CMSC 631 – Program Analysis and Understanding
Fall 2011

What you'll learn

- Formal systems and notations
  - Vocabulary for talking about programs
- Program analysis
  - Automatic reasoning about source code
- Programming language features
  - Affects programs and how we reason about them

How you'll learn it

- Implement
  - You will build some program analyzers as projects using the Objective Caml programming language
- Prove
  - You will mechanize mathematics for reasoning about programs using the Coq proof assistant
    - Interactive theorem proving: ensures your proofs are actually correct, and therefore that you really understand
- Take it one step further: substantial final project

What you'll gain

- Better programming ability
  - By understanding programming languages deeply
- Mathematical methods and maturity
  - Formalization and proof techniques will transfer to other areas
- How to use Coq and program in OCaml
  - Write reliable code faster! Prove the four color theorem (with high assurance)!

Personnel

- Michael Hicks
  - Office: 4131 AVW (for now)
  - E-mail: mwh@cs.umd.edu
  - Office hours: 2 hours, TBD (requests?)
    - Or by appointment

Prerequisite

- CMSC ~~430~~ 330 or equivalent
  - Ideas we will use in this class:
    - Parse trees/abstract syntax trees
    - BNF notation for grammars
    - Programming language maturity
      - Familiarity with several different languages/paradigms
    - General information about programming language design
  - Talk to me if you're not sure

Textbooks

- No required textbooks
  - But see web page for suggestions
  - Recommended text:
    - Pierce, *Types and Programming Languages*
  - A second book, also good:
    - Huth and Ryan, *Logic in Computer Science*

- Neither covers everything in the course
- Recommended two on reserve in CS library

Forum

- Piazza
  - See class web page for link
  - Need to sign up

- Can use piazza to ask and answer questions about lectures, assignments, etc.
  - Please use this forum unless you have personal request (e.g., about your grade, an absence, etc.)

Expectations: Homework (40%)

- Programming assignments
  - Symbolic execution and type inference
- Proofs using Coq
  - From basic mathematics to
  - methods for expressing a program's semantics to
  - methods for proving properties about programs

Late Policy on Assignments

- Programming/Coq assignments: Due at midnight
  - Submit via the submit server (see class web page)

- No late submissions
  - Contact me about extenuating circumstances
    - E.g., religious holidays
  - Inform me as soon as possible

Expectations: Participation (10%)

- Will need to read some papers for class
  - Scattered through the semester
  - Should come prepared to contribute to discussion

- (Possible) student presentations of papers
  - Read 1-2 papers on a topic
  - Present (partial) lecture in class about the material

Expectations: Project (25%)

- Class goal: Teach you how to do research
  - So you have to do research as part of the class
- Substantial research project (25% of grade)
  - Any topic vaguely related to the class is acceptable
    - Will post some suggestions for projects later on
    - May also be able to share project with other class
  - Completed in groups of size 2 (possibly 1 or 3)
- Will occupy the latter 2/3 of semester
  - But will still have some Coq assignments

Expectations: Project (cont'd)

- Deliverables
  - Project proposal (one page) + talk with me
  - Project write-up
    - A conference-style paper (5-15 pages, as appropriate)
  - Implementation, if any
  - In-class presentation
    - 15-20 minutes, depending on # of projects

- In the past, several 631 projects led to papers
  - Not required (!), but possible

Expectations: Exam (25%)

- Final exam
  - Based on course assignments
  - Take home exam
    - The exam will be available for 96 hours
    - You pick a 48-hour window during that time during which to take the exam
  - Dates on class web page

Academic Dishonesty

- Don’t do it

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21 Ideas and Applications in Program Analysis
in 40 Minutes

Abstract Interpretation

- Rice's Theorem: Any non-trivial property of programs is undecidable
  - Uh-oh! We can't do anything. So much for this course...
- Need to make some kind of approximation
  - Abstract the behavior of the program
  - ...and then analyze the abstraction
- Seminal papers: Cousot and Cousot, 1977, 1979

