

# 15-819: Program Analysis

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## Introduction to Program Analysis

Jonathan Aldrich

# Find the Bug!

---

Source: Engler et al., *Checking System Rules Using System-Specific, Programmer-Written Compiler Extensions*, OSDI '00.

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static struct buffer_head *
get_free_buffer(struct stripe_head *sh,
                int b_size) {
    struct buffer_head *bh;
    unsigned long flags;

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    cli();
    if ((bh = sh->buffer_pool) == NULL)
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disable interrupts

re-enable interrupts

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disable interrupts

**ERROR: returning with interrupts disabled**

re-enable interrupts

# Metal Interrupt Analysis

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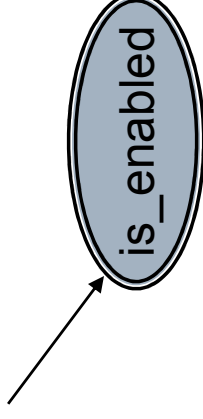
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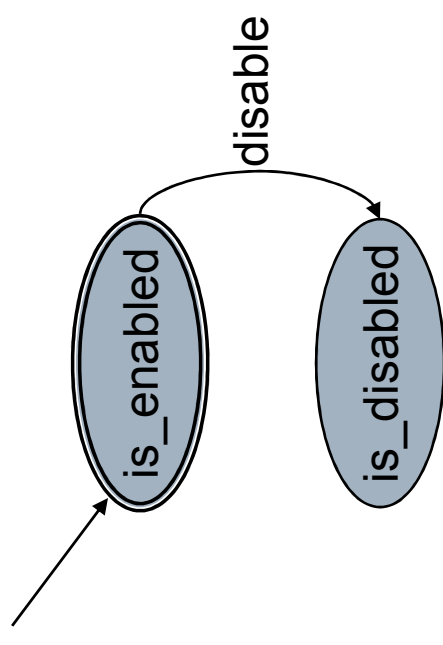
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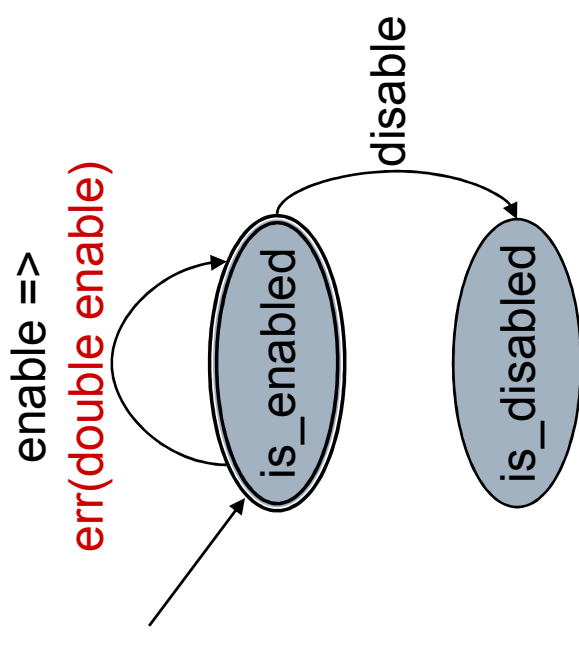
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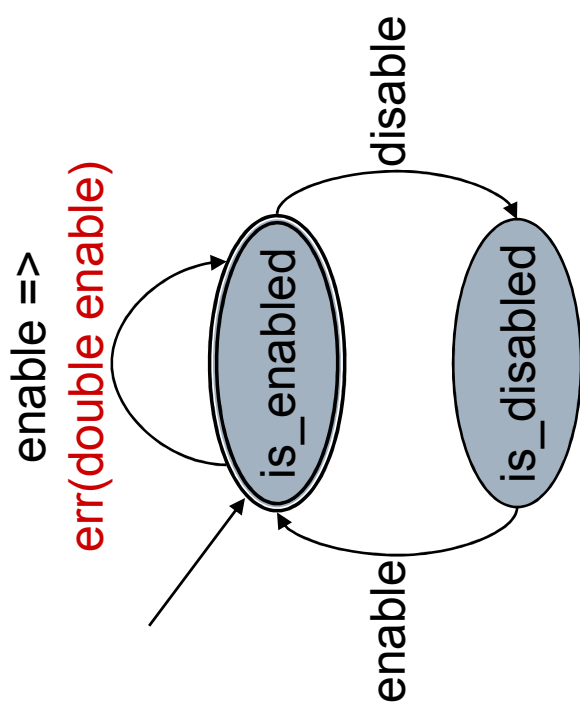
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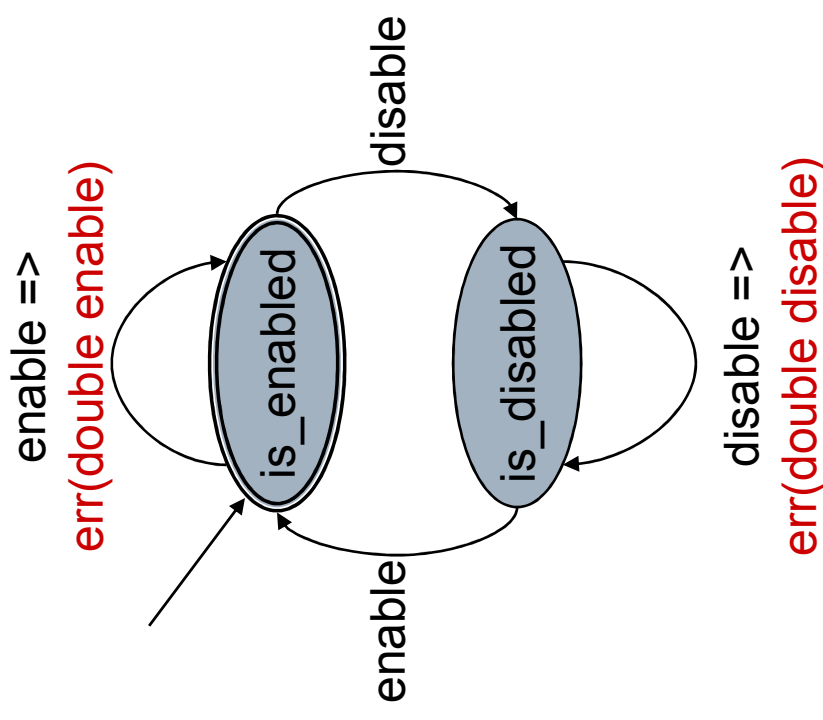
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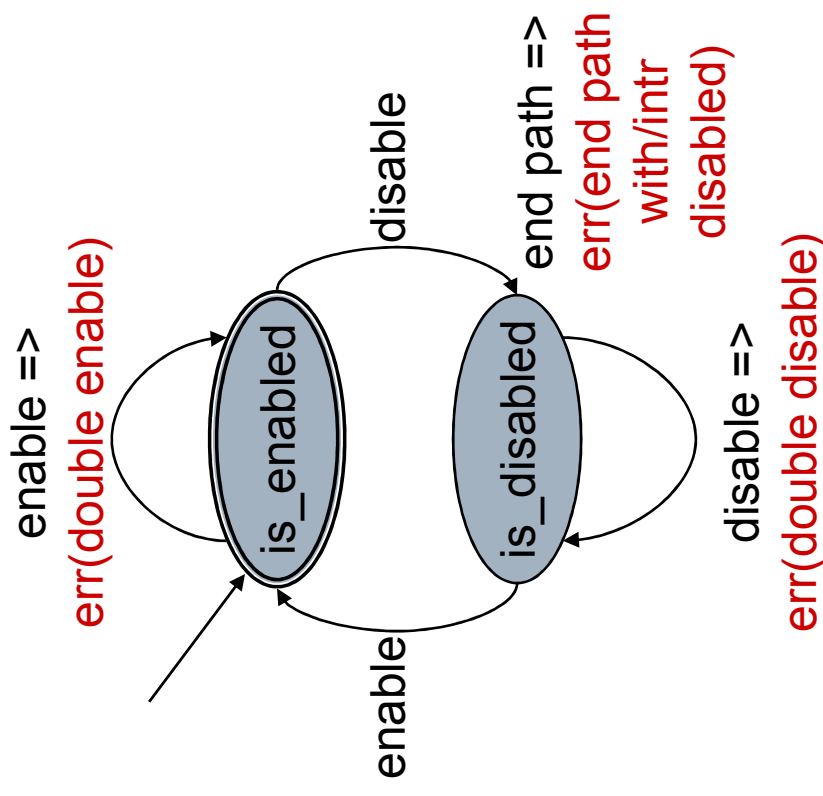
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    sh->buffer_pool = bh->b_next;
    bh->b_size = b_size;
    restore_flags(flags); ← transition to is_enabled
    return bh; ← final state is_enabled is OK
}
```

# Outline

---

- **Why static analysis?**
  - **The limits of testing and inspection**
- **What is static analysis?**
- **Course Outline**
- **Representing programs**
- **AST-walking analyses**

A problem has been detected and windows has been shut down to prevent damage to your computer.

The problem seems to be caused by the following file: SPCMDCON.SYS

PAGE\_FAULT\_IN\_NONPAGED\_AREA

If this is the first time you've seen this stop error screen, restart your computer. If this screen appears again, follow these steps:

Check to make sure any new hardware or software is properly installed. If this is a new installation, ask your hardware or software manufacturer for any windows updates you might need.

If problems continue, disable or remove any newly installed hardware or software. Disable BIOS memory options such as caching or shadowing. If you need to use Safe Mode to remove or disable components, restart your computer, press F8 to select Advanced Startup Options, and then select Safe Mode.

Technical information:

\*\*\* STOP: 0x00000050 (0xFD3094C2, 0x00000001, 0xFBFE7617, 0x00000000)

\*\*\* SPCMDCON.SYS - Address FBFE7617 base at FBFE5000, Datestamp 3d6ddd67c

# Static Analysis Finds “Mechanical” Errors

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- Defects that result from inconsistently following simple, mechanical design rules
- Security vulnerabilities
  - Buffer overruns, unvalidated input...
- Memory errors
  - Null dereference, uninitialized data...
- Resource leaks
  - Memory, OS resources...
- Violations of API or framework rules
