Introduction to Program Analysis

17-355/17-665/17-819: Program Analysis

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course materials developed with Claire Le Goues

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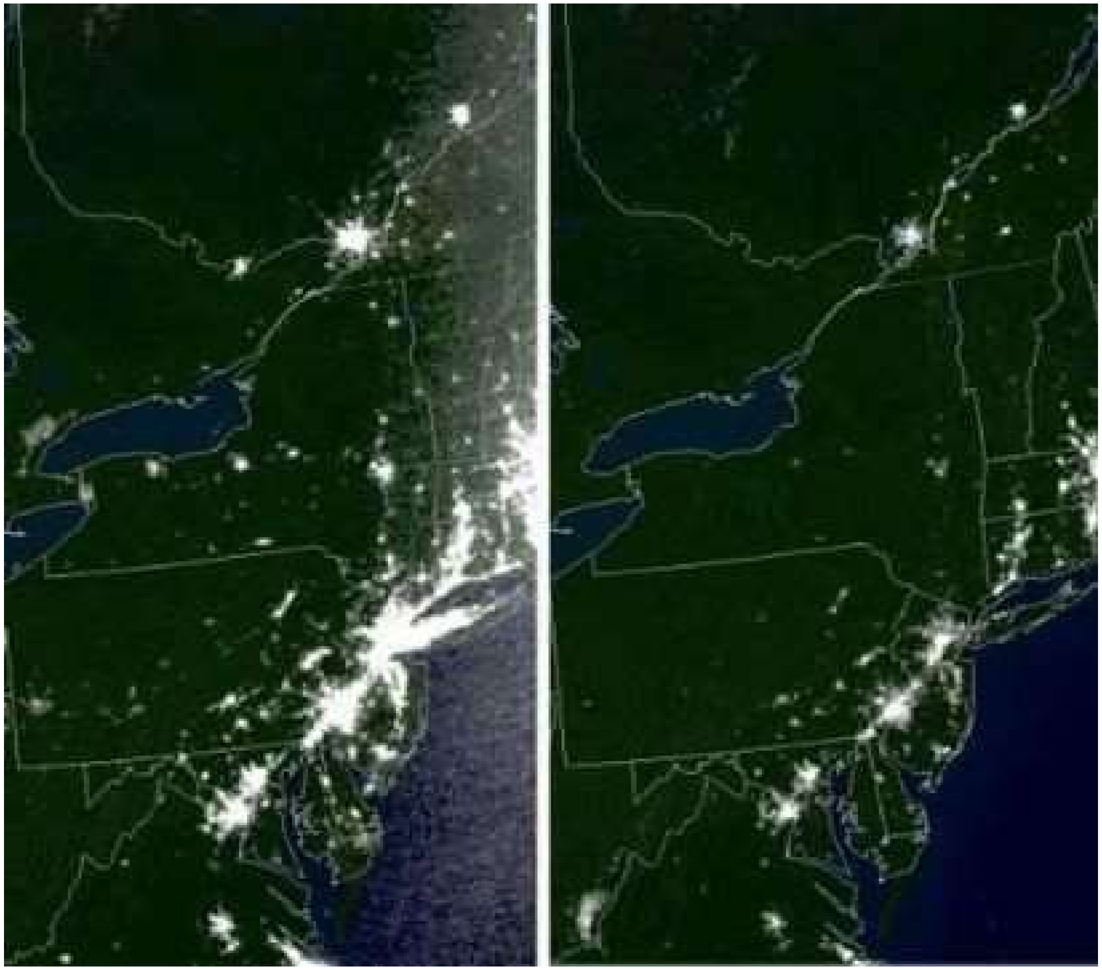