Example

e ::= n | e + e

$$\alpha(n) = \begin{cases} - & n < 0 \\ 0 & n = 0 \\ + & n > 0 \end{cases}$$

+	-	0	+
-	-	-	?
0	-	0	+
+	?	+	+

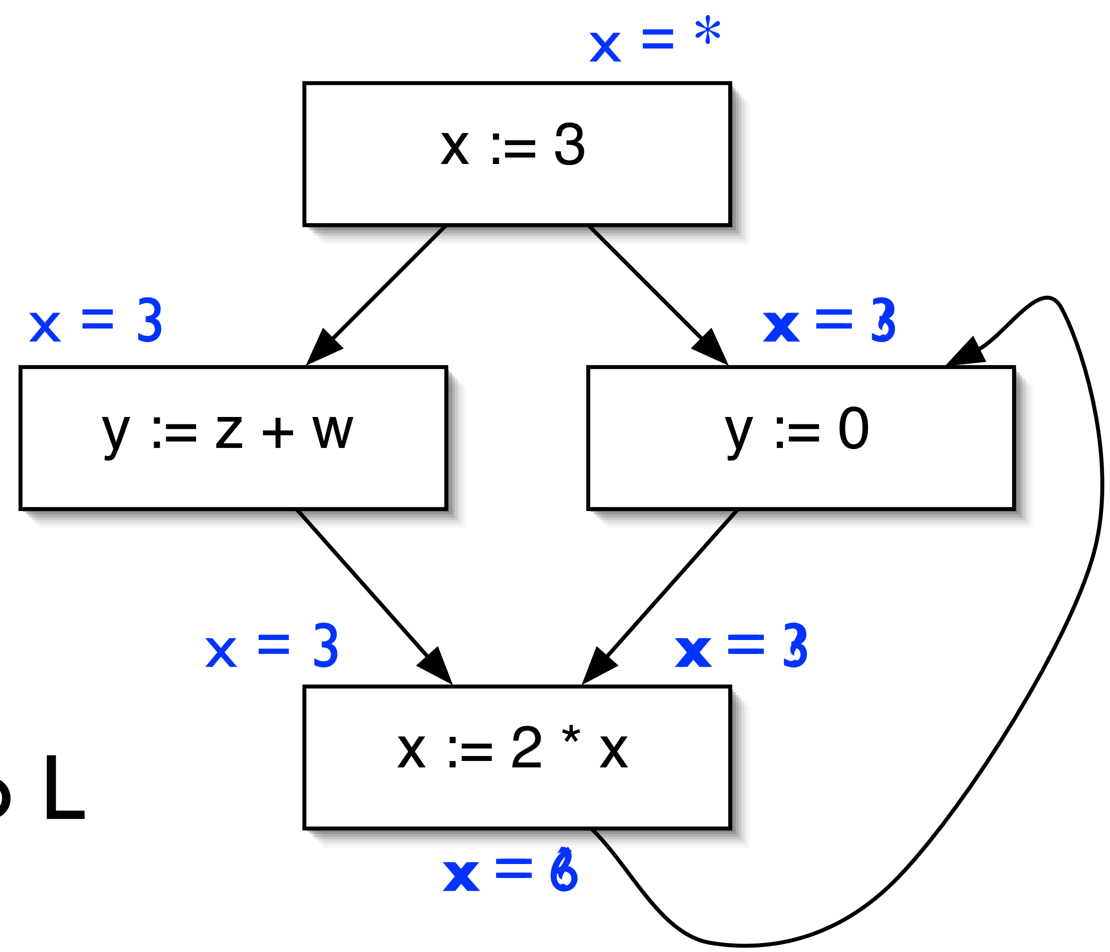
- Notice the need for ? value
  - Arises because of the abstraction

Dataflow Analysis

- Classic style of program analysis
- Used in optimizing compilers
  - Constant propagation
  - Common sub-expression elimination
  - Loop unrolling and code motion
  - etc.
- Efficiently implementable
  - At least, *intraprocedurally* (within a single proc.)
  - Use bit-vectors, fixpoint computation