  - e.g. Windows device drivers; real time libraries; GUI frameworks
- Exceptions
  - Arithmetic/library/user-defined
- Encapsulation violations
  - Accessing internal data, calling private functions...
- Race conditions
  - Two threads access the same data without synchronization

# Difficult to Find with Testing, Inspection

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- **Non-local, uncommon paths**
  - Security vulnerabilities
  - Memory errors
  - Resource leaks
  - Violations of API or framework rules
  - Exceptions
  - Encapsulation violations
- **Non-deterministic**
  - Race conditions

# Quality Assurance at Microsoft (Part 1)

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- Original process: manual code inspection
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- Early 1990s: add massive system and unit testing
  - Tests took weeks to run
    - Diversity of platforms and configurations
    - Sheer volume of tests
  - Inefficient detection of common patterns, security holes
    - Non-local, intermittent, uncommon path bugs
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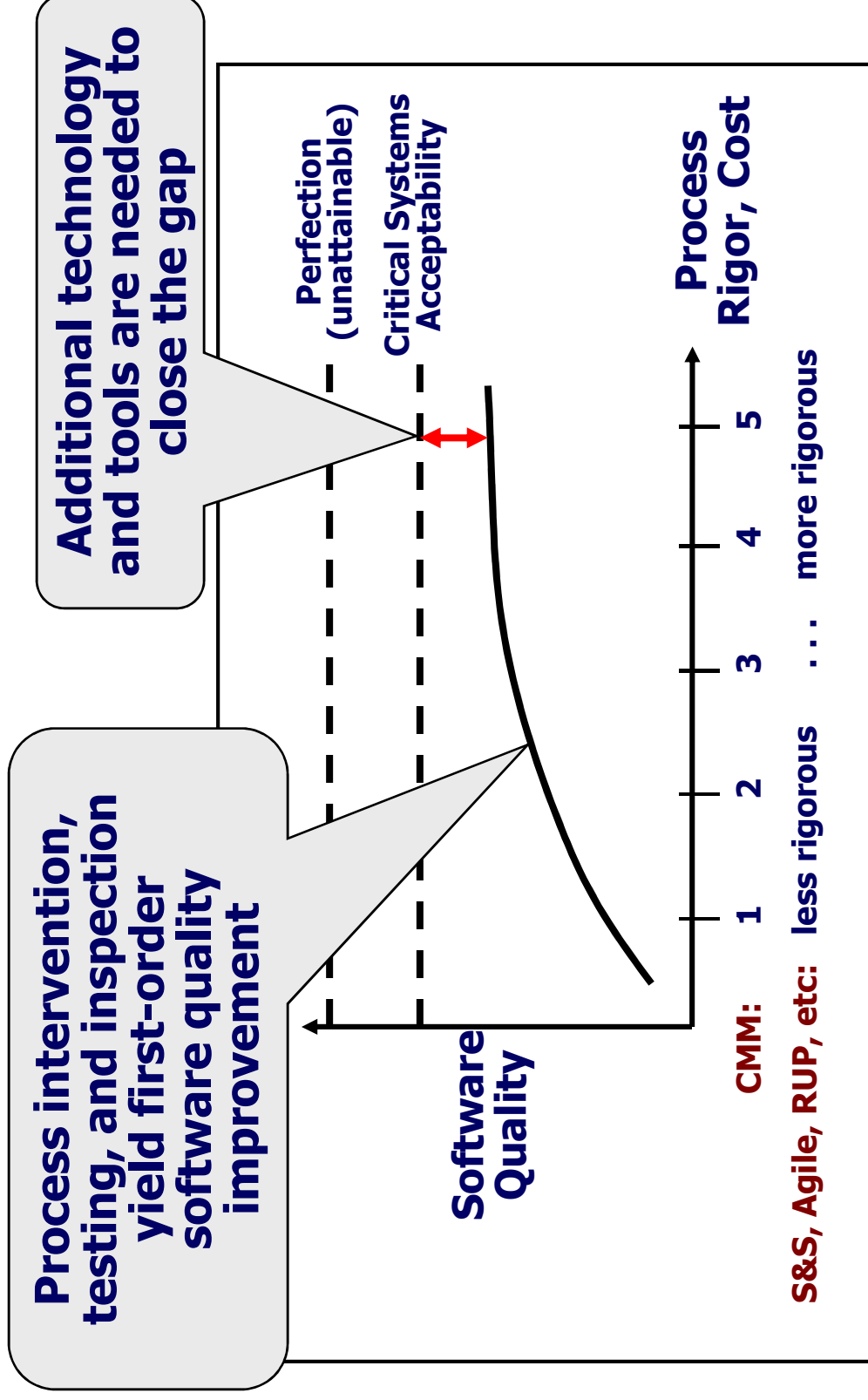
# Quality Assurance at Microsoft (Part 1)

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  - Was treading water in Windows Vista development
- Early 2000s: add static analysis
  - More on this later

# Process, Cost, and Quality

Slide: William Scherlis



# Outline

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- Why static analysis?
- **What is static analysis?**
  - **Abstract state space exploration**
- Course Outline
- Representing programs
- AST-walking analyses

# Static Program Analysis Definition

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- Metal interrupt analysis
  - Abstraction
    - 2 states: enabled and disabled
    - All program information—variable values, heap contents—is abstracted by these two states, plus the program counter

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- Metal interrupt analysis
  - Abstraction
    - 2 states: enabled and disabled
    - All program information—variable values, heap contents—is abstracted by these two states, plus the program counter
  - Systematic
    - Examines all paths through a function
      - What about loops? More later...
    - Each path explored for each reachable state
    - Assume interrupts initially enabled (Linux practice)
    - Since the two states abstract all program information, the exploration is exhaustive

# Static Program Analysis Definition

---

- Static program analysis is the automated, systematic examination of an abstraction of a program's state space
- Mathematical properties (**recurring theme**)
  - Soundness
    - All reported results are true
      - Verification: analysis says OK → correctness property holds
      - Bug-finding: analysis says there is a bug → some (or all) real executions manifest that bug
  - Completeness
    - Everything that is true is reported
      - Verification: the program is correct → the analysis will say so
      - Bug-finding: some execution manifests a bug → the analysis will report it

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- Why static analysis?
