Lecture H:

ASTs, Visitors, & Structural Recursion

CSE401/501m:

Introduction to Compiler Construction

Instructor: Gilbert Bernstein

Administrivia

- HW2 (grammars and LR parsing) due Thursday night, 11:59 pm
- Next project part, parser + AST up soon; due a week from Thursday
  - More details in sections this week, but please start looking at the assignment as soon as I post it, and tinkering then
  - Probably good to finish HW2 first though
  - Then, get the CUP grammar working and cleaned up, before you add actions (the Java code that builds the AST; will cover today)

Outline

The Role of Abstract Syntax Trees

Implementing ASTs

Implementing Passes

The Visitor Pattern

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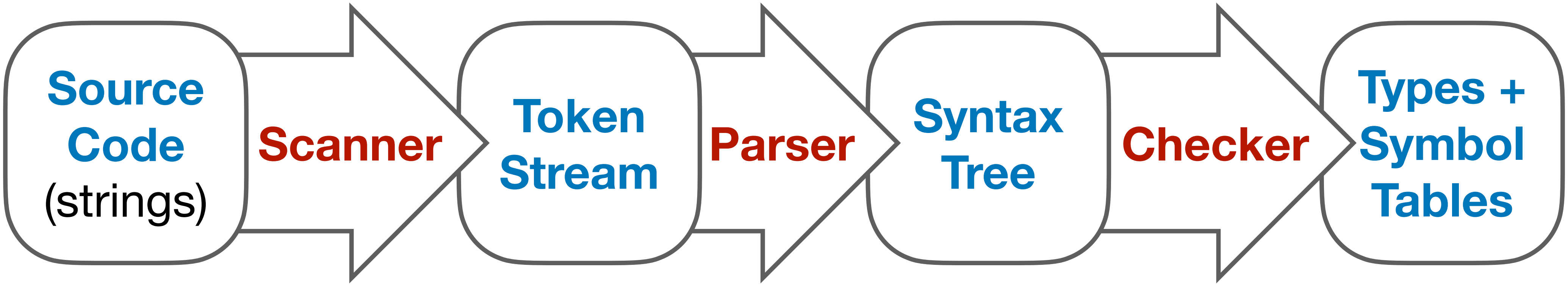
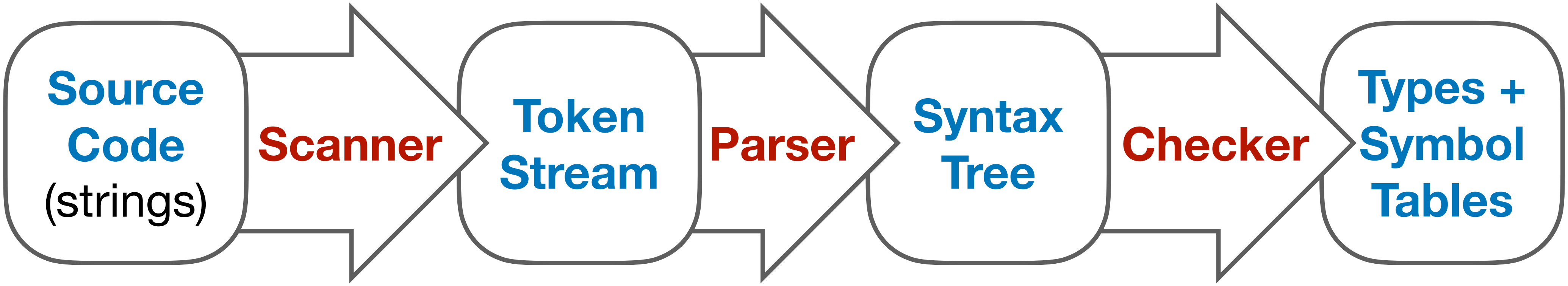
Our Basic Compiler Front-End



