Control Flow Graphs

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Outline

- Control flow graph (CFG)
- Paths
- Call graph (especially for object-oriented code)
- Inteprocedural control flow graph (ICFG)

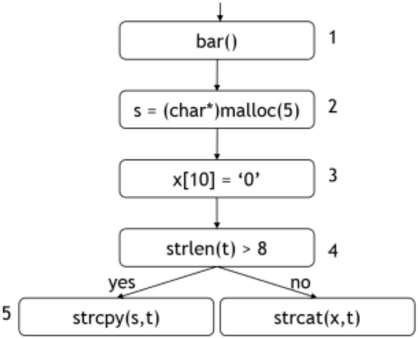
What is program control flow?

- *Control flow*: the execution order of statements of a program
- The problem of identifying control flow: identifying the execution order of statements from program source code (sometimes from binary code)
- There are three types of control flow: *sequential*, *branch* and *loop*
- *Control flow graph (CFG)*: represent such order in a graph representation, the program paths will be available by traversing the graph

Control flow graph (CFG): Example

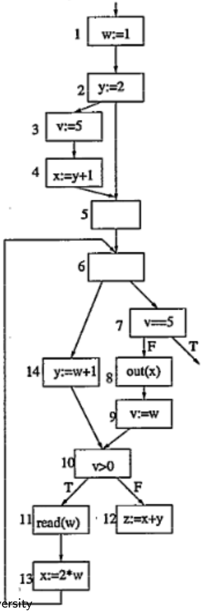
From code to CFG:

```
bar();
s = (char*)malloc(5);
x[10] = '\0';
if(strlen(t)>8)
   strcpy(s,t);
else
    strcat(x,t);
```



Control flow graph: Example

From CFG to code: can you write the C code for this graph?



Control flow graph: Understandings

- first time: 1970, Frances Allen's papers: "Control Flow Analysis" and "A Basis for Program Optimization": using control flow graph to analyze programs for code optimizations
- it is a directed graph
- it has only one entry and one exit
- each function has a CFG
- dependent on the implementation of the CFG: the node is a statement (source code) or an instruction (binary code); a node can also be a *basic block* (a sequence of statements/instructions that do not have branches),
- an edge indicates the order of the two statements/instructions/basic blocks

Program paths, traces

Program paths, traces

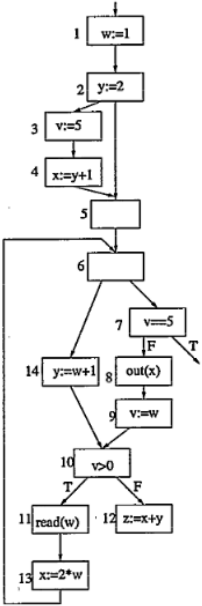
1. *Path*: a sequence of node on the CFG, including an entry node and an exit node
2. *Trace*: a sequence of instructions performed during execution
3. *Infeasible paths*: paths exist in the CFG and never can be executed
4. *Path segment*: a subsequence of nodes along the path

See the above examples for paths, path segments, traces

Infeasible paths

- How infeasible paths exist? A conditional branch has *static correlation* along a path if its outcome can be determined along the path from prior statements or branch outcomes at compile time.
- Experiments show that from 9 to 40% of conditionals in large programs exhibit correlation that is detectable at compile time

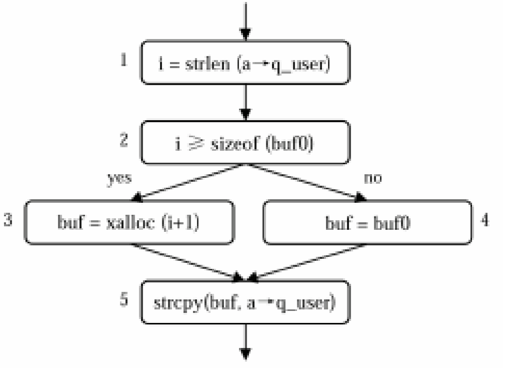
Infeasible path: Example



Control flow graphs and bug finding

Bug detection:

- using buggy code patterns (code smell) to scan new software: has a large number of false positves
- finding erroneous/undesired state on paths