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- **Course Outline**
- Representing programs
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- Course Outline
- **Representing programs**
- **AST-walking analyses**

# Representing Programs: The WHILE Language

---

- A simple procedural language with:
  - assignment
  - statement sequencing
  - conditionals
  - while loops
- Used in early papers (e.g. Hoare 69) as a “sandbox” for thinking about program semantics
- We will use it to illustrate several different kinds of analysis

# WHILE Syntax

---

- Categories of syntax
  - $S \in \mathbf{Stmt}$  statements
  - $a \in \mathbf{AExp}$  arithmetic expressions
  - $x, y \in \mathbf{Var}$  variables
  - $n \in \mathbf{Num}$  number literals
  - $P \in \mathbf{BExp}$  boolean expressions
- Syntax
  - $S ::= x := a \mid \text{skip} \mid S_1; S_2 \mid \text{if } P \text{ then } S_1 \text{ else } S_2 \mid \text{while } P \text{ do } S$
  - $a ::= x \mid n \mid a_1 \text{ op}_a a_2$
  - $\text{op}_a ::= + \mid - \mid * \mid / \mid \dots$
  - $P ::= \text{true} \mid \text{false} \mid \text{not } P \mid P_1 \text{ op}_b P_2 \mid a_1 \text{ op}_r a_2$
  - $\text{op}_b ::= \text{and} \mid \text{or} \mid \dots$
  - $\text{op}_r ::= < \mid \leq \mid = \mid > \mid \geq \mid \dots$

# Example WHILE Program

---

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

Computes the factorial function, with the input in  $x$  and the output in  $z$

# Representing Programs

---

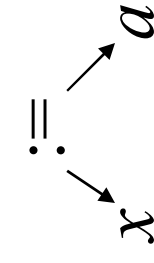
- To analyze software automatically, we must be able to represent it precisely
- Some representations
  - Source code
  - **Abstract syntax trees**
  - Control flow graph
  - Bytecode
  - Assembly code
  - Binary code

# Abstract Syntax Trees

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- A tree representation of source code
- Based on the language grammar
  - One type of node for each production

- $S ::= x := a$  →



- $S ::= \text{while } b \text{ do } S$  →



# Parsing: Source to AST

---

- Parsing process (top down)
  1. Determine the top-level production to use
  2. Create an AST element for that production
  3. Determine what text corresponds to each child of the AST element
  4. Recursively parse each child
- Algorithms have been studied in detail
  - For this course you only need the intuition
  - Details covered in compiler courses

# Parsing Example

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```
y := x;  
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- Top-level production?
- What are the parts?

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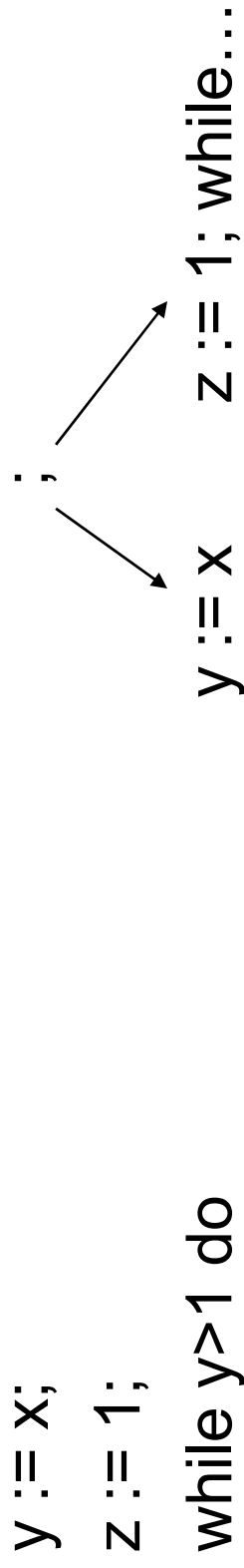
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  ;  
  z := 1; while...
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- Top-level production?
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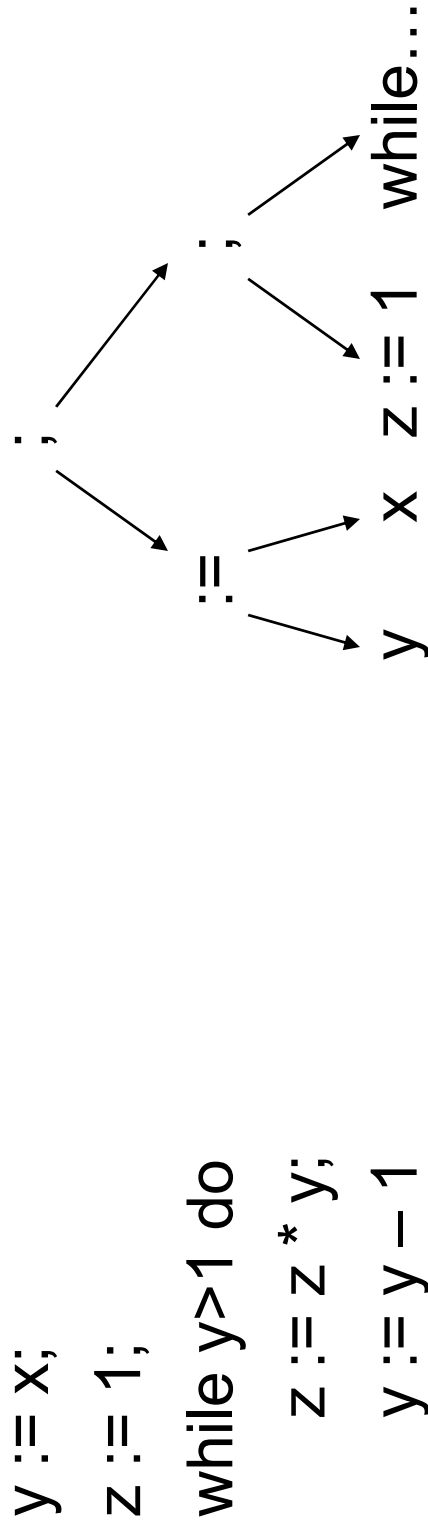
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```
graph TD
    Semicolon1[";"] --> Assign[":="]
    Semicolon1 --> Semicolon2[";"]
    Assign --> Y["y"]
    Assign --> X["x"]
    Assign --> Z["z"]
    Semicolon2 --> While["z := 1; while..."]
```

