Program Analysis (CSCI-4450/CSCI-6450) Spring 2019

www.cs.rpi.edu/~milanova/csci4450/

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Office hours: Wednesdays Noon-2:00PM or by appointment

Outline

- Logistics
  www.cs.rpi.edu/~milanova/csci4450/
- Program analysis, introduction
- Course topics, tools and homework
- Introduction to Dataflow analysis

Logistics

- Course webpage
  http://www.cs.rpi.edu/~milanova/csci4450
  - Schedule, Notes, Reading
    - Schedule, lecture slides and assigned reading
  - Homework
    - Announcement and instructions when new homework assignment is on
  - Submitty
    - All homework submission and grades, forum, announcements
    - Check forum regularly for announcements

Logistics

- Recommended reading
  - **Compilers: Principles, Techniques and Tools,** by Alfred Aho, Monica Lam, Ravi Sethi, and Jeffrey Ullman (the Dragon Book).
  - **Principles of Program Analysis** by Flemming Nielson, Hanne Riis Nielson, and Chris Hankin.
  - **Types and Programming Languages**, by Benjamin C. Pierce.
  - MIT's Open Courseware Class on Program Analysis
- Papers and lecture notes

Logistics

- Syllabus
  www.cs.rpi.edu/~milanova/csci4450/syllabus.htm
  Topics, outcomes, policies and grading
- Take-home final: 25%
- Homework: 40%
- Paper presentation: 10%
- In-class quizzes (8): 20%
- Attendance and participation: 5%

Logistics

- Assignments are to be completed individually unless otherwise specified
- Quizzes are in-class, open-notes, and may be completed individually or in small groups
  - Makeup policy: you'll need an excuse note to makeup a quiz

Late Homework

- Homework assignments must be submitted in Submitty by 2pm on the due date
- You have 6 late days for the semester, with a max of 2 late days per assignment
- Exceptions to policy granted with an excuse note by your CLASS dean

Program Analysis

- Tools and techniques that help us reason about the run-time behavior of the program
  - Dynamic analysis – during program execution
    - Static instrumentation
    - Dynamic (binary) instrumentation (DBI)
  - Static analysis – before program execution
    - E.g., Java compiler's definite-assignment-check
    - E.g., Type checking and type inference are forms of static analysis
    - E.g., Dafny-style verification
    - And many, many more!

Our main focus is Static Analysis

- Many techniques
  - Decades of research and Turing Awards!
  - Dataflow analysis and abstract interpretation
    - Kildall '73, Kam and Ullman '77, Cousot & Cousot '77
  - Types and type-based analysis
    - Following Backus' "Can Programming…" '78
  - Axiomatic semantics (i.e., Hoare Logic)
    - C.A.R. Hoare's "An Axiomatic Basis for Computer Programming", '69

Static Analysis

- What this course is mostly about
  - How can we define the meaning of programs
  - How can we model behavior of programs, and prove theorems about programs
  - How can we use and build tools that automatically reason about programs
- Many applications

Applications

- Compiler optimization, traditional application
  - We'll start with dataflow analysis
- Finding bugs, verifying the absence of bugs
- Designing languages that prevent bugs
- Refactoring and testing
- Improving energy efficiency
- Improving security and privacy
- Education. Submitty uses static analysis!

Examples of Properties Deducible by Static Analysis

- Can **`x`** ever be null at program point **`i: x.m()`**
- Can **`y`** be different than **`1`** at program point **`i: x = y*10`**?
- Can **`n`** at **`x[n]`** cause out-of-bounds access?
- Does an app leak private data (e.g., phone number, phone identifier, location) to ad networks?
  - Answer: Yes!

Examples of Properties Deducible by Static Analysis

- What inputs avoid divide-by-zero at `x/y`?

```
{x!=1 && x!=-2}
y = x + 4;
if (x > 0) {
  y = x*x - 1;
}
else {
  y = y + x;
}
{y!=0}
x = x/y;
```

- Formalism of Axiomatic Semantics (Hoare logic)
  - Different from dataflow and types
- Allows us to specify program behavior with preconditions and postconditions that form logical assertions
  - Support complex logics
  - Enables reasoning about correctness

Nature of Static Analysis

- To remain computable, static analysis must approximate. It is undecidable to find exactly what happens at runtime
  - Typically, analysis errs on the safe (sound) side --- that is, it over-approximates
    - E.g., analysis reports that `x` at `x.m()` may be `null`, even though it cannot ever be `null`
    - A type system rejects correct programs
  - Sometimes, analysis is unsafe (unsound) --- that is, it under-approximates

Nature of Static Analysis

```
read(x);
if (x > 0) {y=1} else {S;y=2};
z=y;
```

Looking at this code, what values of `y` can reach `z=y`?

