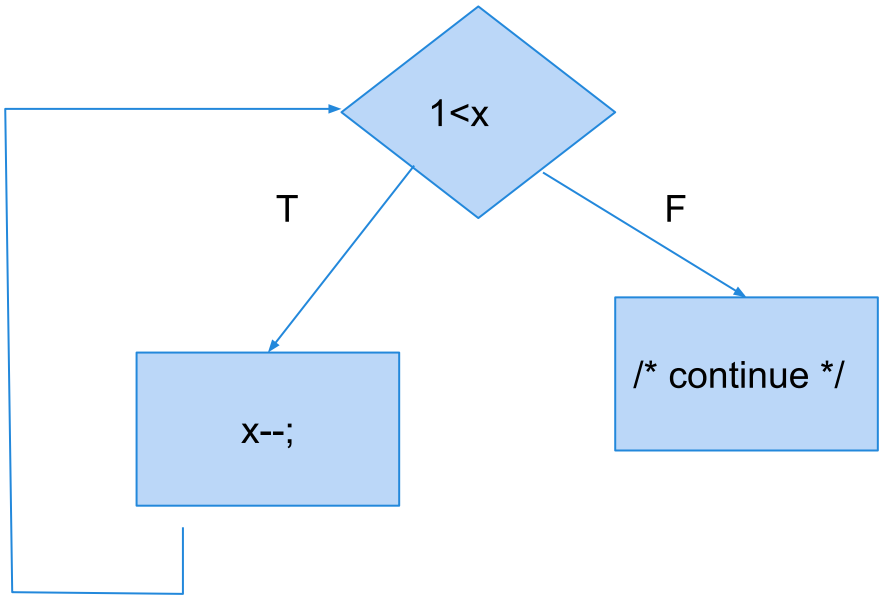
Data Flow Testing

CSCE 747 - Lecture 9 - 02/09/2016

Control Flow

- Capture dependencies between parts of the program, based on “passing of control” between those parts.
- We care about the effect of a statement when it affects the path taken.
    - but deemphasize the information being transmitted.



Data Flow

- Another view - program statements compute and transform data…
  - So, look at how that data is passed through the program.
- Reason about dependence
  - A variable is used here - where does its value from?
  - If the expression assigned to a variable is cha what else would be affected?
  - Def-Use Pairs - a dependence relationship be a definition of a variable and the use of that definition.

Data Flow Analyses

- Used to detect faults and other anomalies.

	Any-Paths	**All-Paths**
Forward (pred)	**Reach** *U* may be preceded by G without an intervening *K*	**Avail** *U* is always preceded by G without an intervening *K*
Backward (succ)	**Live** *D* may lead to *G* before *K*	**Inevitability** *D* always leads to *G* before *K*

- Also can be used to derive test cases.
  - Have we covered the data dependencies?

Dealing with Arrays and Pointers

Dealing With Arrays/Pointers

- Arrays and pointers (including object references and arguments) introduce issues.
  - It is not possible to determine whether two access refer to the same storage location.
    - ```
      a[x] = 13;
      k = a[y];
      ```
      - Are these a def-use pair?
    - ```
      a[2] = 42;
      i = b[2];
      ```
      - Are these a def-use pair?
        - Aliasing = two names refer to the same memory location.

Aliasing

- *Aliasing* is when two names refer to the same memory location.
  - ```
    int[] a = new int[3];
    int[] b = a;
    a[2] = 42;
    i = b[2];
    ```
  - a and b are aliases.
- Worse in C:

  ```
  p = &b;
  *(p + i) = k;
  ```
  ```

Uncertainty

- Dynamic references and aliasing introduce uncertainty into data flow analysis.
  - Instead of a definition or use of one variable, may have a potential def or use of a set of variables.
- Proper treatment depends on purpose of analysis:
  - If we examine variable initialization, might not want to treat assignment to a potential alias as initialization.
  - May wish to treat a use of a potential alias of *v* as a use of *v*.

Dealing With Uncertainty

- Treat uncertainty about aliases like uncertainty about control flow.

```
a[x] = 13;
k = a[y];
```

```
a[x] = 13;
if(x == y)    k = a[x];
else          k = a[y];
```

- In transformed code, all array references are distinct.
  - Any-path analysis - create a def-use pair, but assignment to a[y] does not erase definition to a[x].
  - Gen sets include everything that might be references, kill sets only include definite references.