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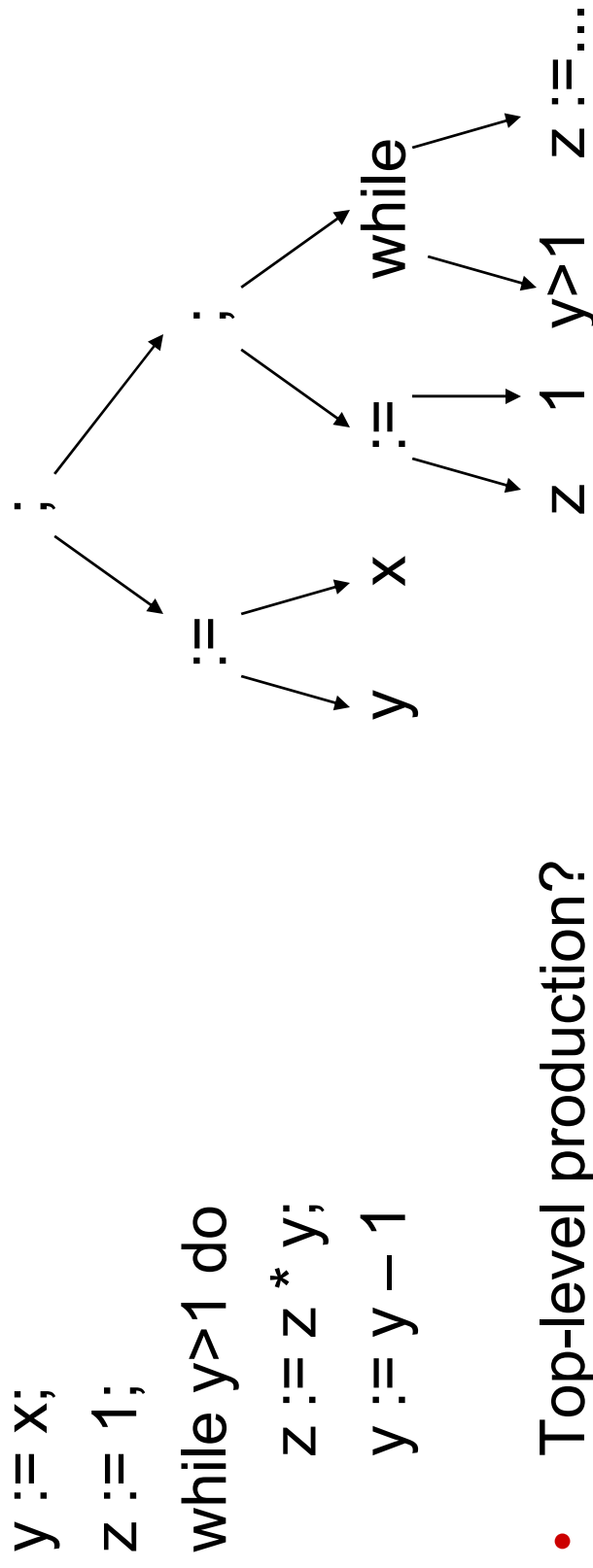