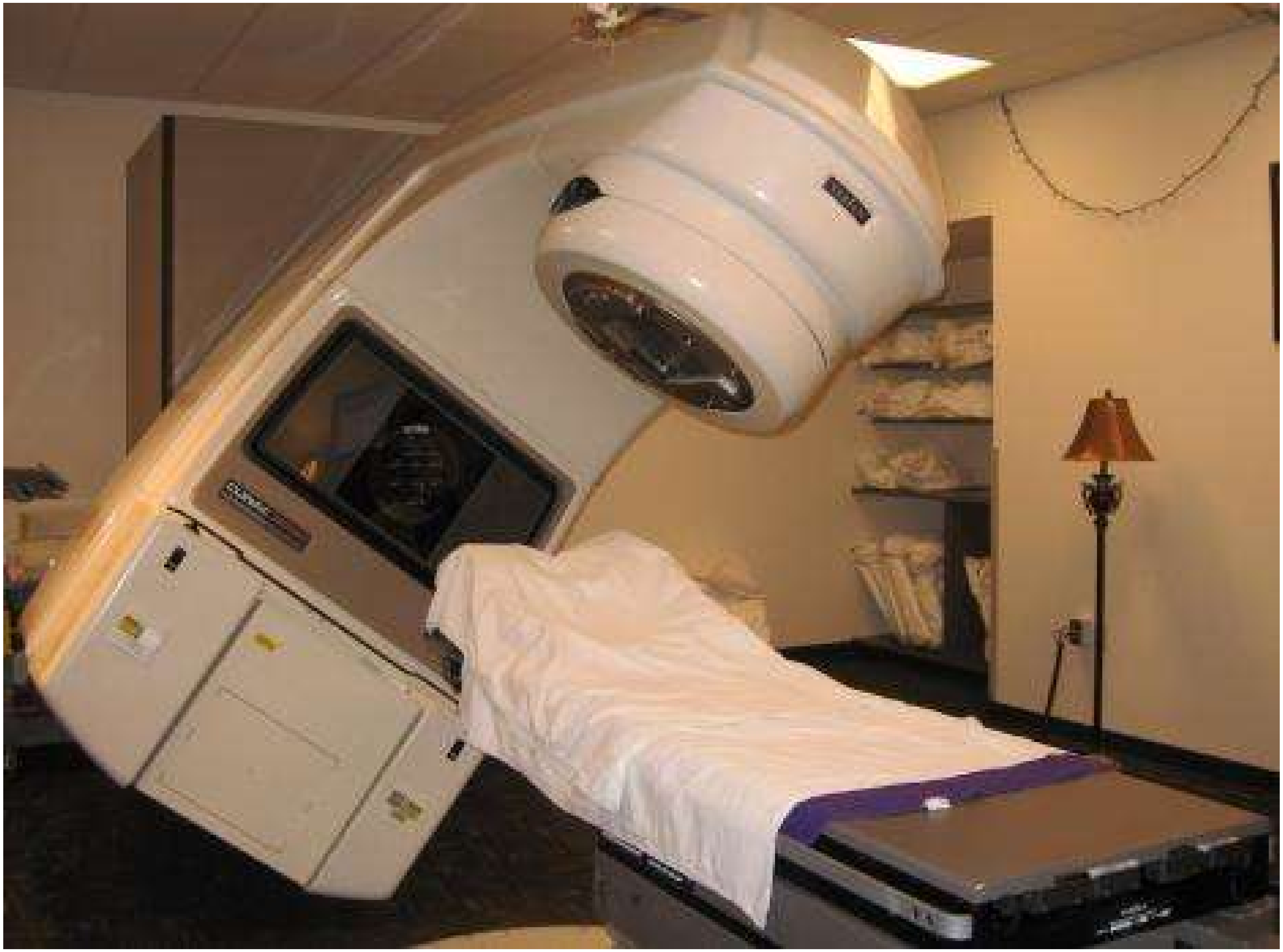

Is there a bug in this code?

```c
/* from Linux 2.3.99 drivers/block/raid5.c */
static struct buffer_head *
get_free_buffer(struct stripe_head * sh,
                int b_size) {
  struct buffer_head *bh;
  unsigned long flags;
  save_flags(flags);
  cli(); // disables interrupts
  if ((bh = sh->buffer_pool) == NULL)
    return NULL;
  sh->buffer_pool = bh -> b_next;
  bh->b_size = b_size;
  restore_flags(flags); // re-enables interrupts
  return bh;
}
```

ERROR: function returns with interrupts disabled!

Example from Engler et al., *Checking system rules Using System-Specific, Programmer-Written Compiler Extensions*, OSDI '000

Could you have found it?