Dealing With Uncertainty

```
a[x] = 13;
k = a[y];
```

```
a[x] = 13;
if(x == y)     k = a[x];
else           k = a[y];
```

- In transformed code, all array references are distinct.
  - Any-path analysis - create a def-use pair, but assignment to a[y] does not erase definition to a[x].
  - All-paths analysis - a definition to a[x] makes only that expression available. Assignment to a[y] kills a [x].
    - Gen sets should include only what is definitely referenced and kill sets should include all possible aliases.

Dealing With Nonlocal Information

- fromCust and toCust may be references to the same object.
    - fromHome and fromWork may also reference the same object.
- One option - treat all nonlocal information as unknown.
    - Treat Customer/PhoneNum objects as potential aliases.
    - Be careful - may result in results so imprecise they are useless.

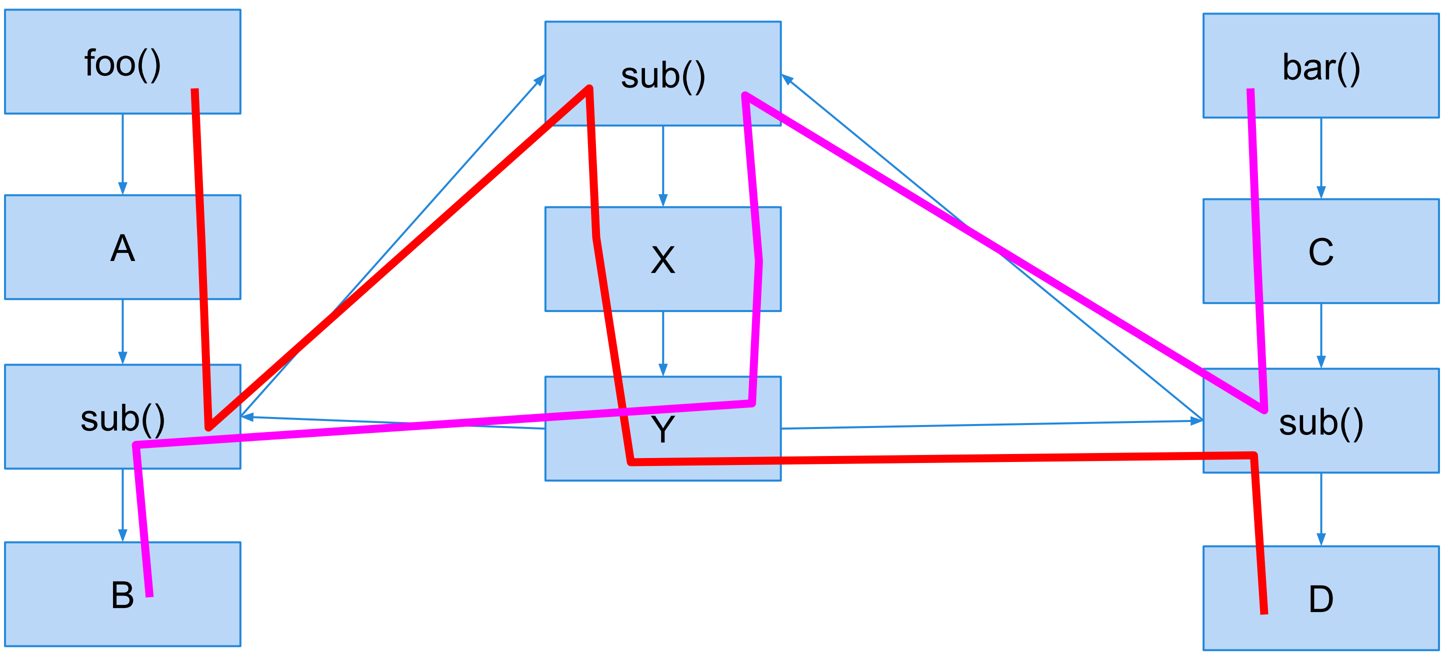
```
public void transfer(Customer
fromCust, Customer toCust){
    PhoneNum fromHome =
        fromCust.getHomePhone();
    PhoneNum fromWork =
        fromCust.getWorkPhone();
    PhoneNum toHome =
        toCust.getHomePhone();
    PhoneNum toWork =
        toCust.getWorkPhone();
}
```