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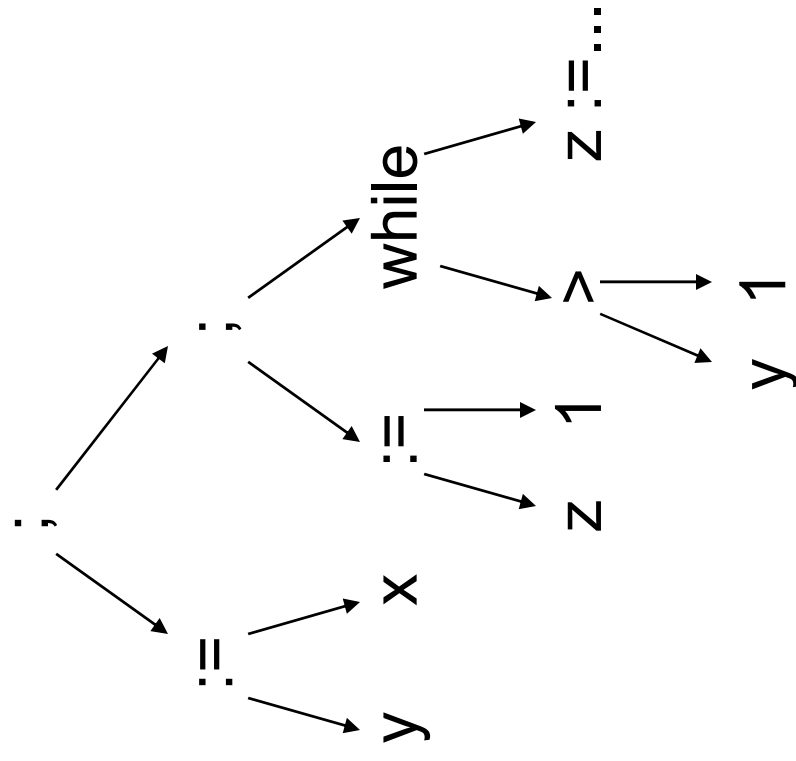
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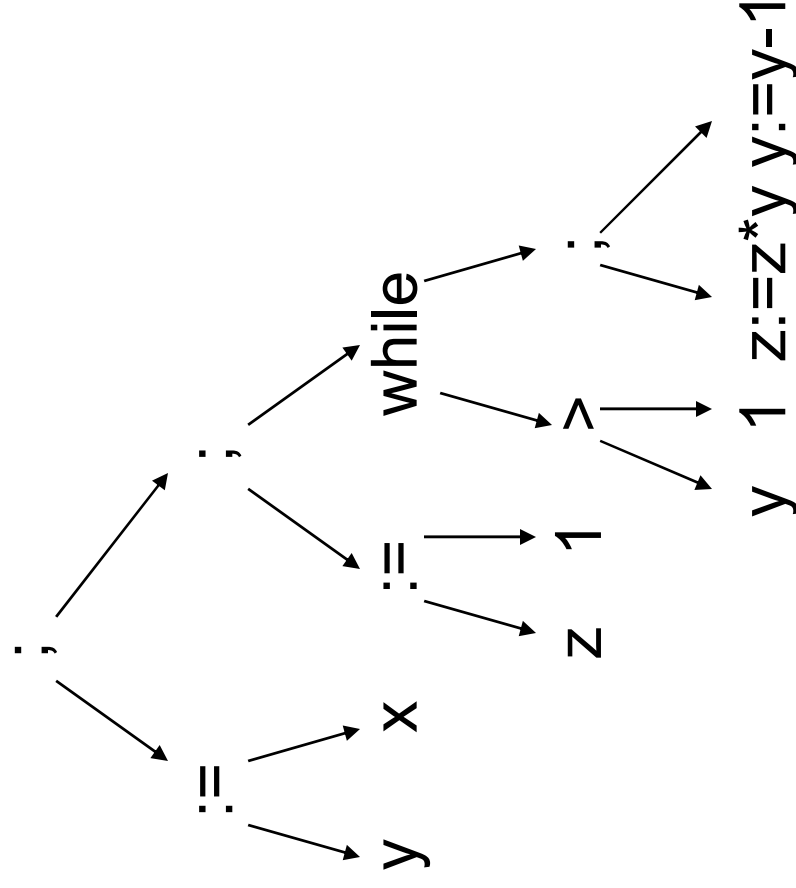
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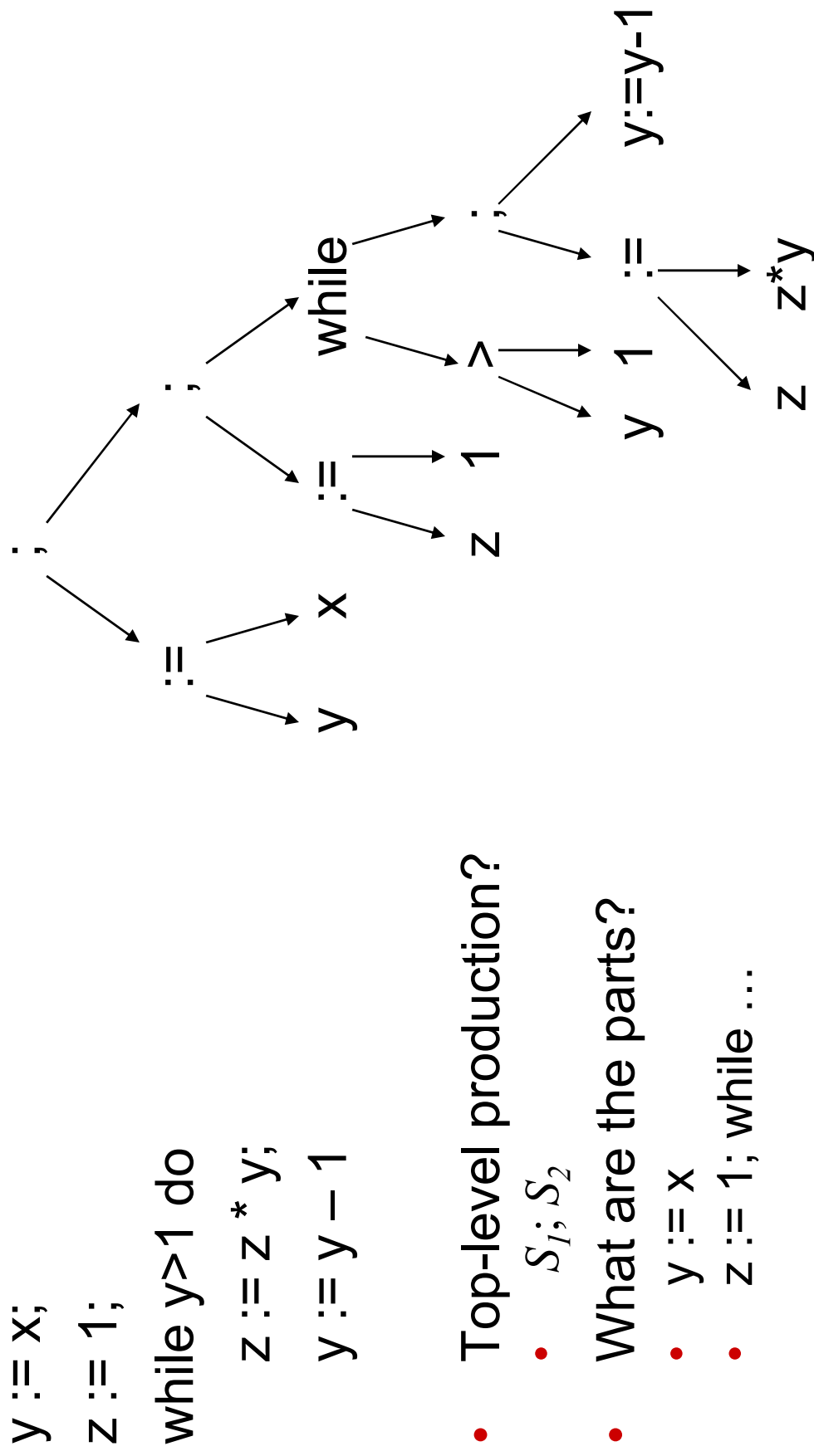