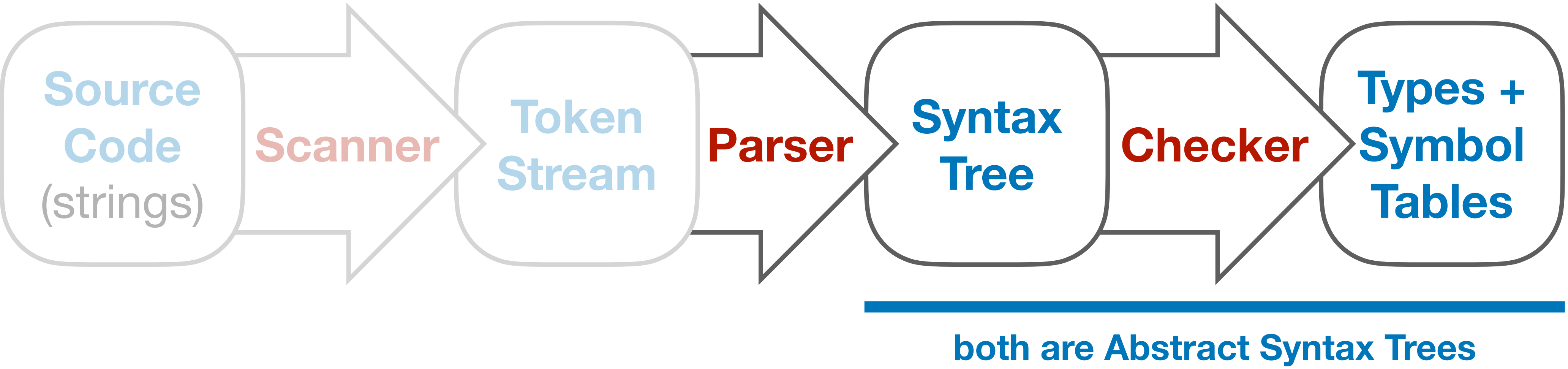
- The software architecture of compilers
  - A sequence of **Intermediate Representations**
  - with **Passes** converting or **lowering** between IRs
- Why? — Separation of concerns
  - Abstraction — Each IR **discards** unnecessary details, while **introducing** a little bit more structure
  - Each pass only worries about these differences

Abstraction in Compilers



- The Scanner
  - **introduces** — token structure on the sequence
  - **discards** — whitespace, comments
- The Parser
  - **introduces** — tree structure to program
  - **discards** — (via AST) delimiters, “syntactic markers”

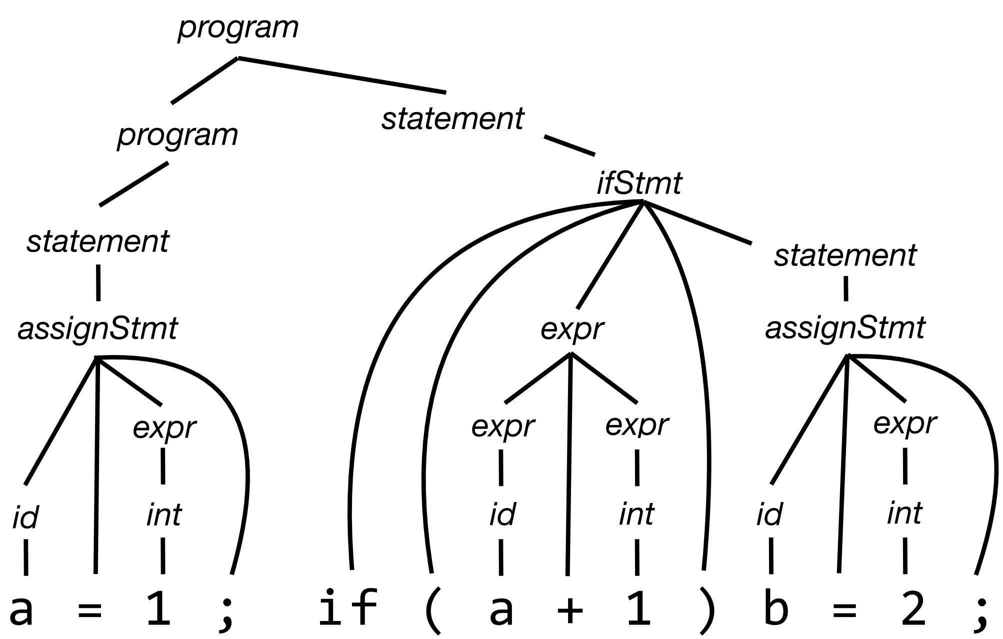
Abstract Syntax Trees (ASTs)



