CS711 Advanced Programming Languages

Topics in Program Analysis

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711?

Program Analysis

- Static analysis: inspect programs at compile-time
- Extract information about program execution
  - Characterize dynamic program executions
- Use analysis results for:
  - Optimizations and transformations
  - Program verification
  - Error detection
  - Program understanding

Static vs. Dynamic

- Static analysis:
  - Work done at compile-time
  - Characterizes all executions
  - Conservative: approximates concrete program states
- Dynamic analysis:
  - Run-time overhead
  - Characterizes one or a few executions
  - Precise: knows the concrete program state
  - Can't "look into the future"

Classifying Program Analyses

- Lots of approaches to static analysis
  - How do they compare to each other?
  - What distinguishes them?
- Main aspects of program analyses:
  - What information are we interested in?
  - What program constructs?
  - How does the analysis work?
  - How much user interaction?
  - Is the analysis sound?

Analysis Information

- Figure out "facts" about the program execution
- Facts typically talk about:
  - The values in the memory
    - Constant propagation: `x = 5`
    - Points-to analysis: x points to y
    - Types: value of x is an integer
    - Verification: the result of `fact(n) = n!`
  - Events during program execution
    - Liveness: variable x never used in the future
    - Temporal properties, e.g. lock-unlock property

Analysis Information

- How much information depends on the client
- E.g., program verification: show lack of errors
- What is an error?
  - Type error?
  - Memory error?
  - Incorrect result?

increasingly difficult

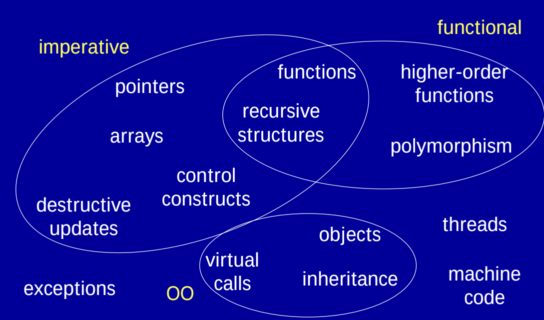
Where Do Facts Hold?

- Facts hold:
  - Either locally (e.g., at a particular program points)
  - Or globally (throughout the program. E.g., types)
- Program points approximate sets of points in dynamic execution traces
- Can refine program points using:
  - The calling stack when the execution reaches a point
  - The program path that lead to a point

Program Constructs

pointers
functions
higher-order functions
arrays
recursive structures
polymorphism
control constructs
destructive updates
objects
threads
exceptions
virtual calls
inheritance
machine code

Program Constructs



Analysis Techniques

- Dataflow analysis, Abstract interpretation
  - Flow-sensitive: track facts through the control-flow
- Type systems
  - Check or infer types for program expressions
  - Typically flow-insensitive
- Constraint methods
  - Reduce the analysis problem to a set of constraints
  - Examples: set constraints, linear systems, boolean formulas, etc.
  - Separates specification from implementation
- Model checking
  - Check properties expressed as temporal logic formulas
- Theorem proving
  - Use logical deduction to prove facts

Abstractions

- Analyses must use abstractions
  - Model computation in the program
  - Model program state
    - describe unbounded sets of unbounded states
    - Finite, tractable abstractions are desirable
- Examples:
  - Dataflow, AI: CFGs, SSA, lattices
  - Model checking: transition systems, temporal logic formulas
  - Type systems: type abstraction, typing rules (type constraints)
  - Constraint methods: constraints
  - Theorem proving: theorems

User Interaction

- Three ways users can interact with analyses:
  - Help the analysis: annotations, specifications
    - Typical example: types
    - Best way to help the analysis: provide information at procedure boundaries, loop invariants (Hoare-style)
  - Help the analysis: interactive
    - Provide help while the analysis runs
  - Tell the analysis what to compute: parameterization
    - User tells what facts the analysis should compute/verify
    - Example: finite state machine models

Soundness

- Soundness: analysis conservatively approximates all program executions
- Unsound analyses: might miss some facts
  - "false negatives" = "missed facts"
  - "false positives" = "facts that never occur"
- Is soundness desirable?
  - Definitely for analyses, transformations, verification
  - Error-detection is a different story
    - Unsound analyses okay
    - Unsound analyses can prove the presence of errors, not their absence
- Sources of unsoundness:
  - Treatment of aliasing, loops, recursion, type-unsafe constructs

Proving Soundness

- How do I know that the analysis is sound?
  - Define program semantics
  - AI framework: show that abstract transformer yields conservative results
  - Fairly straightforward for standard compiler analyses
  - Type systems: progress + preservation
- Another approach:
  - Define abstraction
  - Automatically build sound analyses for that abstraction

Efficiency and Scalability

- Analyses can be expensive
  - E.g., inter-procedural, flow-sensitive analyses
- Ways to make an analysis scalable:
  - Reduce precision
  - Request user annotations
  - Be unsound

This Course

- Programming paradigms and constructs:
  - Focus on analyses for imperative languages
  - Look at: inter-procedural analysis, OO features, pointers, recursive structures, machine code, threads
- Analysis Techniques:
  - Mainly dataflow, AI, type systems, constraint methods
- Bug-finding tools:
  - Including unsound analyses
- Automatic generation of static analyses

Course Structure

- Read significant/recent papers in the area
  - 35 minutes paper presentation
  - 25 minutes discussions
- Background
  - Dataflow analysis, optimizations (CS412)
  - Type systems (CS411, CS611)
- Requirements
  - Attend seminars
  - Read all papers, engage in discussions
  - Present 1-2 papers, start discussions
  - Do an implementation project
    - Or write a survey in a sub-area

A Flavor of Static Analysis

- Can an analysis determine that your program builds a tree? (not a DAG or a cyclic graph)
- Why should I care?
  - Program understanding/verification
  - Can parallelize programs with tree structures
  - Check memory safety

Example

```
rotate(tree * t) {
    tree *x = t->left;
    t->left = x->right;
    x->right = t;
    return x;
}
```

- Can the compile automatically prove that this code preserves the tree shape? How?

Example

```
rotate(tree * t) {
    tree *x = t->left;
    t->left = x->right;
    x->right = t;
    return x;
}
```

- Shape analysis
  - Uses an abstraction that tracks reference counts
  - Tree if all reference count are equal to 1

Find Bugs

```
rotate(tree * t) {
    tree *x = t->left;
    t->left = x->right;
    x->left = t;
    return x;
}
```

- Change "`x->right`" with "`x->left`"
- What goes wrong?

Materials

- Book:
  "Principles of Program Analysis",
  by Nielson, Nielson, Hankin, Springer 1999
- Web site
  http://www.cs.cornell.edu/courses/cs711
- Next time: Inter-procedural analysis
  "Precise Inter-Procedural Dataflow Analysis via Graph Reachability"
  by Reps, Horwitz, Sagiv, POPL'95