But if `S` never terminates for `x<=0`, then only `1` can ever reach `z=y`! Since it is undecidable (in general) whether `S` terminates, we cannot expect analysis to detect this case

Nature of Static Analysis, cont.

- A static analysis is said to be safe (also, sound, correct) if it over-approximates, that is, takes into account every execution path
  - E.g., in previous example the analysis that reports `y` in `{1,2}` is safe, but so is the one that reports `y` in `{1,2,21}`

Analysis Safety

- Safety is crucial when analysis enables compiler optimizations. Why?
  - E.g., an unsafe analysis may report that `y` is always `1` at `z = y*10`, while in fact there is an execution path that sets `y` to `10`.
    If the optimizing compiler changes `z = y*10` to `z = 10`, the program produces incorrect result along the path when `y` is `10`!

Analysis Safety

- Safety is often relinquished when analysis is used in static debugging tools. Why?
- E.g., suppose we have a piece of code that contains 10 “true” null-pointer dereferences
  - Safe analysis A reports 100 potential null-pointer dereferences (all 10 “true” bugs and 90 “false-positives”).
  - Unsafe analysis B reports 10 potential null-pointer dereferences (8 “true” and 2 false-positives). Which one would you take?

Analysis Precision

- Analysis precision refers to how "close" results are to what happens at runtime
  - E.g., in our running example, the analysis that reports `y` in `{1,2}` is more precise than the one that reports `y` in `{1,2,21}`.
  - Typically, we use the term precision with safe analysis (safe analysis has 100% recall)
- Wide spectrum of static analyses and tradeoff between cost and precision

Outline

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- Static analysis, introduction
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- Introduction to Dataflow analysis

Course Topics

- Dataflow analysis
  - Lattices, transfer functions, dataflow frameworks
  - Classical analyses: points-to analysis
- Abstract interpretation (powerful formalism, generalization of DF)
  - Abstract vs. concrete semantics
  - Galois connections

Course Topics

- Types and type-based analysis
  - Simply typed Lambda calculus
  - Type systems and type soundness
  - Simple type inference
  - Hindley Milner type inference
  - Types for imperative languages
  - Pluggable types
  - Type-based information flow analysis (aka taint analysis)

Course Topics

- Axiomatic Semantics
  - You know already: Hoare logic!
  - Logics to specify assertions (as you know them, **P** and **Q** in **{ P }** code **{ Q }**)
  - SMT solvers and proving Hoare triples
  - Symbolic execution

Tools

- Soot
- Checkers
- Z3
- Java
- Haskell
- OCaml

Homework Assignments

- There will be 7-8 homework assignments
  - Each makes about 5-6% of your grade
  - Larger assignments are broken into 2-3 parts
  - Some are individual, some are team assignments
  - Submitty!

Homework Assignments

- HW1
  - Problem set to practice dataflow analysis
- HW2-HW4
  - Classical OO analyses in Soot: the CHA, RTA, and XTA family of analyses
- HW5-HW6
  - Problem set to practice abstract interpretation/ type inference concepts
  - Implement simple type inference (and maybe Hindley Milner) in Haskell

Homework Assignments

- HW7-HW8
  - Implement a tiny C-program verifier using Z3
  - Implement a symbolic execution engine
- HW9 (wish list)
  - Ownership type inference using Max-SMT/Max-SAT

Dataflow Analysis

Key Papers

- Gary Kildall, "A Unified Approach to Global Program Optimization", POPL 1973
- John Kam and Jeff Ullman, "Monotone Dataflow Analysis Frameworks", Acta Inf. 1977

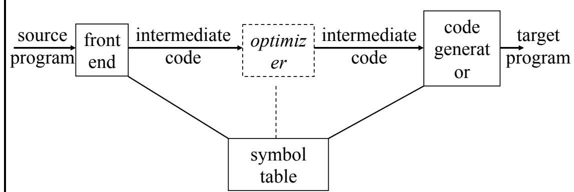
Outline

- Motivation and origin of dataflow analysis: compiler optimization
- Overview of the compiler
- Classical compiler optimizations
- Control flow graphs
- Reading:
  - Dragon Book, Chapter 9.1

Overview of the Compiler

- Phases of the compiler
  - Lexical Analyzer (scanner)
  - Syntax Analyzer (parser)
  - Semantic Analyzer and Intermediate Code Generator
  - Machine-Independent Code Optimizer
  - Code Generator
  - Machine-Dependent Code Optimizer

Overview of the Compiler



An optimization is a semantics-preserving transformation

Classical Compiler Optimizations

- We will show the classical optimizations using an example Fortran loop
- Opportunities for optimization due to automatic generation of intermediate code