Interprocedural Analysis

Interprocedural Analysis - Control Flow

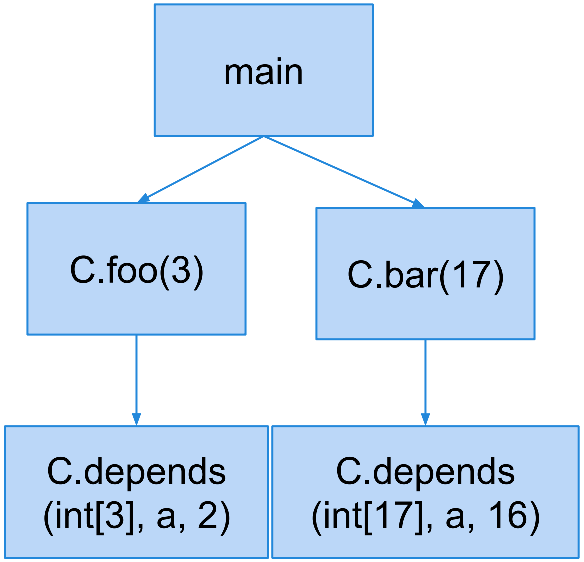
- First op   dures in a large C

Problem - infeasible paths!



Context-Sensitivity

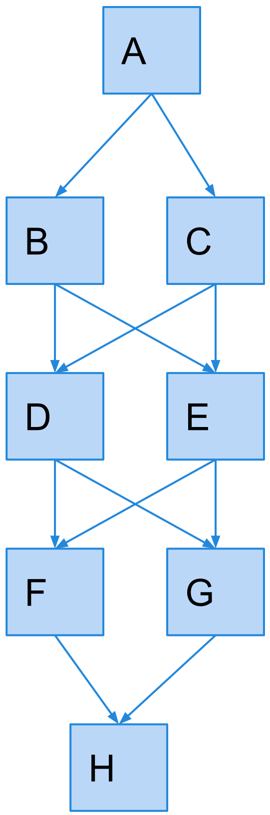
```
public class Context{
    public static void main(String args[]){
        Context c = new Context();
        c.foo(3);
        c.bar(17);
    }
    void foo(int n){
        int[] a = new int[n];
        depends(a,2);
    }
    void bar(int n){
        int[] a = new int[n];
        depends(a,16);
    }
    void depends(int[] a, int n){
        a[n] = 42;
    }
}
```



Context-Sensitive

Context-Sensitive Analysis

- Copy the called procedure for each point that it is called.
- Problem - the number of contexts a procedure is called in is exponentially higher than the number of procedures.
  - Precise, but expensive analysis.
- In practice, only feasible for small groups of related procedures.

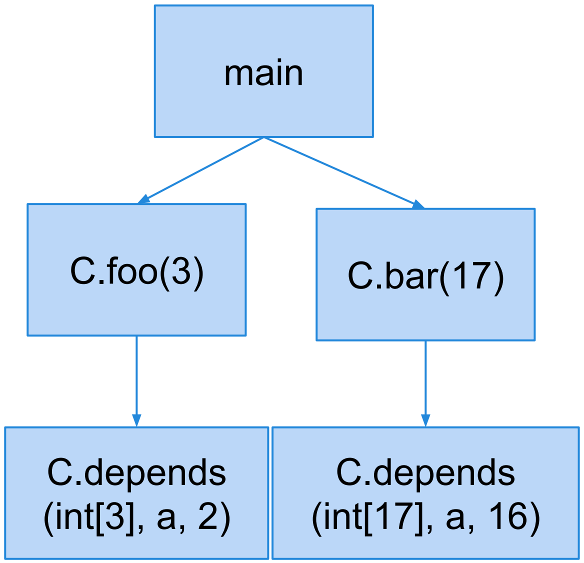


Context-Insensitive Analysis

- Unhandled exception analysis
  - If procedure A calls procedure B that throws an exception, A must handle or declare that exception.
  - Analysis steps hierarchically through the call graph.
- Two conditions:
  - Information needed to analyze calling procedure must be small.
  - Information about the called procedure must be independent of caller (context-insensitive)
- Analysis can start from leaves of call graph and work upward to the root.