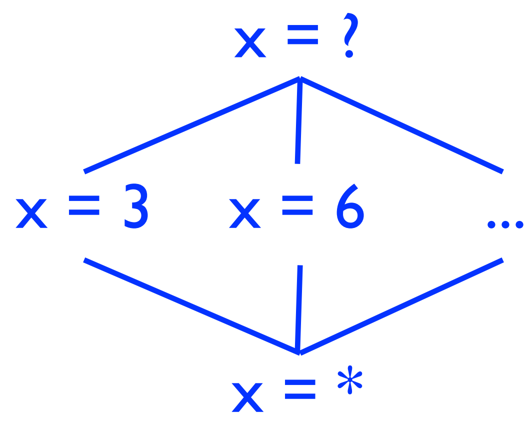
Control-Flow Graph

```
x := 3
if (!x) then
  y := z + w
else
  L: { y := 0 }
x := 2 * x
if (!x) then goto L
```



Lattices and Termination

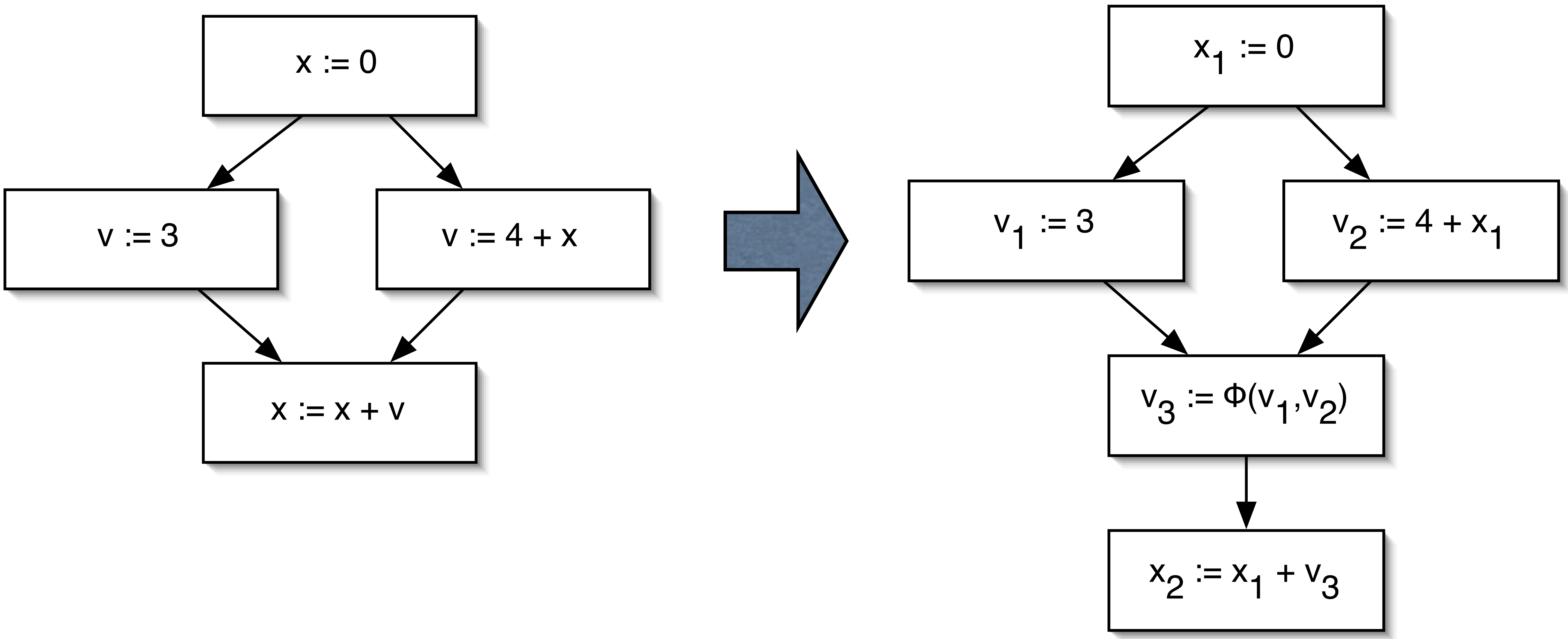
- Dataflow facts form a lattice



- Each statement has a transformation function
  - Out(S) = Gen(S) U (In(S) - Kill(S))
- Terminates because
  - Finite height lattice
  - Monotone transformation functions