- How often would that bug trigger?
- What happens if you return from a driver with interrupts disabled?
- Consider: that's one function
  - …in a 2000 LOC file
  - …in a module with 60,000 LOC
  - …IN THE LINUX KERNEL
- **Moral:** *Some defects are very difficult to find via testing, inspection.*

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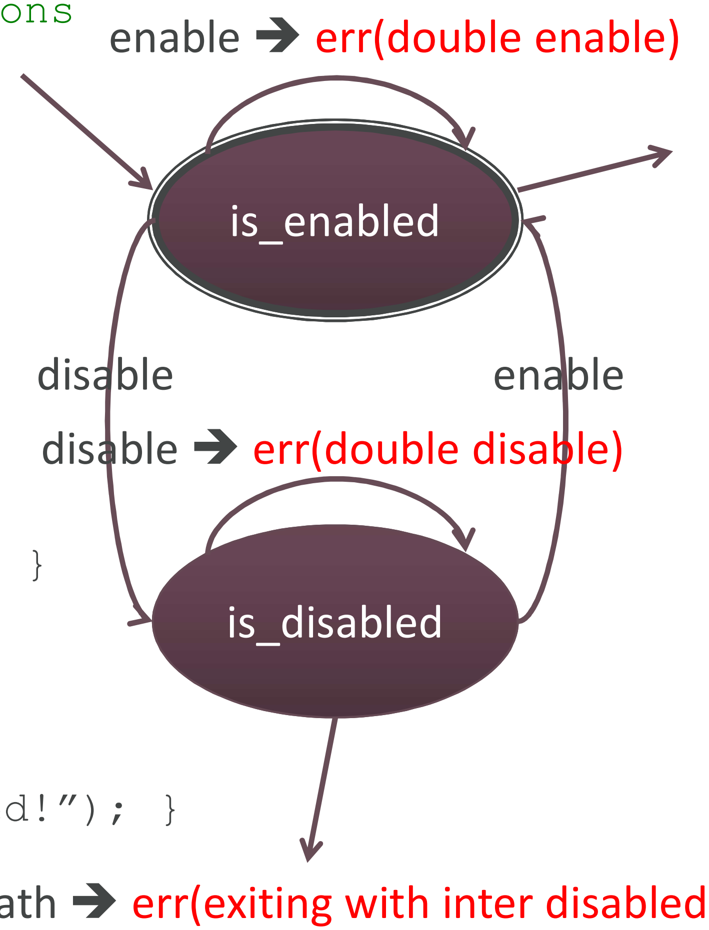
```
sm check_interrupts {
// variables; used in patterns
decl { unsigned } flags;
// patterns specify enable/disable functions
pat enable = { sti() ; }
           | { restore_flags(flags); } ;
pat disable = { cli() ; }
//states; first state is initial
is_enabled : disable ➔ is_disabled
    | enable ➔ { err("double enable"); }
;
is_disabled : enable ➔ is_enabled
    | disable ➔ { err("double disable"); }
//special pattern that matches when
// end of path is reached in this state
    | $end_of_path$ ➔
        { err("exiting with inter disabled!"); }
;
}
```



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Initial state: is_enabled

Example from Engler et al., *Checking system rules Using System-Specific, Programmer-Written Compiler Extensions*, OSDI '000

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```

Transition to: is_disabled

Example from Engler et al., *Checking system rules Using System-Specific, Programmer-Written Compiler Extensions*, OSDI '000

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Final state: is_disabled

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Final state: is_enabled

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Defects of interest…

- Are on uncommon execution paths.
  - Hard to exercise when testing.
- Executing (or analyzing) all paths is infeasible
- **Want to check the entire possible state space of the program**
  - **Usually abstractly**

Defects *Static* Analysis can Catch

- **Defects that result from inconsistently following simple, mechanical design rules.**
  - **Security:** Buffer overruns, improperly validated input.
  - **Memory safety:** Null dereference, uninitialized data.
  - **Resource leaks:** Memory, OS resources.
  - **API Protocols:** Device drivers; real time libraries; GUI frameworks.
  - **Exceptions:** Arithmetic/library/user-defined
  - **Encapsulation:** Accessing internal data, calling private functions.
  - **Data races:** Two threads access the same data without synchronization

Key: check compliance to simple, mechanical design rules

Definition: software analysis

The systematic examination of a software artifact to determine its properties.

Principal techniques

- **Dynamic:**
  - **Testing:** Direct execution of code on test data in a controlled environment.
  - **Analysis:** Tools extracting data from test runs.
- **Static:**
  - **Inspection:** Human evaluation of code, design documents (specs and models), modifications.
  - **Analysis:** Tools reasoning about the program without executing it.

Fundamental concepts

- **Abstraction.**
  - Elide details of a specific implementation.
  - Capture semantically relevant details; ignore the rest.
- **The importance of *semantics*.**
  - We prove things about analyses with respect to the semantics of the underlying language.
- **Implementation**
  - You do not understand analysis until you have written several.

The Bad News: Rice's Theorem

"Any nontrivial property about the language recognized by a Turing machine is undecidable."