Flow-Sensitivity

- Aliasing information requires context.
- Some analyses can sacrifice precision on another aspect: control-flow information
  - Call graphs are flow-insensitive.



Insensitive Pointer Analysis

- Treat each statement as a constraint.
  `x = y;` (where y is a pointer)
- Note that x may refer to any of the same objects that y refers to.
  - References(x) ⊇ References(y) is a constraint independent of the path taken.
  - Procedure calls are assignments of values to arguments.
- Results are imprecise, but better than just assuming that any two pointers might refer to the same object.

Data Flow Testing

Overcoming Limitations of Path Coverage

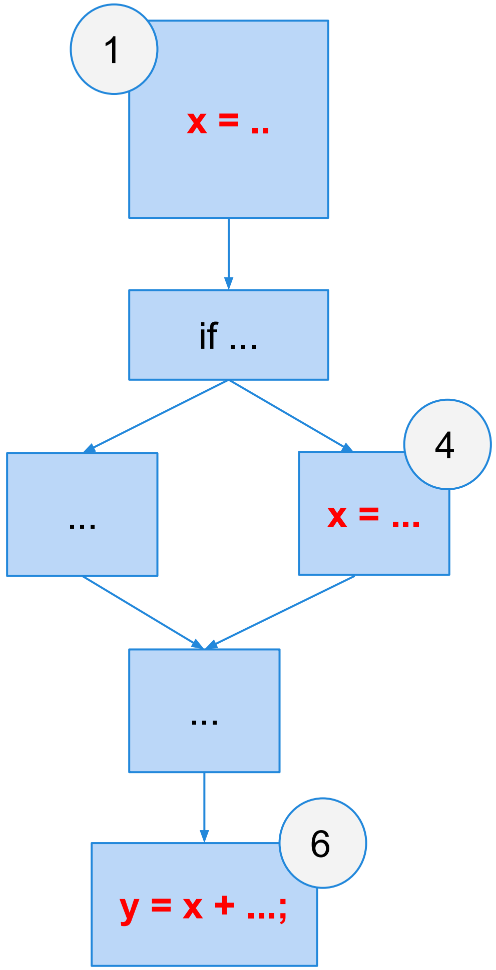
- We can potentially expose many faults by targeting particular *paths* of execution.
- Full path coverage is impossible.
- What are the important paths to cover?
  - Some methods impose heuristic limitations.
  - Can also use data flow information to select a subset of paths based on how one element can affect the computation of another.

Choosing the Paths

- Branch or MC/DC coverage already cover many paths. What are the remaining paths that are important to cover?
- Basis of data flow testing - computing the wrong value leads to a failure only when that value is *used*.
  - Pair definitions with usages.
  - Ensure that definitions are actually used.
  - Select a path where a fault is more likely to propagate to an observable failure.

Review - Def-Use Pairs

- Incorrect computation of x at either 1 or 4 could be revealed if used at 6.
- (1,6) and (4,6) are *DU pairs* for x.
  - DU Pair = there exists a *definition-clear path* between the definition of x and a use of x.
  - If x is redefined on the path, the original definition is *killed* and replaced.



Def-Use Pairs

- `++counter, counter++, counter+=1`
  `counter = counter + 1`
  - These are equivalent. They are a *use* of counter, then a new *definition* of counter.
- `*ptr = *otherPtr`
  - Need a policy for how you deal with aliasing.
  - Ad-hoc option:
    - Definition of string *ptr
    - Use of index ptr, string *otherPtr, and index otherPtr.
- `ptr++`
  - Use of index ptr, and a definition of both the index and string *ptr.
  - Change to index moves the pointer to a new location.

Activity - DU Pairs

- For the provided code, identify all DU pairs.
  - Hint - first, find all definitions and uses, then link them.
  - DU Pair = there exists a *definition-clear path* between the definition of x and a use of x.
    - If x is redefined on the path, the original definition is *killed* and replaced.
  - Remember that there is a loop.

