# CS412/413

Introduction to Compilers

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Lecture 36: Advanced Analyses

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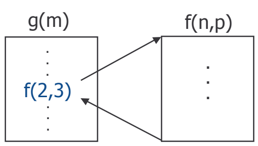
## Dataflow Analysis

- Builds the CFG, iterate over basic blocks
- Compute information at each program point
  - E.g. constants, live variables, etc.
- Discussed: intra-procedural analysis
  - considers only the computation in the current procedure
- At function calls, assume worst case
  - Live variables: all globals/fields live before the call
  - Constant folding: globals/fields not constant after call



## Inter-Procedural Analysis

- Precisely analyze interactions between functions/methods
- Same as dataflow analysis, but at each call analyze take into account the computation in the invoked function
- Examples: inter-procedural constant folding, inter-procedural register allocation, etc.





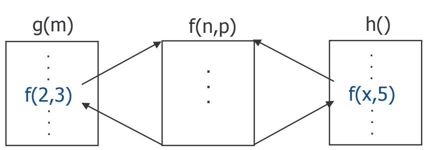

## Issues

- Obtain a stack of analyses which corresponds to the execution stack of the program
- Analysis must bind actual parameters to formals before analyzing the callee
  - n = 2; m = 3;
- Another issue: different functions/methods have different analysis domains
  - E.g. for live variables, analysis domain includes set of variables local to the current function
  - Must change the analysis domain when analysis moves from caller to callee



## Multiple Call Sites

- Another aspect: a function may be invoked from multiple call sites
- At different call sites, the analysis is different
  - Input context = analysis information at call site
- Hence, must re-analyze function in each context






## Analysis Contexts

- The analysis of a function yields an analysis context which is a pair of:
  - an input context: the dataflow information at the entry (or exit) of the function
  - and a corresponding analysis result: the information at the exit (or entry) of the function, plus the return value
- Useful for memoization: whenever the information at a call site matches some input context, can reuse analysis result

## Example

- Consider inter-procedural constant folding for the following program:

```
int a;
void h() {
  int b;
  scanf("%d", &b);
  a = 1;
  b = f(2,f(b,3));
}

int f(int m, int n) {
  int t;
  t = a+m;
  a = a+n;
  return t;
}
```

- What are the contexts for function f?
- What is the value of b at the end of function h?



## Recursion

- So far, analysis of recursive procedures doesn't terminate
- Analysis creates an unbounded number of analysis contexts
- Need a fixed point algorithm
  - Similar to analysis of loops in dataflow analysis
- Approach: for each analysis context, keep a current best analysis result
  - Initialize current best to top
  - At recursive call sites use current result
  - At return: if result has changed, re-analyze function



## Indirect Calls

- Problem: calls for which the invoked function cannot be precisely determined at compile time
  - Function pointers in C/C++
  - Dynamically dispatched functions in Java/C++
- Approach:
  - Analyze all possibly invoked functions
  - Then merge all of the results together
- To be precise, must accurately compute the possible targets of each indirect call
  - Function pointers: need points-to information
  - Virtual functions: need class hierarchy information



## Exponential Blow-up

- Problem: the number of procedure calls in a program may be exponential in the program size:

```
int f() { g(); g(); }
int g() { h(); h(); }
int h() { k(); k(); }
```

- Call graph = graph describing the call structure
  - Nodes are functions, edges are call sites
  - Functions close to the leaves get executed many time
- Similarly, inter-procedural analysis may re-analyze functions many times; hence the analysis becomes expensive



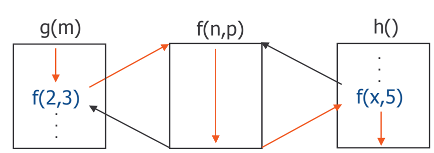
## Context-Insensitive Analysis

- So far: different analyses of a function for different input context (i.e., context-sensitive analysis)
- Alternative: context-insensitive analysis
  - Merge together all of the input contexts
  - Get a conservative input context
  - Analyze function for that input
  - Use analysis result for all of the call sites
- Less precise because it doesn't distinguish between different input contexts at different call sites
  - But more efficient: analyzes functions fewer times



## Unrealizable Paths

- Source of imprecision: information may flow from one call site to another
- The results models execution paths that don't follow the stack discipline, i.e. unrealizable paths



# Flow-Sensitivity

- Dataflow analysis follows the control flow in the program to compute the result; hence, it is flow-sensitive
- Alternative: flow-insensitive analysis
  - Ignores the control flow!
  - Regards a program as a collection of statements
  - Assumes that statements can be executed multiple times, in any order
  - More efficient, less precise than flow-sensitive
- Similarity: type information is essentially flow insensitive
  - To check types of variables , just check assignments
  - Okay if assignments executed in a different order



# Flow-Insensitive Analysis

- Since the control flow is ignored, it is meaningless to compute a result per program point
- Instead, compute a single result valid for the whole program!
- General approach:
  - Derive constraints for each statement
  - Solve the system of constraints
- Example: points-to analysis -- for each pointer variable v, want to compute the set Ptr(v) of possible targets of v



# Algorithm 1

- Steensgaard algorithm:
  - for each variable v, compute a "pointer type" $\tau_v$ = Type(v)
  - Then Ptr(v) = {u | $\tau_v = *\tau_u$ and $\tau_u$ = Type(u) }
- To compute types, use a standard type inference algorithm based on unification
- Generated constraints :

| | | |
|---|---|---|
| x = &y | : | $\tau_x = *\tau_y$ |
| x = y | : | $\tau_x = \tau_y$ |
| *x = y | : | $*\tau_x = \tau_y$ |
| x = *y | : | $\tau_x = *\tau_y$ |



# Example

- Consider the following program:

```
if (cond) {
   a = &b;
   b = &d;
} else {
   a = &c;
   *a = &e;
}
```

- Result (valid at all program points):

$\tau_1$: a → $\tau_2$: b,c → $\tau_3$: d,e



# Algorithm 2

- Andersen's algorithm: generate set inclusion constraints for each statement

| | | |
|---|---|---|
| x = &y | : | $\{y\} \subseteq$ Ptr(x) |
| x = y | : | Ptr(y) $\subseteq$ Ptr(x) |
| x = *y | : | Ptr(z) $\subseteq$ Ptr(x), for all z $\in$ Ptr(y) |
| *x = y | : | Ptr(y) $\subseteq$ Ptr(z), for all z $\in$ Ptr(x) |

- Subset relation similar to subtyping
- More precise than Steensgaard, less precise than dataflow
- Both algorithms create a spurious edge b $\rightarrow$ d, as a result of statements a = &b, *a = d
  - However, this sequence never happens during execution



# Summary

- Inter-procedural analysis:
  - Context sensitive
  - Context insensitive
- Intra-procedural analysis:
  - Flow-sensitive (dataflow analysis)
  - Flow-insensitive
- Flow, context-sensitive: more precise, expensive
- Flow, context-insensitive: less precise, efficient