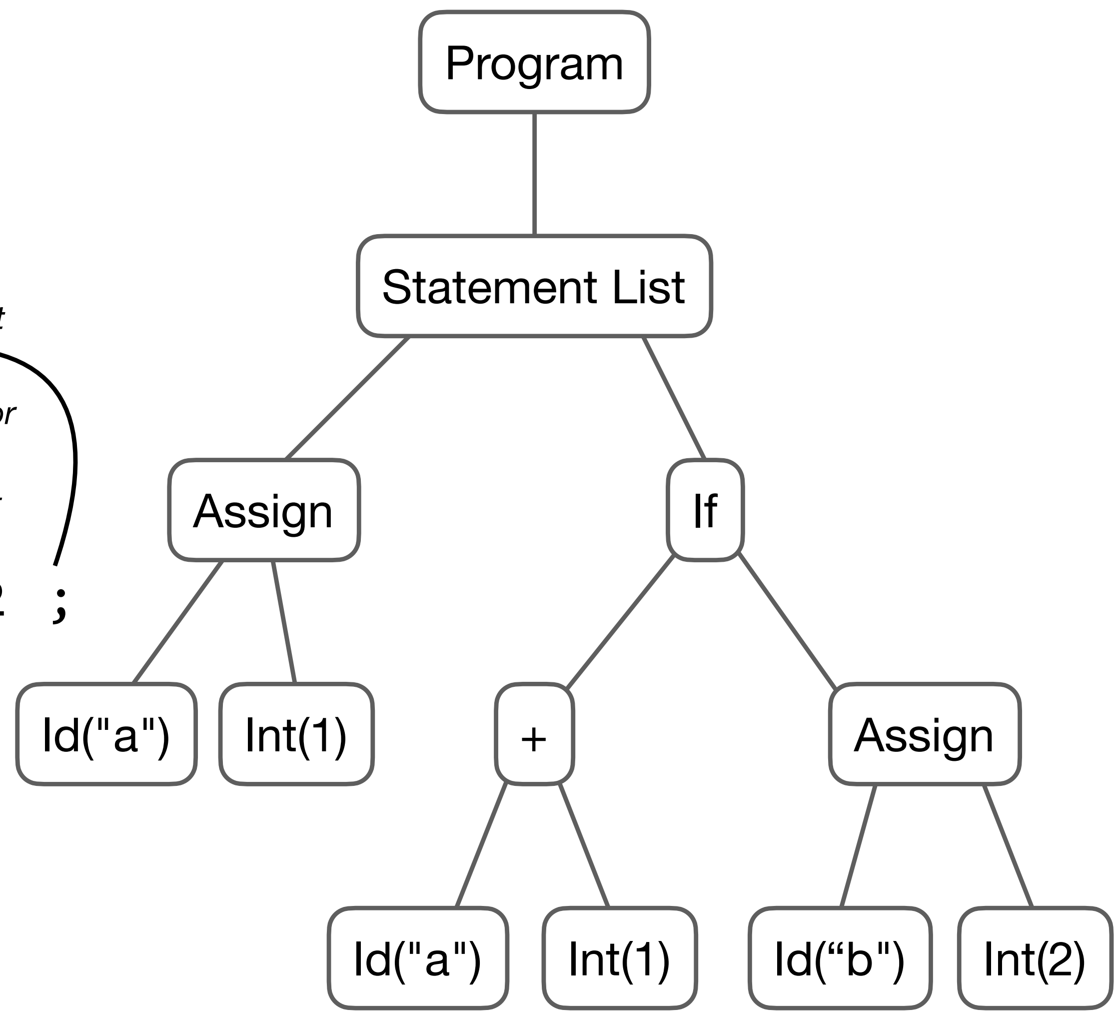
- The grammar describes concrete syntax trees
  - ✦ But we should ***abstract away*** useless details
- Abstract Syntax Trees (ASTs) are the primary IR used by compiler front-ends
  - The checker will both consume and produce ASTs
  - "When you leave ASTs, you've left the front-end"

Parse Tree vs. AST (ex. 1)

Full Parse Tree

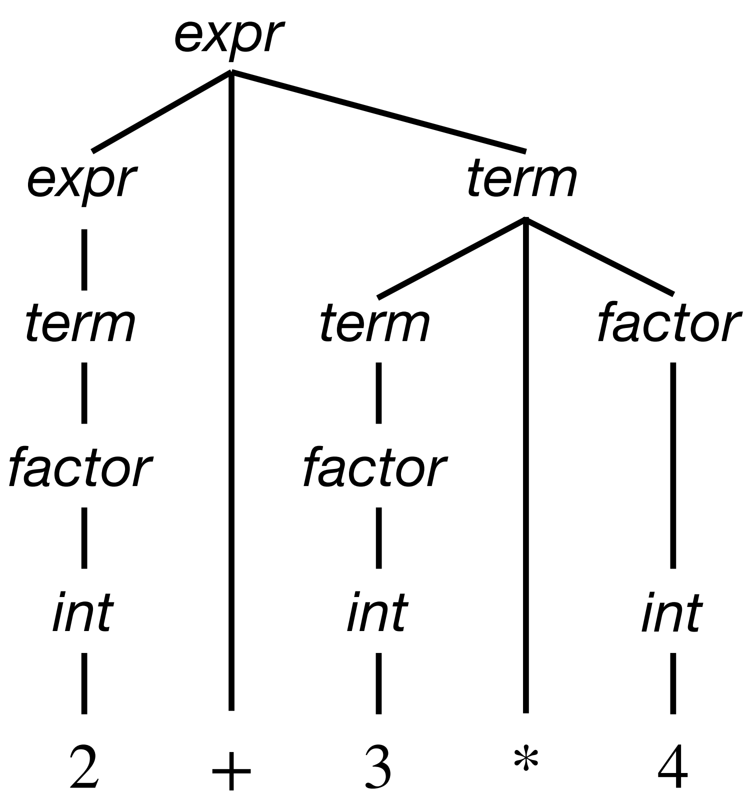


Abstract Syntax (AST)