Source: Marple: A Demand-Driven Path-Sensitive Buffer Overflow Detector

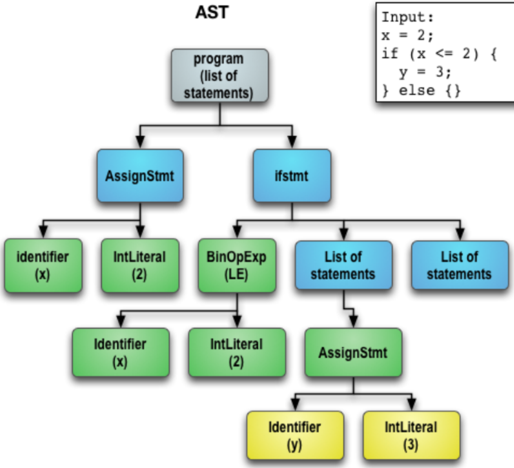
Automatically constructing CFG

Existing tools: ATLAS (C and Java), LLVM (C and C++), SOOT (Java), Wala (Java), Phoenix (Microsoft managed C++)

Algorithm:

- Step 1: build *abstract syntax tree (AST)*: parse tree in an abstract form
- Step 2: convert AST to CFG

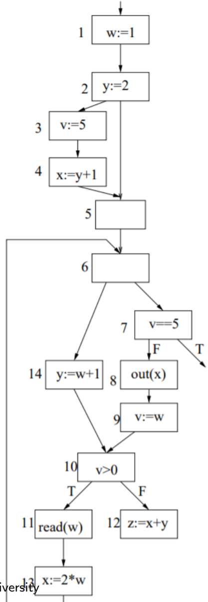
AST to CFG




```
Input:
x = 2;
if (x <= 2) {
  y = 3;
} else {}
```

Automatic infeasible paths detection [1997:Bodik]

Branch correlation



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.

1. Loop terminologies: *single loop*, *nested loop*, *inner loop*, *outer loop*
2. CFG is *reducible* if every loop is a *natural loop*, intuitively
   - there is a single entry node (e)
   - no jumps into middle of loop (i.e., e dominates all nodes in loop)
   - requires a *back edge* into loop header ($n \to e$, $n \in L$)
   - *back edge* – head (ancestor) dominates its tail (decedent), any edge from tail to head is a back edge

Reducibility in practice

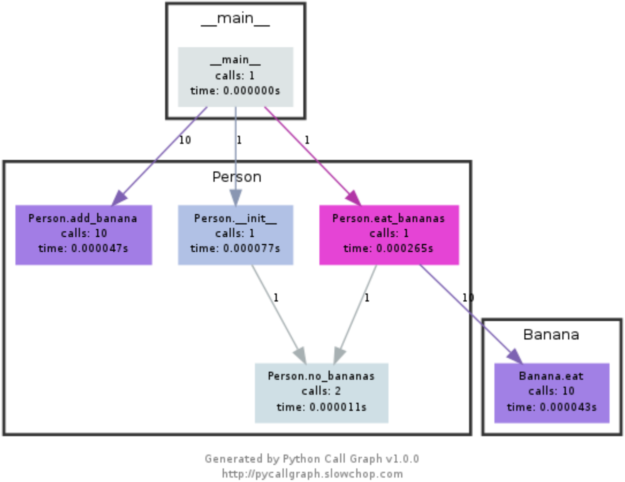
- If you use only while-loops, for-loops, repeat-loops, if-then(-else), break, and continue, then your control flow graph is reducible.
- Some languages only permit procedures with reducible control flow graphs (e.g., Java)
- “GOTO Considered Harmful”: can introduce irreducibility
  - FORTRAN
  - C
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

Interprocedural control flow graph (ICFG)

- ICFG: representing control flow for the entire program
- what is a valid interprocedural path and how to represent it in ICFG?
- Combining: CFG and *call graph*: calling relationships of functions

Call graph

- *Call graph*: representing calling relations between functions, there is an edge from caller to callee See example from wiki [1]



[1] https://en.wikipedia.org/wiki/Call_graph

Constructing call graphs

There are off-the-shelf tools: llvm for c/c++; soot for java, except that the following challenges are still under active research:

- function pointers (C code)
- virtual functions (OO code)
- event-driven and framework based architecture like Android: *callbacks* (the library code calls user's functions)

Function pointers [2004:atkinson]

Resolving function pointers based on the types in function signatures

```
int (*q) ()
int main() { ...
  char *x = "a";
  int *y = 1;
  (*q) (2, x); ...
  (*q) (3, y);
}
char q1(int x, int *p) { ... }
int q2(int x, int *p) { ... }
int q3(int x, char *p) { ... }
```