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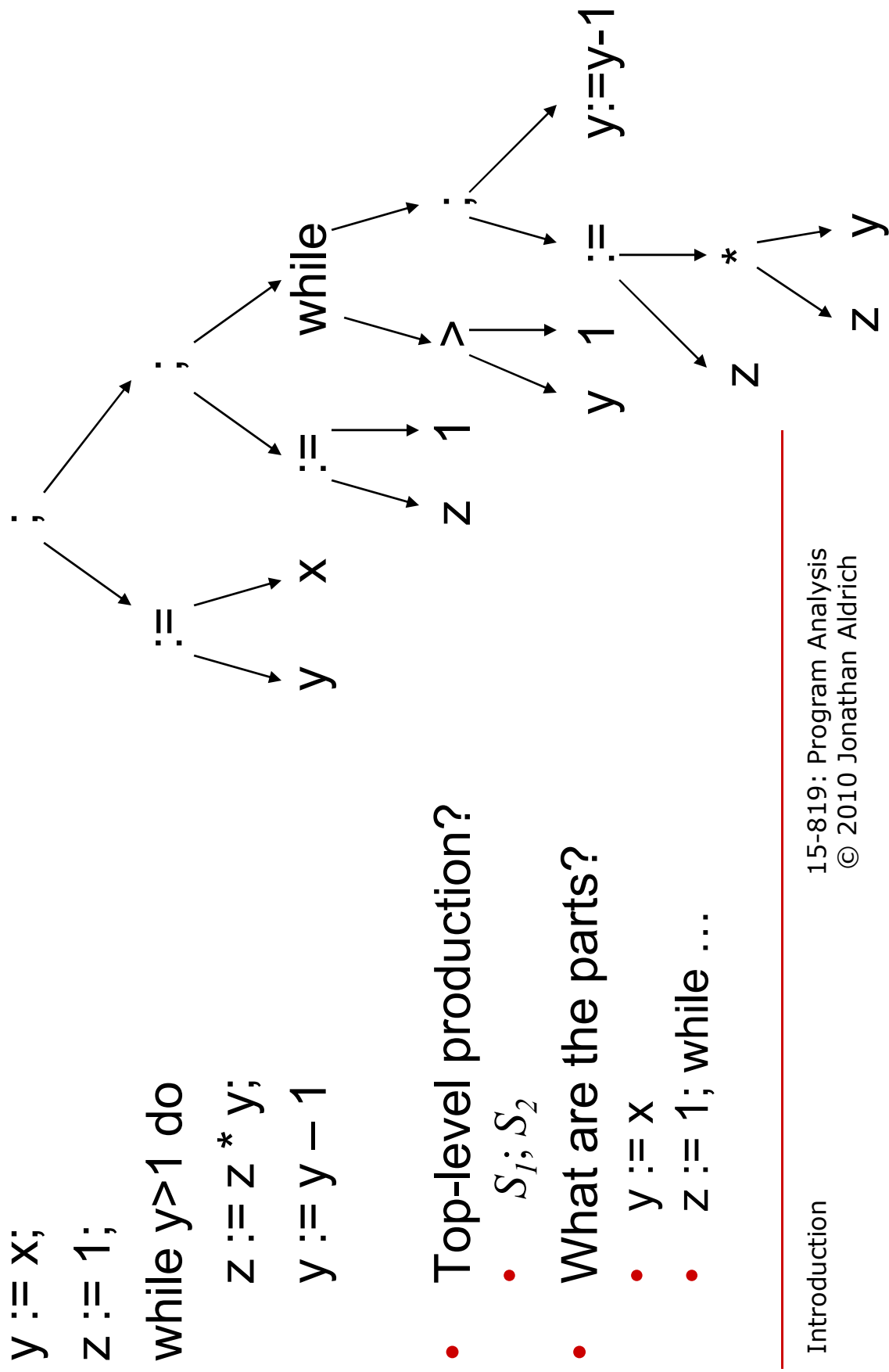
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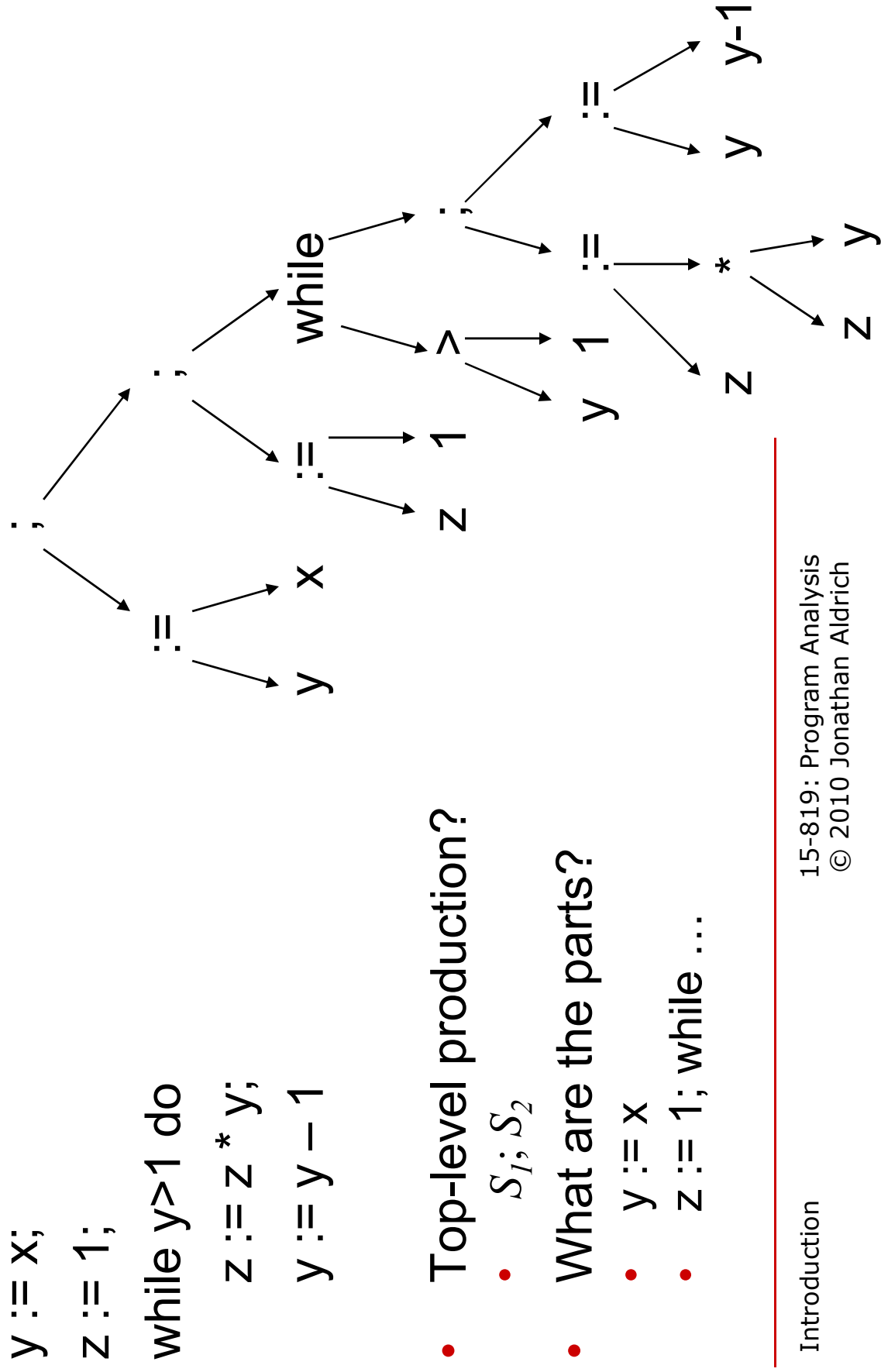
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- Top-level production?
  - $S_1; S_2$
- What are the parts?
  - `y := x`
  - `z := 1; while ...`

