shape first;
   Shape second;
   SPair(Shape s1, Shape s2) {
      first = s1; second = s2;
   }
}
```

```
class Example {
   float test(float v1, float v2) {
      return A(v1, v2) + B(v1, v2);
   }

   float A(float v1, float v2) {
      Circle c1 = new Circle(v1);
      Circle c2 = new Circle(v2);
      return sumArea(new SPair(c1, c2));
   }

   float B(float v1, float v2) {
      Square s1 = new Square(v1);
      Square s2 = new Square(v2);
      return sumArea(new SPair(s1, s2));
   }

   float sumArea(SPair p) {
      return p.first.area() + p.second.area();
   }
}
```

(a) Example program fragment

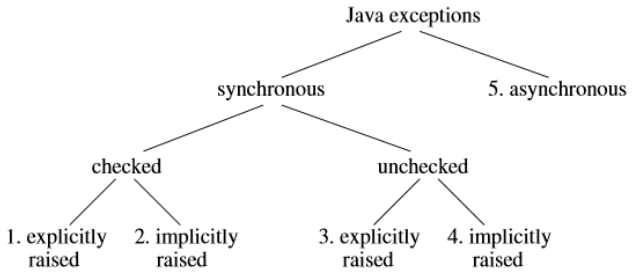


(b) Context-Insensitive (c) Context-Sensitive

Fig. 1. Context-insensitive vs. context-sensitive call graph.

```
try
{
    divide(10, 0);
}
catch(int i)
{
    if(i==DivideByZero)
    {
        cerr<<"Divide by zero error";
    }
}
```

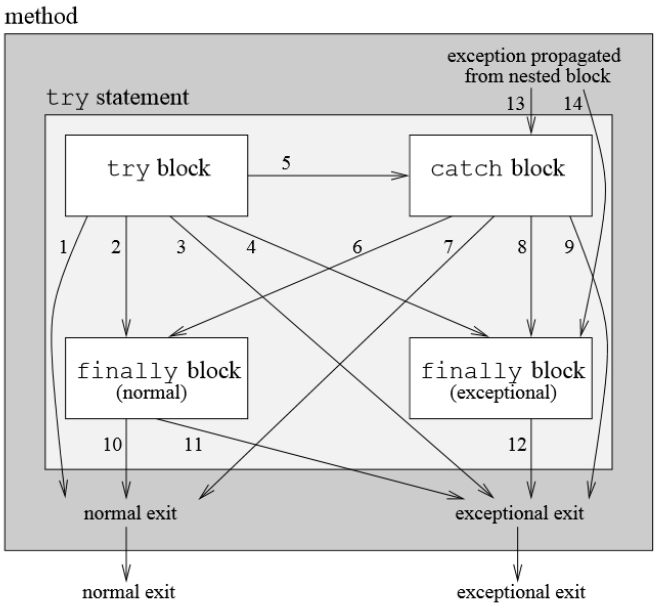
```
try {
// guarded section
   . . .
}
catch (ExceptionType1 t1) {
// handler for ExceptionType1
   . . .
}
catch (ExceptionType2 t2) {
// handler for ExceptionType2
   . . .
}
   . . .
catch (Exception e) {
// handler for all exceptions
   . . .
}
finally {
// cleanup code
   . . .
}
```




```
public void openFile(){
    try {
        // constructor may throw FileNotFoundException
        FileReader reader = new FileReader("someFile");
        int i=0;
        while(i != -1){
            //reader.read() may throw IOException
            i = reader.read();
            System.out.println((char) i );
        }
        reader.close();
        System.out.println("--- File End ---");
    } catch (FileNotFoundException e) {
        //do something clever with the exception
    } catch (IOException e) {
        //do something clever with the exception
    }
}
```