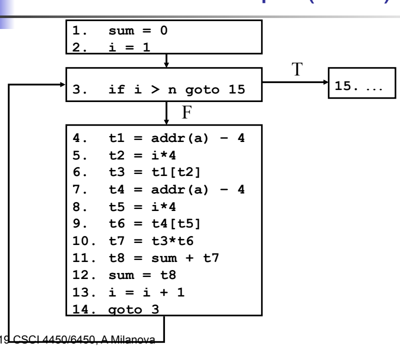
```
…
sum = 0
do 10 i = 1, n
 10   sum = sum + a[i]*a[i]
 …
```


Three Address Code Intermediate Representation (IR)

```
sum = 0               => initialize sum
i = 1                 => initialize loop counter
if i > n goto 15      => loop test, check for limit
t1 = addr(a) - 4      }
t2 = i * 4            }  a[i]
t3 = t1[t2]           }
t4 = addr(a) - 4      }
t5 = i * 4            }  a[i]
t6 = t4[t5]           }
t7 = t3 * t6          => a[i]*a[i]
t8 = sum + t7         }
sum = t8              }  increment sum
i = i + 1             => increment loop counter
goto 3

...
```


Control Flow Graph (CFG)



Common Subexpression Elimination

```
sum = 0
i = 1
if i > n goto 15
t1 = addr(a) - 4
t2 = i*4
t3 = t1[t2]
t4 = addr(a) - 4
t5 = i*4
t6 = t4[t5]
t7 = t3*t6
t8 = sum + t7
sum = t8
i = i + 1
goto 3
…
```

```
1.  sum = 0
2.  i = 1
3.  if i > n goto 15
4.  t1 = addr(a) - 4
5.  t2 = i*4
6.  t3 = t1[t2]
7.  t4 = addr(a) - 4
8.  t5 = i*4
9.  t6 = t4[t5]
10. t7 = t3*t6
10a t7 = t3*t3
11. t8 = sum + t7
12. sum = t8
13. i = i + 1
14. goto 3
```

After Common Subexpression Elimination

```
1.  sum = 0
2.  i = 1
3.  if i > n goto 15
4.  t1 = addr(a) – 4
5.  t2 = i*4
6.  t3 = t1[t2]
10a t7 = t3*t3
11. t8 = sum + t7
12. sum = t8
13. i = i + 1
14. goto 3
```


Copy Propagation

```
1.  sum = 0
2.  i = 1
3.  if i > n goto 15
4.  t1 = addr(a) – 4
5.  t2 = i * 4
6.  t3 = t1[t2]
10a t7 = t3 * t3
11  t8 = sum + t7
12. sum = t8
13. i = i + 1
14. goto 3
15. …
```

```
1.  sum = 0
2.  i = 1
3.  if i > n goto 15
4.  t1 = addr(a) - 4
5.  t2 = i * 4
6.  t3 = t1[t2]
10a t7 = t3 * t3
11. t8 = sum + t7
11a sum = sum + t7
12. sum = t8
13. i = i + 1
14. goto 3
15. …
```


After Copy Propagation

```
1.  sum = 0
2.  i = 1
3.  if i > n goto 15
4.  t1 = addr(a) – 4
5.  t2 = i * 4
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
13. i = i + 1
14. goto 3
15. …
```


Invariant Code Motion

```
1.  sum = 0
2.  i = 1
3.  if i > n goto 15
4.  t1 = addr(a) – 4
5.  t2 = i * 4
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
13. i = i + 1
14. goto 3
15. …
```

```
1.  sum = 0
2.  i = 1
2a  t1 = addr(a) - 4
3.  if i > n goto 15
4.  t1 = addr(a) - 4
5.  t2 = i * 4
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
13. i = i + 1
14. goto 3
15. …
```


After Invariant Code Motion

```
1.  sum = 0
2.  i = 1
2a  t1 = addr(a) – 4
3.  if i > n goto 15
5.  t2 = i * 4
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
13. i = i + 1
14. goto 3
15. …
```


Strength Reduction

```
1.  sum = 0
2.  i = 1
2a  t1 = addr(a) – 4
3.  if i > n goto 15
5.  t2 = i * 4
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
13. i = i + 1
14. goto 3
15. …
```

```
1.  sum = 0
2.  i = 1
2a  t1 = addr(a) - 4
2b  t2 = i * 4
3.  if i > n goto 15
5.  t2 = i * 4
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
11b t2 = t2 + 4
13. i = i + 1
14. goto 3
15. …
```