Virtual functions

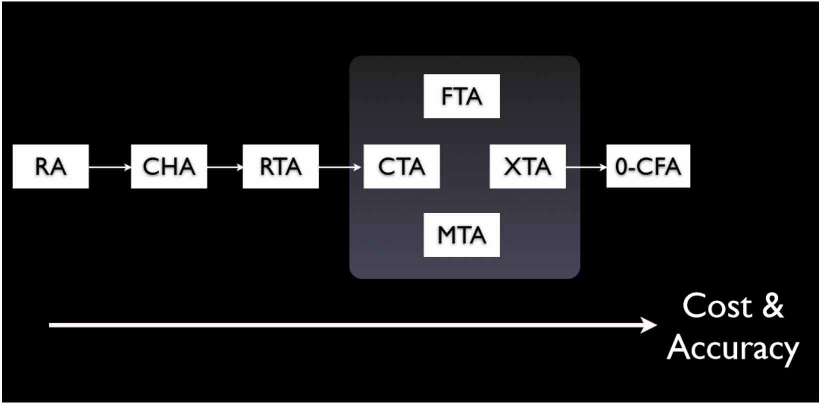
```
class A {
public:
   virtual void f();
   ...
};
```

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

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

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

Algorithms for handling virtual functions



Details see paper: Scalable Propagation-Based Call Graph Construction Algorithms by Frank Tip and Jens Palsberg

CHA: class hierarchy analysis

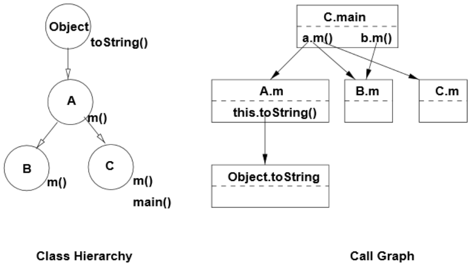
```
class A extends Object {
  String m() {
    return(this.toString());
  }
}

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

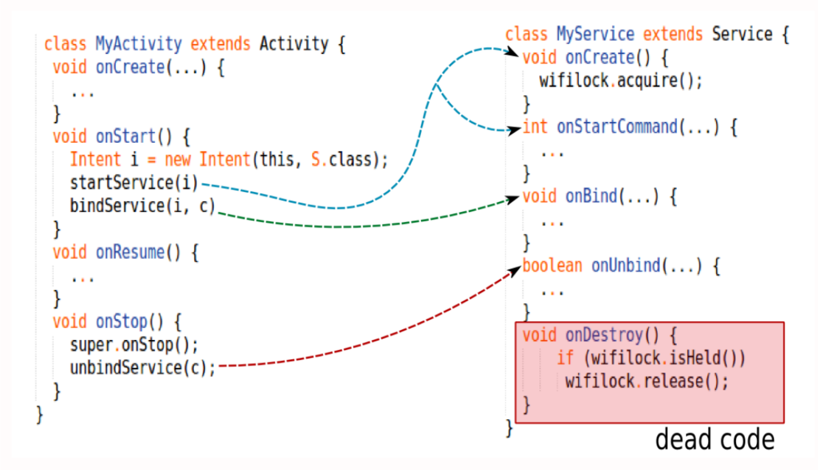


(b) Class Hierarchy and Call Graph

Relations of type inference, alias analysis, call graph construction

- Call graph construction needs to know the type of the object receivers for the virtual functions
- Determine types of the set of relevant variables: *type inferences* – infer types of program variables
- Object receivers may alias to a set of reference variables so we need to perform *alias analysis*
- Alias analysis determines whether two pointers `a` and `b` point to the same memory location, e.g., statement int* b = a indicates that pointers b and a get the same value (address)

Callbacks


class MyActivity extends Activity {
void onCreate(...) {
...
}
void onStart() {
Intent i = new Intent(this, S.class);
startService(i)
bindService(i, c)
}
void onResume() {
...
}
void onStop() {
super.onStop();
unbindService(c);
}
}
class MyService extends Service {
void onCreate() {
wifilock.acquire();
}
int onStartCommand(...) {
...
}
void onBind(...) {
...
}
boolean onUnbind(...) {
...
}
void onDestroy() {
if (wifilock.isHeld())
wifilock.release();
}
}
dead code

Interprocedural control flow graph (ICFG)

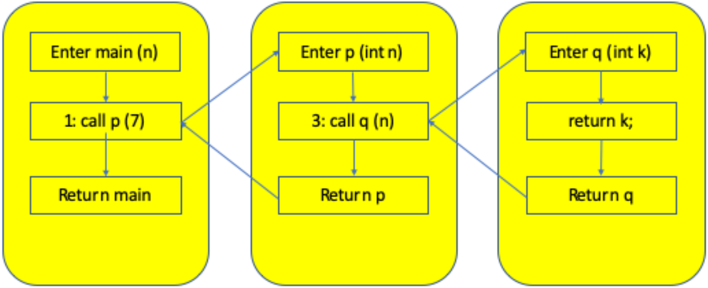
After callgraph, let's come back to the concept of ICFG:

- ICFG: representing control flow for the entire program
- Finding the potentially valid execution paths for the entire program

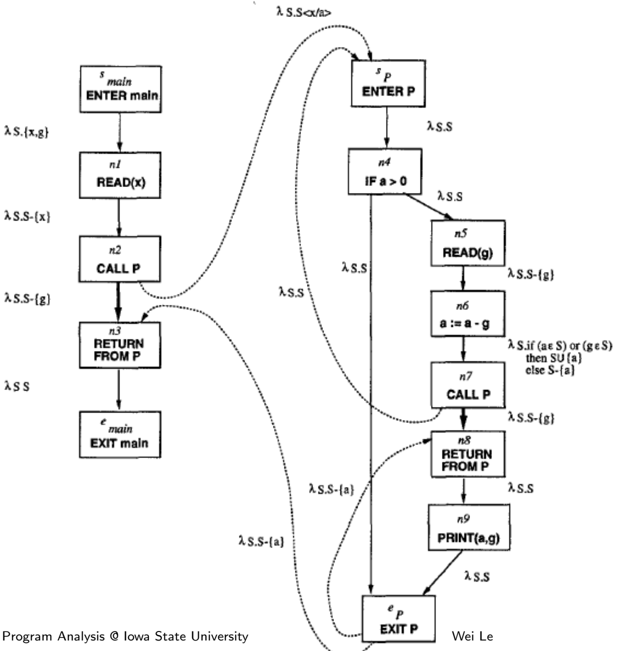
```
main() {
  1: p(7);