```
public void openFile(){
    FileReader reader = null;
    try {
        reader = new FileReader("someFile");
        int i=0;
        while(i != -1){
            i = reader.read();
            System.out.println((char) i );
        }
    } catch (IOException e) {
        //do something clever with the exception
    } finally {
        if(reader != null){
            try {
                reader.close();
            } catch (IOException e) {
                //do something clever with the exception
            }
        }
        System.out.println("--- File End ---");
    }
}
```

Subject		Number of classes	Number of methods	Methods with EH constructs
Name	Description			
antlr	Framework for compiler construction	175	1663	175 (10.5%)
debug	Sun's Java debugger	45	416	80 (19.2%)
jaba	Architecture for analysis of Java bytecode	312	1615	200 (12.4%)
jar	Sun's Java archive tool	8	89	14 (15.7%)
jas	Java bytecode assembler	118	408	59 (14.5%)
jasmine	Java Assembler Interface	99	627	54 (8.6%)
java_cup	LALR parser generator for Java	35	360	32 (8.9%)
javac	Sun's Java compiler	154	1395	175 (12.5%)
javadoc	Sun's HTML document generator	3	99	17 (17.2%)
javasim	Discrete event process-based simulation package	29	216	37 (17.1%)
jb	Parser and lexer generator	45	543	55 (10.1%)
jdk-api	Sun's JDK API	712	5038	582 (11.6%)
jedit	Text editor	439	2048	173 (8.4%)
jflex	Lexical-analyzer generator	54	417	31 (7.4%)
jlex	Lexical-analyzer generator for Java	20	134	4 (3.0%)
joie	Environment for load-time transformation of Java classes	83	834	90 (10.8%)
sablecc	Framework for generating compilers and interpreters	342	2194	106 (4.8%)
swing-api	Sun's Swing API	1588	12304	583 (4.7%)
Total		3951	30400	2467 (8.1%)



1 try block raises no exception
2 try block raises no exception; finally block specified
3 try block raises exception; catch block does not handle exception; no finally block
4 try block raises exception; catch block does not handle exception; finally block specified
5 try block raises exception; catch block handles exception
6 catch block handles exception; finally block specified
7 catch block handles exception; no finally block
8 catch block handles exception, raises another exception; finally block specified
9 catch block handles exception; raises another exception no finally block
10 finally block raises no exception
11 finally block raises exception
12 finally block propagates previous exception, or raises another exception
13 nested block propagates exception; catch block handles exception
14 nested block propagates exception; catch block does not handle exception; finally block specified

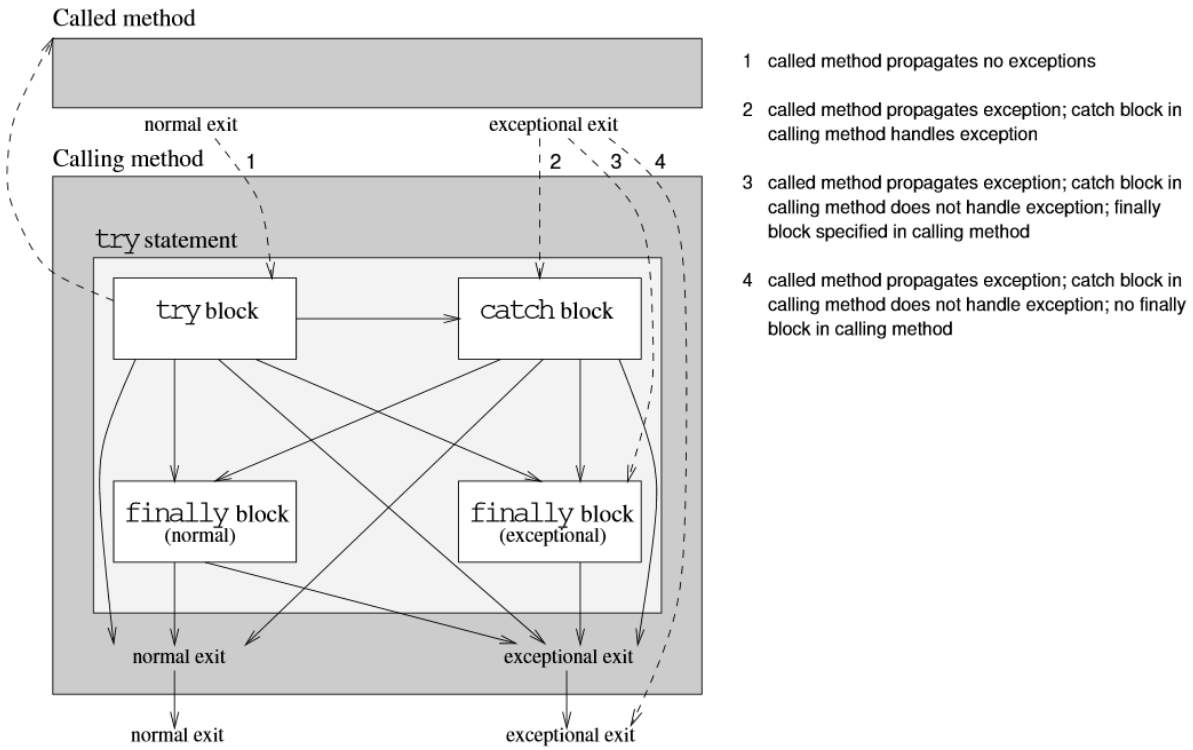


Figure 9: Interprocedural control flow in exception-handling constructs .