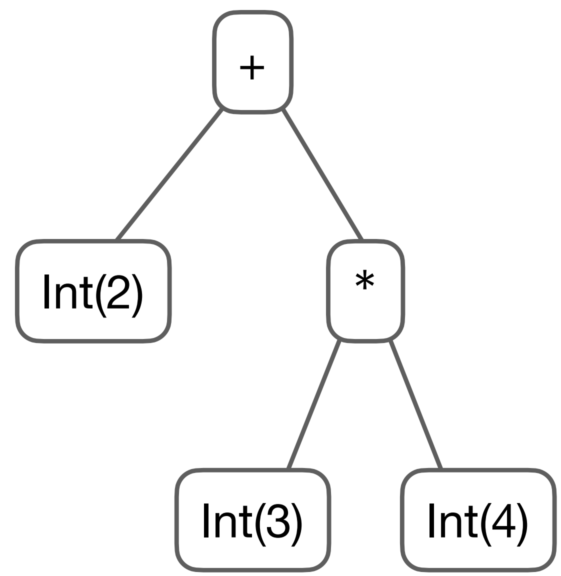


Parse Tree vs. AST (ex. 2)

Full Parse Tree



Abstract Syntax (AST)



Anticipating Checking

- The checking step will filter out programs that are grammatical but still invalid in some way
  - ✦ e.g.

```
public class Foo {
    public int bar(int y) { return x; }
}
```

- But checking will also analyze the program, producing useful information, e.g. types like “y is an integer”
- So, we will want to annotate or **decorate** our ASTs
  - ✦ Should we have different kinds of ASTs?
  - ✦ Should we support not-yet-complete ASTs?

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“Abstract” Grammars*

- Backus-Naur Form (BNF) was invented to specify the concrete syntax of programming languages
- However, many languages/compilers also use BNF to specify the abstract syntax (e.g. CPython, Haskell, WebAssembly)
  - ✦ BNF specification of abstract syntax is ***extremely*** common in research papers or for whiteboard/napkin design of new languages
- Ambiguity, LR, LL, etc. are all *not important* for “abstract grammars.” The purpose is a shorthand for describing an IR (i.e. data structures) not specifying concrete syntax!

***I don’t know of any standard name for this practice, but it is very common**

Example from First Lecture

Classes for Simplified Calculator

```
abstract public class Expr {}

public class Num extends Expr {
    public int i;
    public Num(int v) { i = v; }
}

public class Add extends Expr {
    public Expr e0, e1;

    public Add(Expr a0, Expr a1) {
        e0 = a0;
        e1 = a1;
    }
}
```

"Abstract" BNF

$$
\begin{aligned}
Expr ::= &\ Num\ int \\
\mid &\ Add\ Expr\ Expr
\end{aligned}
$$

"Abstract" BNF (w/names)

$$
\begin{aligned}
Expr ::= &\ Num(int\ i) \\
\mid &\ Add(Expr\ e0, Expr\ e1)
\end{aligned}
$$

***Note: this slide is meant to help you understand the ideas; you will not be tested on it**

Expanded Example

Classes for Simplified Calculator

```
abstract public class Expr {}

public class Num extends Expr {
    public int i;
    public Num(int v) { i = v; }
}

public class Var extends Expr {
    public String s;
    public Var(String v) { s = v; }
}

public class Add extends Expr {
    public Expr e0, e1;

    public Add(Expr a0, Expr a1) {
        e0 = a0;
        e1 = a1;
    }
}

public class Mul extends Expr {
    public Expr e0, e1;

    public Mul(Expr a0, Expr a1) {
        e0 = a0;
        e1 = a1;
    }
}

abstract public class Stmt {}

public class Assign extends Stmt {
    public String lname;
    public Expr rhs;

    public Assign(String nm, Expr r) {
        lname = nm;
        rhs = r;
    }
}
```

```
public class StmtList {
    public List<Stmt> stmts;
    public StmtList(List<Stmt> xs)
    { stmts = xs; }
}

public class IfStmt extends Stmt {
    public Expr cond;
    public StmtList tbody, fbody;

    public IfStmt(Expr c,
                  StmtList t,
                  StmtList f) {
        cond = c;
        tcase = t;
        fcase = f;
    }
}

public class WhileStmt extends Stmt {
    public Expr cond;
    public StmtList body;

    public WhileStmt(Expr c,
                     StmtList b) {
        cond = c;
        body = b;
    }
}
```