}

p(int n) {
  3: q(n);
}
q(int k) {
  return k;
}
```



ICFG with recursive calls



Getting paths from ICFG

Context-sensitive and realizable paths:

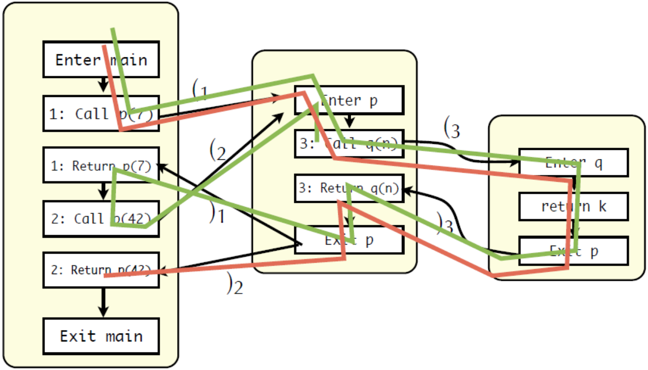
- *Context-sensitive*: when a call is invoked twice, do we distinguish at which callsite the callee should return (when traversing ICFG for paths)?
- *Realizable paths*: ICFG contains more paths than valid execution paths. Realizable paths are the paths on ICFG that represent potentially valid exeuctions.

source: Precise Interprocedural Dataflow Analysis via Graph Reachability

ICFG and realizable paths

```
main() {
  1: p(7);
  2: x:=p(42);
}

p(int n) {
  3: q(n);
}
q(int k) {
  return k;
}
```



Representing realizable paths in grammar - optional

Idea: restrict attention to **realizable paths**: paths that have proper nesting of procedure calls and exits

For each call site i, let's label the call edge "$(_i$" and the return edge "$)_i$"

Define a grammar that represents balanced paren strings

```
matched ::= ∈                      empty string
          | e                      anything not containing parens
          | matched matched
          | (ᵢ matched )ᵢ
```

- Corresponds to matching procedure returns with procedure calls

Define grammar of partially balanced parens (calls that have not yet returned)

```
realizable ::= ∈
             | (ᵢ realizable
             | matched realizable
```

From grammar to language: CFL (context-free language) - optional

Reducing to the *CFL reachability problem* (reachability on graph defined by CFL): Let L be a context-free language over alphabet Σ

- Let G be graph with edges labeled from Σ
- Each path in G defines word over Σ
- A path in G is an L-path if its word is in L

Computing Realizable paths $O(n^3)$ - optional

- All-pairs L-path problem: for all pairs of nodes n1 and n2, finding an L-path from n1 to n2
- Single-source L-path problem: for all nodes n2, finding an L-path from given node n1 to n2
- Single-target L-path problem: for all nodes n1, finding an L-path from n1 to given node n2
- Single-source single-target L-path problem: finding an L-path from given node n1 to given node n2

Bug detection on ICFG

- Enumerate all the paths to check if they are buggy: too many paths
- *Deman-driven* algorithms: new after 2000
- Summary based algorithms: summarize the effect of a callee and then use the summary for bug detection

Demand-driven algorithm

See slides