Activity Solution - Defs and Uses

Variable	Definitions	Uses
*encoded	14	15
*decoded	14	16
*eptr	15, 25, 26, 37	18, 20, 25, 26, 34
eptr	15, 25, 26, 37	15, 18, 20, 25, 26, 34, 37
*dptr	16, 23, 31, 34, 36, 39	
dptr	16, 36	16, 23, 31, 34, 36, 39
ok	17, 29	40
c	20	22, 24
digit_high	25	27, 31
digit_low	26	27, 31
Hex_Values	-	25, 26

Activity Solution - D-U Pairs

Variable	DU Pairs
*encoded	(14, 15)
*decoded	(14, 16)
*eptr	(15, 18), (15, 20), (15,25), (15, 34), (25, 26), (26, 37), (37, 18), (37, 20), (37,25), (37, 34)
eptr	(15, 15), (15, 18), (15, 20), (15, 25), (15, 34), (15, 37), (25, 26), (26, 37), (37, 18), (37, 20), (37, 26), (37, 34), (37, 37)
dptr	(16, 16) , (16, 23), (16, 31), (16, 34), (16, 36), (16, 39), (36, 23), (36, 31), (36, 34), (36, 36), (36, 39)
ok	(17, 40), (29, 40)
c	(20, 22), (20, 24)
digit_high	(25, 27), (25, 31)
digit_low	(26, 27), (26, 31)

All DU Pair Coverage

- Requires each DU pair be exercised in at least one program execution.
  - Erroneous values produced by one statement might be revealed if used in another statement.

$$\text{Coverage} = \frac{\text{number exercised DU pairs}}{\text{number of DU pairs}}$$

- Can easily achieve structural coverage without covering all DU pairs.

All DU Paths Coverage

- One DU pair might belong to many execution paths. Cover all simple (non-looping) paths at least once.
  - Can reveal faults where a path is exercised that should use a certain definition but doesn't.

$$\text{Coverage} = \frac{\text{number of exercised DU paths}}{\text{number of DU paths}}$$

Path Explosion Problem

- Even without looping paths, the number of SU paths can be exponential to the size of the program.
- When code between definition and use is irrelevant to that variable, but contains many control paths.

```
void countBits(char ch){
     int count = 0;
     if (ch & 1)  ++count;
     if (ch & 2)  ++count;
     if (ch & 4)  ++count;
     if (ch & 8)  ++count;
     if (ch & 16) ++count;
     if (ch & 32) ++count;
     if (ch & 64) ++count;
     if (ch & 128)    ++count;
     printf("'%c' (0X%02X) has %d
bits set to 1\n", ch, ch, count);
}
```

All Definitions Coverage

- All DU Pairs/All DU Paths are powerful and often practical, but may be too expensive in some situations.
- In those cases, pair each definition with at least one use.

$$\text{Coverage} = \frac{\text{number of covered definitions}}{\text{number of definitions}}$$

Dealing With Aliasing

- Requires trade-off between precision and computational efficiency.
- Underestimate potential aliases
  - Could miss *def-use* pairs
- Overestimate potential aliases
  - Could have infeasible pairs, leading to unsatis coverage obligations
- What is a suitable approximation of potential aliases for testing?

Infeasibility Problem

- Metrics may ask for impossible test cases.
- Path-based metrics aggravates the problem by requiring infeasible combinations of feasible elements.
  - Alias analysis may add additional infeasible paths.
- All Definitions Coverage and All DU-Pairs Coverage often reasonable.
  - All DU-Paths is much harder to fulfill.

We Have Learned

- Arrays, pointers, and complex data structures introduce uncertainty into analysis.
  - Requires a policy for how aliasing is handled.
  - Trade-off between computational feasibility and precision.
- Analyses must handle non-local references.
  - Similar trade-off. Can gain efficiency by sacrificing flow sensitivity and context sensitivity.

We Have Learned

- If there is a fault in a computation, we can observe it by looking at where the computation is used.
- By identifying DU pairs and paths, we can create tests that trigger faults along those paths.
  - All DU Pairs coverage
  - All DU Paths coverage
  - All Definitions coverage

Next Class

- Model-Based Testing

- Reading: Chapter 14
- Homework:
  - Homework 2 is out - Due February 23
  - Reading Assignment 2 due Thursday