“Abstract” BNF

$$
\begin{aligned}
Expr ::= \; & Num(int\ i) \\
\mid \; & Var(String\ s) \\
\mid \; & Add(Expr\ e0, Expr\ e1) \\
\mid \; & Mul(Expr\ e0, Expr\ e1)
\end{aligned}
$$

$$StmtList ::= Stmt^*$$

$$
\begin{aligned}
Stmt ::= \; & Assign(String\ nm, Expr\ rhs) \\
\mid \; & If(Expr\ cond, StmtList\ tbody, \\
& \qquad StmtList\ fbody) \\
\mid \; & While(Expr\ cond, \\
& \qquad StmtList\ body)
\end{aligned}
$$

***Note: this slide is meant to help you understand the ideas; you will not be tested on it**

Translating to Classes (1)

- For each “abstract” non-terminal, create a base class e.g.

```
abstract public class Expr {}
```

- For each “abstract” production, create a sub-class e.g.

```
public class Add extends Expr { … }
```

Translating to Classes (2)

- Simple Refinements on naive strategy
  - Use native lists in the implementation language

```
public class StmtList {
    public List<Stmt> stmts; …
```

  - Derive all nodes from a common ancestor, which keeps track of universal data (e.g. location in original source)

```
abstract public class ASTNode {}
public class Expr extends ASTNode { … }
```

- No need to follow this idea *exactly.* However, systems (including compilers) are easier to build and maintain if they consistently follow simple, boring rules

Decorating ASTs (1)

- Approach 1 — Add fields to AST Nodes (Mega IRs)
  - e.g. change $Var(String\ s)$ to $Var(String\ s, Type\ t)$
  - Pros — Conceptually Simple; smallest change to code; efficient
  - Con — Exposed to all passes using this AST IR;
  - Big Con — Mutating IRs makes code harder to reason about; e.g. which fields are defined or used at different points in the compiler?
  - **primary approach suggested for your project**

Decorating ASTs (2)

- Approach 2 — Create a New IR with extra fields
  - ✦ Same as approach 1, but a separate IR
  - ✦ Pros — IR is **immutable** after being constructed; allows us to ***discard*** fields not used in later passes
  - ✦ Cons — Usually leads to highly duplicative data structure definitions (opportunity for bugs); can lead to compiler inefficiencies (lots of small memory allocations)
  - ✦ Used when implementing compilers with functional languages; also common in teaching & research; production compilers written in imperative languages avoid this approach

Decorating ASTs (3)

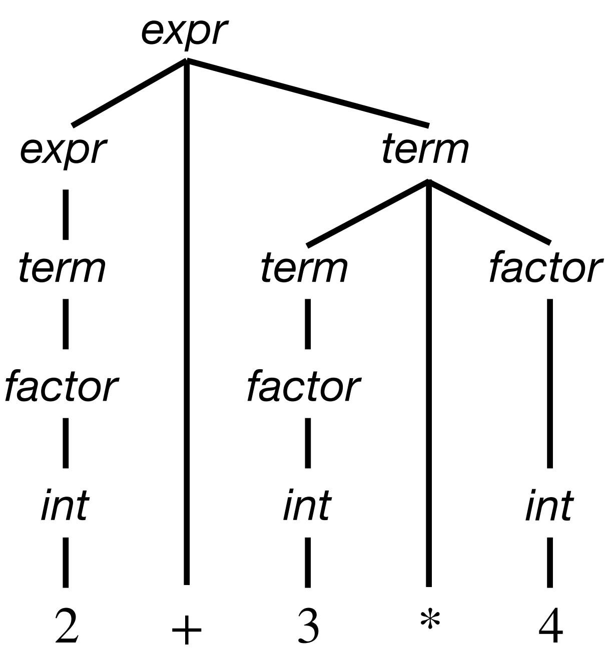
- Approach 3 — Create a map from nodes to data
  - e.g. define an auxiliary `HashMap<Expr, Type> types;`
  - Pros — Does not require redefining a new IR; leaves the base AST immutable; still quite efficient
  - Cons — Requires managing and passing around auxiliary mapping tables; less convenient if *many* passes will use the data (e.g. types are broadly used)
  - This approach can be highly effective if the decorations are **transient** — e.g. one pass **computes** decorations, another pass consumes, and then they are **discarded**

Building ASTs

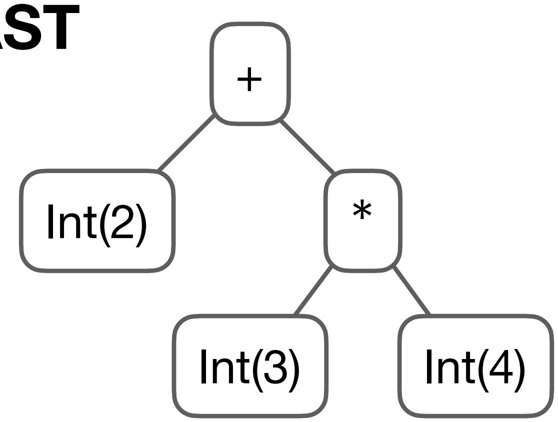
- Underlying idea — define a correspondence between the *concrete parse tree* and the *abstract syntax tree*
  - More specifically, define how to construct the abstract syntax tree *using structural recursion* on the parse tree
- Realization of idea — the parser implicitly traverses the concrete syntax tree in a post-fix traversal
  - At each production $A ::= X_1 \cdots X_n$, a **parser action** takes **intermediate values** for $X_1 \cdots X_n$ as input and produces an **intermediate value** for A
  - for us, **intermediate values** are AST nodes
- More in section and in the Parser project