Static Single Assignment Form

- Transform CFG so each use has a single defn



Lambda Calculus

- Three syntactic forms

$e ::= x$ variable

$\mid \lambda x.e$ function

$\mid e\ e$ function application

- One reduction rule
  - $(\lambda x.e_1)\ e_2 \rightarrow e_1[e_2 \backslash x]$ (replace x by e_2 in e_1)

- Can represent any computable function!

Example

- Conditionals
  - true = $\lambda x.\lambda y.x$ false = $\lambda x.\lambda y.y$
  - if a then b else c = a b c
    - if true then b else c = $(\lambda x.\lambda y.x)\ b\ c \rightarrow (\lambda y.b)\ c \rightarrow b$
    - if false then b else c = $(\lambda x.\lambda y.y)\ b\ c \rightarrow (\lambda y.y)\ c \rightarrow c$
- Can also represent numbers, pairs, data structures, etc, etc.
- Result: Lingua franca of PL

ML: Meta-Language

- ML designed originally for theorem provers
  - But after a while, realized could be general-purpose

- Mostly-functional language
  - Similar to lambda-calculus
    - Mostly functional, encouraged not to use side-effects
    - Call-by-value

- We'll use OCaml for programming assignments

Program Semantics

- To be able to analyze programs, we have to know what they mean
  - *Semantics* comes from the Greek *semaino*, "to mean"
- Three styles of formal semantics
  - Operational semantics (major focus)
    - Like an interpreter
  - Denotational semantics
    - Like a compiler
  - Axiomatic semantics
    - Based on what you can prove about programs

Operational Semantics

- Evaluation is described as transitions in some abstract machine
  - Example: Beta reduction from lambda calculus

$$(\lambda x.e_1)\ e_2 \rightarrow e_1[e_2\backslash x]$$

  - State of machine described by current expression
- There are different styles of abstract machines
  - Small-step (as above), big-step, etc
- The *meaning* of a program is its fully reduced form (a.k.a. a *value*)

Denotational Semantics

- The meaning of a program is defined as a mathematical object, e.g., a function or number
- Typically define an *interpretation function* ⟦ ⟧
  - Program fragment as argument and returns meaning
  - E.g., ⟦ 3+4 ⟧ = 7
- Gets interesting when we try to find denotations of loops or recursive functions

Denotational Semantics Example

- b ::= true | false | $b \vee b$ | $b \wedge b$
- e ::= 0 | 1 | ... | e + e | e * e
- s ::= e | if b then s else s
- Semantics:
  - $[\![\text{ true }]\!] = \text{true}$
  - $[\![\text{ b1 b2 }]\!] = \begin{cases} \text{true} & \text{if } [\![\text{b1}]\!] = \text{true or } [\![\text{b2}]\!] = \text{true} \\ \text{false} & \text{otherwise} \end{cases}$
  - $[\![\text{ if b then s1 else s2 }]\!] = \begin{cases} [\![\text{s1}]\!] & \text{if } [\![\text{b}]\!] = \text{true} \\ [\![\text{s2}]\!] & \text{if } [\![\text{b}]\!] = \text{false} \end{cases}$

Axiomatic Semantics

- Operational and denotational semantics let us reason about the meaning of a program
  - Are two programs equivalent? Does a program terminate? Does a program implement a particular specification

- *Axiomatic semantics* define a program's meaning in terms of what one can prove about it
  - Hoare, Dijkstra, Gries, others

Hoare Triples

- {P} S {Q}
  - If statement S is executed in a state satisfying precondition P, then S will terminate, and Q will hold of the resulting state
  - Partial correctness: ignore termination

- Weakest precondition for assignment
  - Axiom: {Q[e\x]} x := e {Q}
  - Example: {y > 3} x := y {x > 3}

Type Systems

- Machine represents all values as bit patterns
  - Is 00110110111100101100111010101000
    - A signed integer? Unsigned integer? Floating-point number? Address of an integer? Address of a function? etc.