# Parsing Example

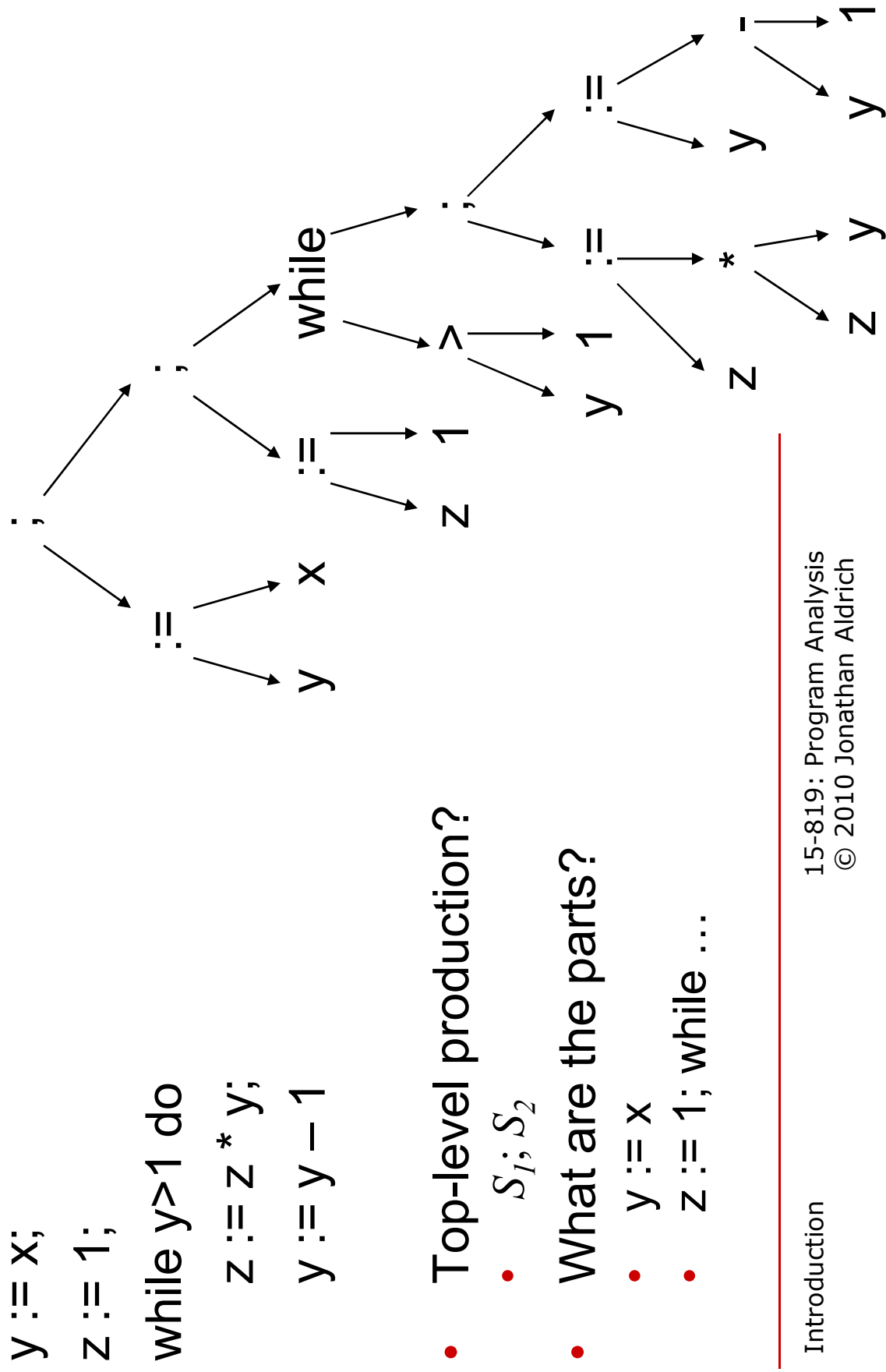
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- Top-level production?
  - $S_1; S_2$
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# Parsing Example

---



- Top-level production?
  - $S_1; S_2$
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  - `y := x`
  - `z := 1; while ...`

# Quick Quiz

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Draw a parse tree for the function below. You can assume that the “for” statement is at the top of the parse tree.

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

# WHILE ASTs in Java

---

- Java data structures mirror grammar

- $S ::= x := a$

```
class AST { ... }
class Stmt extends AST { ... }
class Assign extends Stmt {
    Var var;
    AExpr expr;
}
```

# WHILE ASTs in Java

---

- Java data structures mirror grammar

•  $S ::= x := a$   
| skip

```
class AST { ... }
class Stmt extends AST { ... }
class Assign extends Stmt {
    Var var;
    AExpr expr;
}
class Skip extends Stmt { }
```

# WHILE ASTs in Java

---

- Java data structures mirror grammar

- $S ::= x := a$   
| skip  
|  $S_1; S_2$

```
class AST { ... }
class Stmt extends AST { ... }
class Assign extends Stmt {
    Var var;
    AExpr expr;
}
class Skip extends Stmt {}
class Seq extends Stmt {
    Stmt left;
    Stmt right;
}
```