Example: Building AST

Parse Tree



AST



Grammar	Actions
$expr ::= expr + term$	`{ return new Add(lhs, rhs); }`
$\mid\ expr - term$	`{ return new Sub(lhs, rhs); }`
$\mid\ term$	`{ return arg; }`
$term ::= term * factor$	`{ return new Mul(lhs, rhs); }`
$\mid\ term\ /\ factor$	`{ return new Div(lhs, rhs); }`
$\mid\ factor$	`{ return arg; }`
$factor ::= int$	`{ return arg; }`
$\mid\ (expr)$	`{ return arg; }`
$int ::= 0 \mid 1 \mid 2 \mid 3 \mid 4$	`{ return new Int(0); }`
$\mid\ 5 \mid 6 \mid 7 \mid 8 \mid 9$	…

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Implementing Passes

The Visitor Pattern

Operations on ASTs

- Many different **passes** are defined on ASTs (and other IRs)
  - Print a readable dump of the tree data structure
  - Print a parseable (source-code) version of the tree; aka. "pretty-printing" (the reverse of scanning & parsing)
  - Perform checking, annotate types, & report errors
  - (less common) optimize the AST code directly
  - Generate another IR from the AST
  - Generate assembly code from the AST directly
  - …

Obj-Oriented Approach (1)

- "Good" object-oriented style says we should define an interface for AST Nodes that requires each node to implement each pass

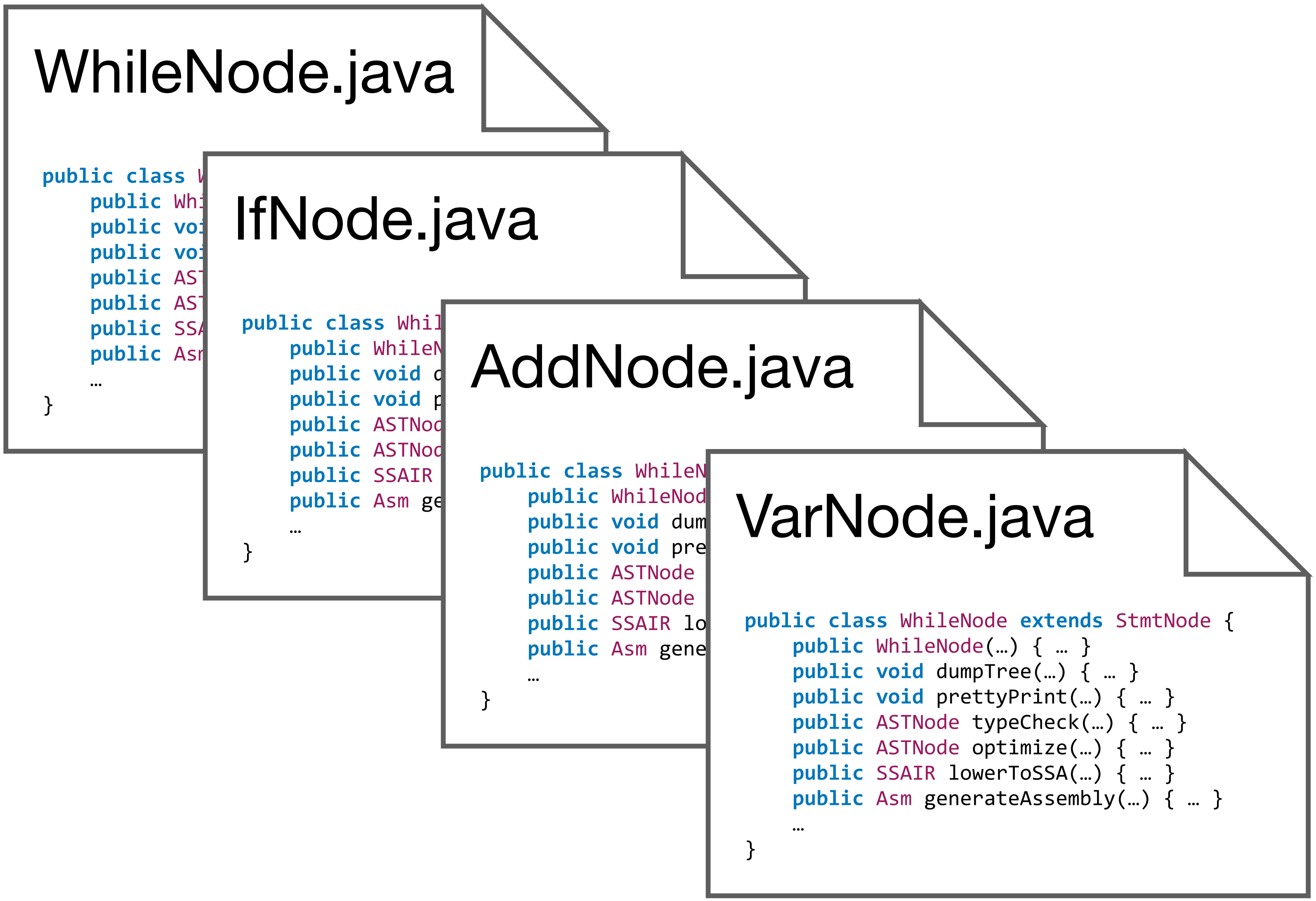
```
abstract public class ASTNode {
  abstract public void dumpTree(…) { … }
  abstract public void prettyPrint(…) { … }
  abstract public ASTNode typeCheck(…) { … }
  abstract public ASTNode optimize(…) { … }
  abstract public SSAIR lowerToSSA(…) { … }
  abstract public Asm generateAssembly(…) {…}
  …
}
```