- Type systems allow us to distinguish these
  - To choose operation (which + op), e.g., FORTRAN
  - To avoid programming mistakes
    - E.g., don’t treat integer as a function address

Simply-typed λ-calculus

$e ::= x \mid n \mid \lambda x{:}\tau.e \mid e\ e$

$\tau ::= \mathrm{int} \mid \tau \to \tau$

$A \vdash e : \tau$ in type environment A, expression e has type τ

$$\frac{}{A \vdash n : \mathrm{int}} \qquad \frac{x \in \mathrm{dom}(A)}{A \vdash x : A(x)}$$

$$\frac{A[\tau \backslash x] \vdash e : \tau'}{A \vdash \lambda x{:}\tau.e : \tau \to \tau'} \qquad \frac{A \vdash e1 : \tau \to \tau' \quad A \vdash e2 : \tau}{A \vdash e1\ e2 : \tau'}$$

Subtyping

- Liskov:
  - If for each object o_1 of type S there is an object o_2 of type T such that for all programs P defined in terms of o_1, the behavior of P is unchanged when o_2 is substituted for o_1 then S is a subtype of T.

- Informal statement
  - If anyone expecting a T can be given an S instead, then S is a subtype of T.

Other Technologies and Topics

- Control-flow analysis
- CFL reachablity and polymorphism
- Constraint-based analysis
- Alias and pointer analysis
- Region-based memory management
- Garbage collection
- More...

Applications: Dataflow analysis

- Optimizing compilers
  - I.e., any good compiler
- ESP: Path-sensitive program cheker (Microsoft)
  - Example: can check for correct file I/O properties, like files are opened for reading before being read
- Meta-level compilation (Coverity)
- ...

Applications: Abstract Interp.

- Terminator (Microsoft)
  - Analyzes code to prove that it terminates (!)
  - Applied to device drivers for Windows kernel
    - Tricky part is reasoning about the heap
    -
- ASTREE (INRIA and others)
  - Used to detect all possible runtime failures (divide by zero, null pointer deref, array out of bounds) on embedded code
  - Used regularly on Airbus avionics software

Applications: Symbolic Execution

- A symbolic executor is a language interpreter++
  - Rather than only work on concrete values, also works on symbolic values
  - Ex: y = fresh(); assert(f(y) == 2*y-1);
  - Solver conceptually "forks" on tests of symbolic values
- Uses SMT solver to check assertions, path feasiblity
  - SMT = Satisfiability Modulo Theory = SAT++
  - Solvers can solve very large instances, even though SAT theoretically intractable (i.e., NP Hard)
- Very popular: DART, CUTE, EXE, KLEE, Otter, Rubyx, etc
  - SAGE tool in regular use at Microsoft for fuzz testing

Applications: Axiomatic Semantics

- Extended Static Checker
  - Can perform deep reasoning about programs
  - Array out-of-bounds
  - Null pointer errors
  - Failure to satisfy internal invariants

- Uses the Simplify theorem prover

Applications: Type Systems

- Type qualifiers
  - Format-string vulnerabilities, deadlocks, file I/O protocol errors, kernel security holes

- Jif (Java+Information Flow)
  - Annotate standard types with additional security labels, where type correctness implies correct protection of sensitive data

Conclusion

- PL has a great mix of theory and practice
  - Very deep theory
  - But lots of practical applications

- Recent exciting new developments
  - Focus on program correctness (and security)
    - instead of speed
  - Scalability to large programs
  - In greater use in mainstream development