```
public class VendingMachine {

  private int totValue;
  private int currValue;
  private int currAttempts;
  private Dispenser d;

  public VendingMachine() {
 1  totValue = 0;
 2  currValue = 0;
 3  currAttempts = 0;
 4  d = new Dispenser();
  }

  public void insert( Coin coin ) {
 5  int value = valueOf( coin );
 6  if ( value == 0 ) {
 7    throw new IllegalCoinException();
    }
 8  currValue += value;
 9  showMsg( "current value = "+currValue );
  }

  public void returnCoins() {
10  if ( currValue == 0 ) {
11    throw new ZeroValueException();
    }
12  showMsg( "Take your coins" );
13  currValue = 0;
14  currAttempts = 0;
  }

  public void vend( int selection ) {
15  if ( currValue == 0 ) {
16    throw new ZeroValueException();
    }
    try {
17    d.dispense( currValue, selection );
18    int bal = d.value( selection );
19    totValue += currValue - bal;
20    currValue = bal;
21    returnCoins();
    }
22  catch( SelectionException s ) {
23    currAttempts++;
24    if ( currAttempts < MAX_ATTEMPTS ) {
25      showMsg( "Enter selection again" );
      }
      else {
26      currAttempts = 0;
27      throw s;
      }
    }
28  catch( ZeroValueException z ) {
    }
  }
}
```

```
public class Dispenser {
  public void dispense( int currVal, int sel ) {
29  Exception e = null;
30  if ( sel < MIN_SELECTION || sel > MAX_SELECTION ) {
31    showMsg( "selection "+sel+" is invalid" );
32    e = new IllegalSelectionException();
    }
    else {
33    if ( !available( sel ) ) {
34      showMsg( "selection "+sel+" is unavailable" );
35      e = new SelectionNotAvailableException();
      }
      else {
36      int val = value( sel );
37      if ( currVal < val ) {
38        e = new IllegalAmountException( val-currVal );
        }
      }
    }
39  if ( e != null ) {
40    throw e;
    }
41  showMsg( "Take selection" );
  }
}
```