Henry Gordon Rice, 1953

OK, so?

- If you could infallibly statically tell if any program had a non-trivial property (never dereferences null, always releases all file handles, etc, etc), you could also solve the halting problem.
- …but the halting problem is *definitely* impossible.
- So: no static analysis is perfect. They will always have false positives or false negatives (or both), or will not provably terminate.

Proof by contradiction (sketch)

Assume that you have a function that can determine if a program *p* has some nontrivial property (like `divides_by_zero`):

```
int silly(program p, input i) {
  p(i);
  return 5/0;
}
bool halts(program p, input i) {
 return divides_by_zero(`silly(p,i)`);
}
```

	Error exists	No error exists
Error Reported	True positive (correct analysis result)	False positive
No Error Reported	False negative	True negative (correct analysis result)

Sound Analysis:

reports all defects
-> no false negatives
typically overapproximated

Complete Analysis:

every reported defect is an actual defect
-> no false positives
typically underapproximated

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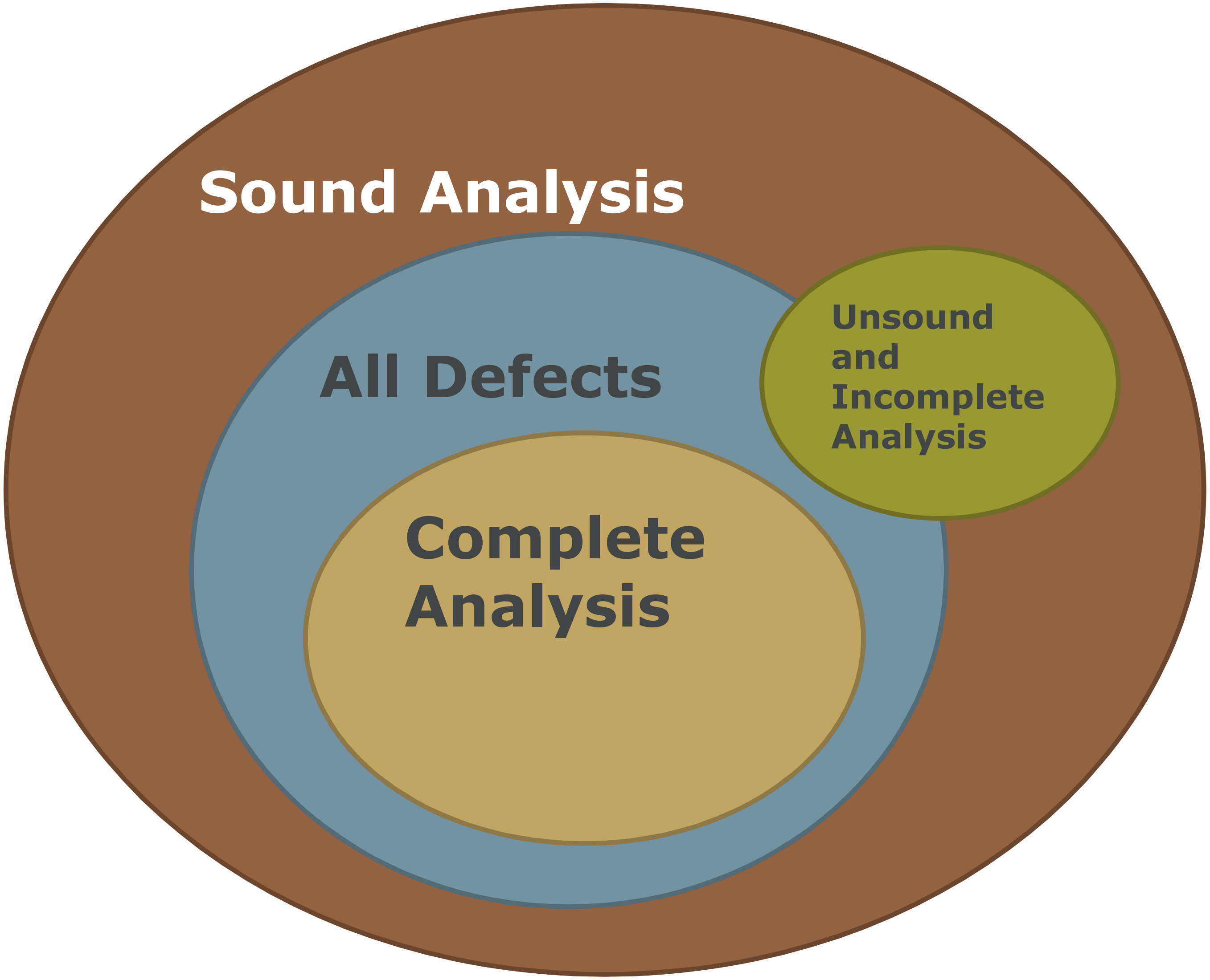
Sound Analysis
All Defects
Complete
Analysis
Unsound
and
Incomplete
Analysis