Obj-Oriented Approach (2)

- Then each kind of AST Node implements this interface. The code for each (NodeClass, Pass) pair is located with the NodeClass

```
public class WhileNode extends StmtNode {
  public WhileNode(…) { … }
  public void dumpTree(…) { … }
  public void prettyPrint(…) { … }
  public ASTNode typeCheck(…) { … }
  public ASTNode optimize(…) { … }
  public SSAIR lowerToSSA(…) { … }
  public Asm generateAssembly(…) { … }
  …
}
```

The Whole System Viewpoint



■ ■ ■

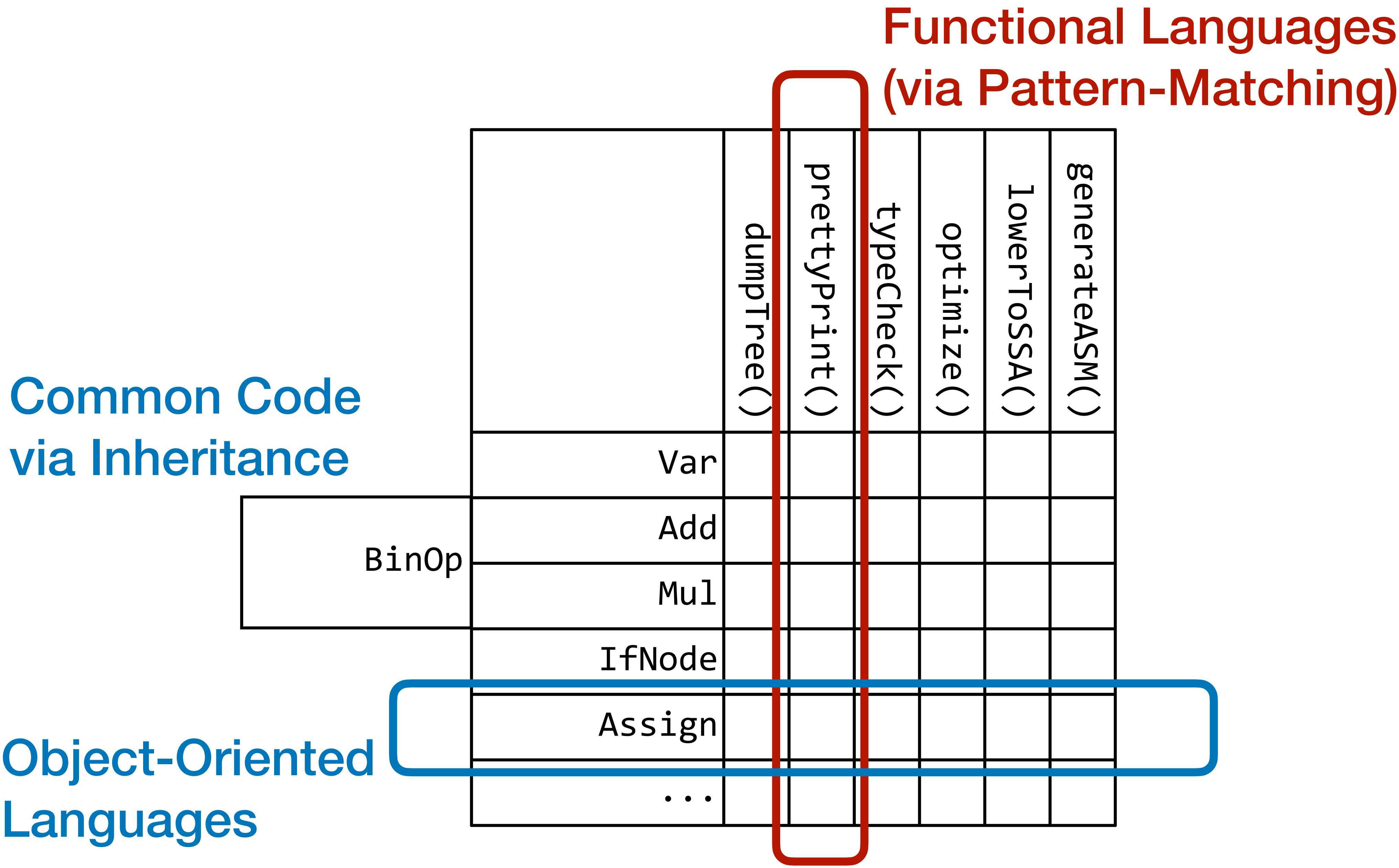
System Design Concepts

- Review of Terms
  - **Locality** (Lexical) — Which parts of the system are close to each other in the source code?
  - **Encapsulation** — Which parts of the system are allowed (via type system) to access which other parts?
  - **Extensibility** & Maintenance — What is required to add X to the system or modify X?

Consequences of This Design

- The object-oriented design enforces **lexical locality** (i.e. which class in which file) according to the AST Nodes, in order to **encapsulate** private data fields
  - but we make data fields public on AST Nodes, so this isn’t necessary
- The object-oriented design makes it easy to **extend** the system with new AST Nodes, or **modify** single existing AST nodes, because of this **lexical** grouping.
- The object-oriented design makes it possible to **factor out** common code by using deeper inheritance hierarchies; e.g. ASTNode → Exp → BinaryOp → Add

The Expression Problem*



* *Originally formulated by Philip Wadler in 1998*

Expression Problem: Tradeoffs

- If code is **grouped lexically by data**, then it is easier to add, modify, and share across different **Classes in the IR**
  - This is the right choice if the set of operations changes less frequently in your system
- If code is **grouped lexically by function**, then it is easier to add, modify, and share across different **Passes**
  - This is the right choice if the set of AST/IR Classes changes less frequently in your system
- **Key conclusion** — The second option is usually the right choice for compilers. Why? …