```
  public static void main() {
42  VendingMachine vm = new VendingMachine();
43  while ( true ) {
      try {
        try {
44        switch( action ) {
45          case INSERT: vm.insert( coin );
46          case VEND:   vm.vend( selection );
47          case RETURN: vm.returnCoins();
          }
        }
48      catch( SelectionException s ) {
49        showMsg( "Transaction aborted" );
50        vm.returnCoins();
        }
51      catch( IllegalCoinException i ) {
52        showMsg( "Illegal coin" );
53        vm.returnCoins();
        }
54      catch( IllegalAmountException i ) {
55        int val = i.getValue();
56        showMsg( "Enter more coins"+val );
        }
      }
57    catch( ZeroValueException z ) {
58      showMsg( "Value is zero.  Enter coins" );
      }
    }
```

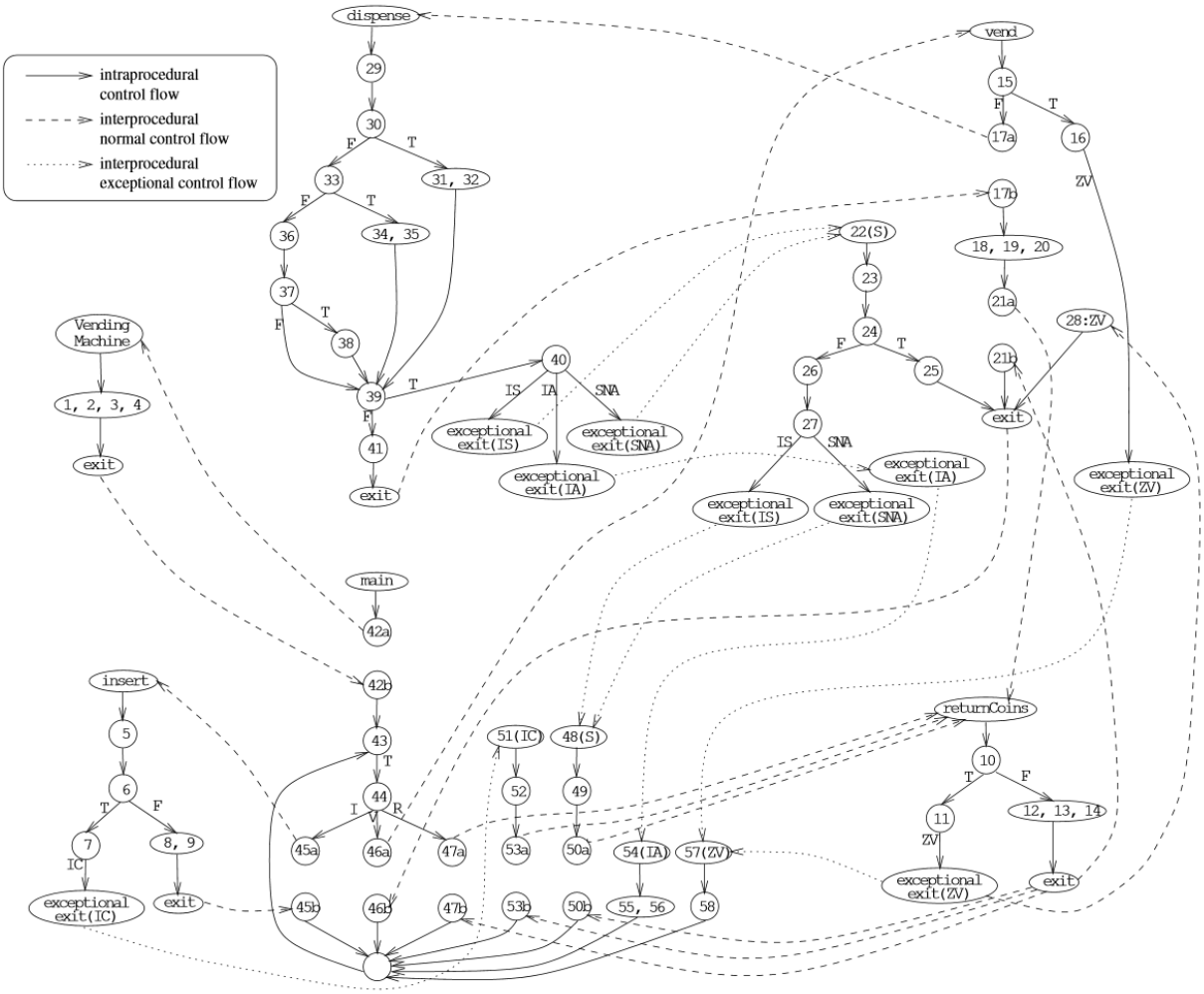


Figure 10: ICFG for the vending-machine program.