HOW THE CLASS WILL WORK

Course Topics

Dataflow Analysis

- Program representation
- Semantics
- Abstract interpretation
- Example analyses
- Termination, complexity
- Widening, collecting
- Interprocedural analysis
- Pointer analysis
- Control flow analysis

Extensions and Applications *(potential)*

- Hoare logic
- Model checking
- SAT/SMT solvers
- Symbolic execution
- Dynamic analysis
- Test generation
- Program synthesis
- Program repair
- Gradual types

Language definitions

- Concrete syntax: The rules by which programs can be expressed as strings of characters.
  - Use finite automata and context-free grammars, automatic lexer/parser generators
- Abstract syntax: a subset of the parse tree of the program.

WHILE abstract syntax

Concrete syntax would be similar, but would add things like (parentheses) for disambiguation during parsing

- Categories:
  - *S*∈ **Stmt** statements
  - *a*∈ **Aexp** arithmetic expressions
  - *x, y* ∈ **Var** variables
  - *n*∈ **Num** number literals
  - *P* ∈ **BExp** boolean predicates
  - l ∈ **labels** statement addresses (line numbers)
- Syntax:
  - S ::= x := a | skip | S_1 ; S_2
    | if P then S_1 else S_2 | while P do S
  - a ::= x | n | a_1 op_a a_2
  - op_a ::= + | - | * | / | …
  - P ::= true | false | not P | P_1 op_b P_2 | $a1$ op_r $a2$
  - op_b ::= and | or | …
  - op_r ::= < | ≤ | = | > | ≥ | ...

Example WHILE program

```
y := x;
z := 1;
while y > 1 do
   z := z * y;
   y := y - 1
```

Exercise (class): Building an AST

```
y := x;
z := 1;
while y > 1 do
  z := z * y;
  y := y - 1
```

Exercise: Building an AST for C code

```
void copy_bytes(char dest[], char source[], int n)
{
        for (int i = 0; i < n; ++i)
                dest[i] = source[i];
}
```

WHILE3ADDR: An Intermediate Representaiton

- Simpler, more uniform than WHILE syntax
- Categories:
  - I ∈ **Instruction** instructions
  - x, y ∈ **Var** variables
  - n ∈ **Num** number literals
- Syntax:
  - I ::= x := n | x := y | x := y op z
    | goto n | if x op_r 0 goto n
  - op_a ::= + | - | * | / | …
  - op_r ::= < | ≤ | = | > | ≥ | ...
  - P ∈ **Num** → I

Exercise: Translating to WHILE3ADDR

- Categories:
  - $I \in$ **Instruction** instructions
  - $x, y \in$ **Var** variables
  - $n \in$ **Num** number literals

- Syntax:
  - I ::= x := n | x := y | x := y op z
    | goto n | if x op_r 0 goto n
  - op_a ::= + | - | * | / | …
  - op_r ::= < | ≤ | = | > | ≥ | ...
  - P ∈ **Num** → I

WHILE3ADDR Extensions (more later)

- Syntax:
  - I ::= x := n | x := y | x := y op z
    | goto n | if x op_r 0 goto n
    | x := $f(y)$
    | return x
    | x := $y.m(z)$
    | x := $\&p$
    | x := $*p$
    | $*p$:= x
    | x := $y.f$
    | $x.f$:= y

Syntactic Analysis

- Walks a program representation, searching for errors
  - Example: bad shift analysis

```
For each instruction I in the program
  if I is a shift instruction
     if (type of I's left operand is int
          && I's right operand is a constant
          && value of constant < 0 or > 31)
        warn("Shifting by less than 0 or more
              than 31 is meaningless")
```

Practice: String concatenation in a loop

- Write pseudocode for a simple syntactic analysis that warns when string concatenation occurs in a loop
  - In Java and .NET it is more efficient to use a StringBuffer
  - Assume any appropriate AST elements

For next time

- Get on Piazza and Canvas
- Read our lecture notes and the course syllabus