# WHILE ASTs in Java

---

- Java data structures mirror grammar

- $S ::= x := a$

- | skip

- |  $S_1; S_2$

- | if  $b$  then  $S_1$  else  $S_2$

```
class AST { ... }
class Stmt extends AST { ... }
class Assign extends Stmt {
    Var var;
    AExpr expr;
}
class Skip extends Stmt {}
class Seq extends Stmt {
    Stmt left;
    Stmt right;
}
class If extends Stmt {
    BExpr cond;
    Stmt thenStmt;
    Stmt elseStmt;
}
```

# WHILE ASTs in Java

---

- Java data structures mirror grammar

- $S ::= x := a$

- | skip

- |  $S_1; S_2$

- | if  $b$  then  $S_1$  else  $S_2$

- | while  $b$  do  $S$

```
class AST { ... }
class Stmt extends AST { ... }
class Assign extends Stmt {
    Var var;
    AExpr expr;
}
class Skip extends Stmt {}
class Seq extends Stmt {
    Stmt left;
    Stmt right;
}
class If extends Stmt {
    BExpr cond;
    Stmt thenStmt;
    Stmt elseStmt;
}
class While extends Stmt {
    BExpr cond;
    Stmt body;
}
```

# Outline

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- Why static analysis?
- What is static analysis?
  - Abstract state space exploration
- Course Outline
- Representing programs
- **AST-walking analyses**

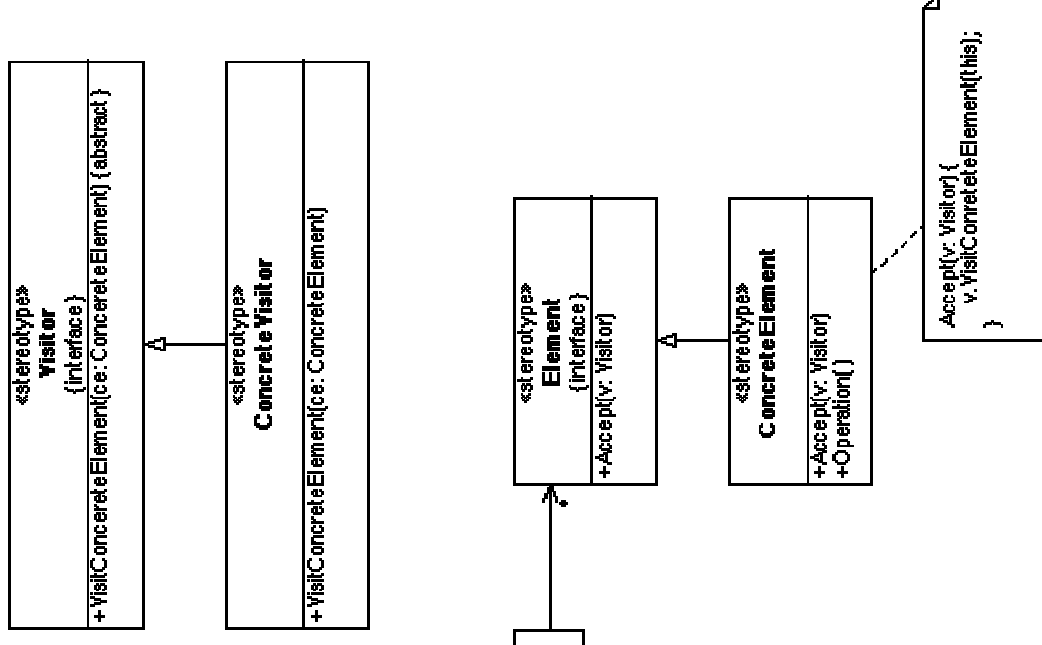
# Matching AST against Bug Patterns

---

- **AST Walker Analysis**
  - Walk the AST, looking for nodes of a particular type
  - Check the immediate neighborhood of the node for a bug pattern
  - Warn if the node matches the pattern
- **Semantic grep**
  - Like grep, looking for simple patterns
  - Unlike grep, consider not just names, but semantic structure of AST
    - Makes the analysis more precise
- **Common architecture based on Visitors**
  - class Visitor has a visitX method for each type of AST node X
  - Default Visitor code just descends the AST, visiting each node
  - To find a bug in AST element of type X, override visitX

# Behavioral Patterns: Visitor

- Applicability
  - Structure with many classes
  - Want to perform operations that depend on classes
  - Set of classes is stable
  - Want to define new operations
- Consequences
  - Easy to add new operations
  - Groups related behavior in Visitor
  - Adding new elements is hard
  - Visitor can store state
  - Elements must expose interface



## Example: Shifting by more than 31 bits

---

```
class BadShiftAnalysis extends Visitor
    visitShiftExpression(ShiftExpression e) {
        if (type of e's left operand is int
            && e's right operand is a constant)
            && value of constant < 0 or > 31)
                warn("Shifting by less than 0 or more than
                    31 is meaningless")
        super.visitShiftExpression(e);
    }
```

# Practice: String concatenation in a loop

---

- Write pseudocode for a simple AST-walker 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

To get you started:

```
class StringConcatLoopAnalysis extends Visitor {  
    void visitStringConcat(StringConcat e) {  
  
    }  
  
}
```

# Practice: String concatenation in a loop

---

```
class StringConcatLoopAnalysis extends Visitor {
    private int loopLevel = 0;

    void visitStringConcat(StringConcat e) {
        if (loopLevel > 0)
            warn("Performance issue: String concatenation in loop (use
                StringBuffer instead)")
            super.visitStringConcat(e);    // visits AST children
        }

    void visitWhile(While e) {
        loopLevel++;
        super.visitWhile(e);             // visits AST children
        loopLevel--;
    }
    // similar for other looping constructs
}
```

# Crystal Static Analysis Infrastructure

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- See other slide deck

# Example Tool: FindBugs

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- Origin: research project at U. Maryland
  - Now freely available as open source
  - Standalone tool, plugins for Eclipse, etc.
- Checks over 250 “bug patterns”
  - Over 100 correctness bugs
  - Many style issues as well
  - Includes the two examples just shown
- Focus on simple, local checks
  - Similar to the patterns we’ve seen
  - But checks bytecode, not AST
    - Harder to write, but more efficient and doesn’t require source
- <http://findbugs.sourceforge.net/>

# Example FindBugs Bug Patterns

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- Correct equals()
- Use of ==
- Closing streams
- Illegal casts
- Null pointer dereference
- Infinite loops
- Encapsulation problems
- Inconsistent synchronization
- Inefficient String use
- Dead store to variable

# FindBugs Experiences

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- Useful for learning idioms of Java
  - Rules about libraries and interfaces
    - e.g. equals()
- Customization is important
  - Many warnings may be irrelevant, others may be important – depends on domain
    - e.g. embedded system vs. web application
- Useful for pointing out things to examine
  - Not all are real defects
  - Turn off false positive warnings for future analyses on codebase