After Strength Reduction

```
1.  sum = 0
2.  i = 1
2a  t1 = addr(a) - 4
2b  t2 = i * 4
3.  if i > n goto 15
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
11b t2 = t2 + 4
13. i = i + 1
14. goto 3
15. …
```


Test Elision and Induction Variable Elimination

```
1.  sum = 0
2.  i = 1
2a  t1 = addr(a) - 4
2b  t2 = i * 4
3.  if i > n goto 15
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
11b t2 = t2 + 4
13. i = i + 1
14. goto 3
15. …
```

```
1.  sum = 0
2.  i = 1
2a  t1 = addr(a) - 4
2b  t2 = i * 4
2c  t9 = n * 4
3.  if i > n goto 15
3a  if t2 > t9 goto 15
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
11b t2 = t2 + 4
13. i = i + 1
14. goto 3a
15. …
```


After Test Elision and Induction Variable Elimination

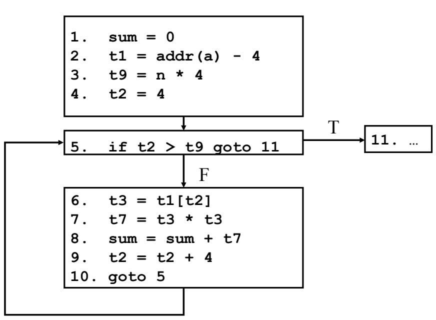
```
1.   sum = 0
2.   i = 1
2a   t1 = addr(a) - 4
2b   t2 = i * 4
2c   t9 = n * 4
3a   if t2 > t9 goto 15
6.   t3 = t1[t2]
10a  t7 = t3 * t3
11a  sum = sum + t7
11b  t2 = t2 + 4
14.  goto 3a
15.  …
```


Constant Propagation and Dead Code Elimination

```
1.  sum = 0
2.  i = 1
2a  t1 = addr(a) - 4
2b  t2 = i * 4
2c  t9 = n * 4
3a  if t2 > t9 goto 15
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
11b t2 = t2 + 4
14. goto 3a
15. …
```

```
1.  sum = 0
2.  i = 1
2a  t1 = addr(a) - 4
2b  t2 = i * 4
2c  t9 = n * 4
2d  t2 = 4
3a  if t2 > t9 goto 15
6.  t3 = t1[t2]
10a t7 = t3 * t3
11a sum = sum + t7
11b t2 = t2 + 4
14. goto 3a
15. …
```


New Control Flow Graph



Classical Compiler Optimizations

- To summarize
  - Common subexpression elimination
  - Copy propagation
  - Strength reduction
  - Test elision and induction variable elimination
  - Constant propagation
  - Dead code elimination
- Dataflow analysis enables these optimizations

Building the Control Flow Graph

Build the CFG from linear 3-address code:

- Step 1: partition code into basic blocks
  - Basic blocks are the nodes in the CFG
- Step 2: add control flow edges

- Aside: in Principles of Software, we built a CFG from structured IR:
  - S ::= x = y op z | S;S | if (b) then S else S | while (b) S

Step 1. Partition Code Into Basic Blocks

1. Determine the *leader* statements:
   (i) First program statement
   (ii) Targets of conditional or unconditional goto's
   (iii) Any statement following a goto
2. For each leader, its basic block consists of the leader and all statements up to, but not including, the next leader or the end of the program

Question. Find the Leader Statements

```
1.  sum = 0
2.  i = 1
3.  if i > n goto 15
4.  t1 = addr(a) – 4
5.  t2 = i*4
6.  t3 = t1[t2]
7.  t4 = addr(a) – 4
8.  t5 = i*4
9.  t6 = t5[t5]
10. t7 = t3*t6
11. t8 = sum + t7
12. sum = t8
13. i = i + 1
14. goto 3
15. …
```


Step 2. Add Control Flow Edges

- There is a directed edge from basic block B_1 to block B_2 if B_2 can immediately follow B_1 in some execution sequence
- Determine edges as follows:
  (i) There is an edge from B_1 to B_2 if B_2 follows B_1 in three-address code, and B_1 does not end in an unconditional goto
  (ii) There is an edge from B_1 to B_2 if there is a goto from the last statement in B_1 to the first statement in B_2

Question. Add Control Flow Edges

```
1.  sum = 0
2.  i = 1
3.  if i > n goto 15
4.  t1 = addr(a) – 4
5.  t2 = i*4
6.  t3 = t1[t2]
7.  t4 = addr(a) – 4
8.  t5 = i*4
9.  t6 = t5[t5]
10. t7 = t3*t6
11. t8 = sum + t7
12. sum = t8
13. i = i + 1
14. goto 3
15. …
```


Next Class

- Dataflow analysis
- Four classical dataflow analysis problems