Many Passes

Compilers have **a lot** of different passes on IRs, and the abstract syntax for a given language doesn't change often

```
targetlibinfo
tti
no-aa
tbaa
scoped-noalias
assumption-
  cache-tracker
basicaa
ipsccp
globalopt
deadargelim
domtree
instcombine
simplifycfg
basiccg
prune-eh
inline-cost
inline
functionattrs
domtree
sroa
early-cse
lazy-value-info
jump-threading
tailcallelim
simplifycfg
reassociate
domtree
loops
loop-simplify
lcssa
loop-rotate
licm
loop-unswitch
instcombine
scalar-evolution
loop-simplify
lcssa
indvars
loop-idiom
loop-deletion
loop-unroll
mldst-motion
domtree
memdep
gvn
memdep
memcpyopt
jump-threading
correlated-
propagation
domtree
memdep
dse
loops
loop-simplify
lcssa
licm
adce
simplifycfg
domtree
instcombine
barrier
float2int
domtree
loops
loop-simplify
lcssa
loop-rotate
branch-prob
block-freq
scalar-evolution
simplifycfg
domtree
instcombine
loops
loop-simplify
lcssa
scalar-evolution
loop-unroll
instcombine
loop-simplify
lcssa
licm
scalar-evolution
alignment-from-
  assumptions
strip-dead-
  prototypes
elim-avail-
  extern
globaldce
constmerge
verify
```

LLVM Optimization Passes using -O2 (first lecture)

The Expression Problem*

How do we achieve this in an Object-Oriented Language?

Functional Languages (via Pattern-Matching)

	dumpTree()	prettyPrint()	typeCheck()	optimize()	lowerToSSA()	generateASM()
Var						
Add						
Mul						
IfNode						
Assign						
...						

Object-Oriented Languages

** Originally formulated by Philip Wadler in 1998*

Simple Structural Recursion (1)

```
public class … {

  public void foo(ASTNode n) {
    if (n instanceof Var) {…}
    else if (n instanceof Add) {…}
    else if (n instanceof Mul) {…}
    else if (n instanceof IfNode) {…}
    else if (n instanceof Assign) {…}
    …
  }
}
```

	dumpTree()	prettyPrint()	typeCheck()	optimize()	lowerToSSA()	generateASM()
Var						
Add						
Mul						
IfNode						
Assign						
...						

- Pro — Simple and Direct
- Con — “missing case” bugs
- Con — no support for “defaults” (needs all cases)

Simple Structural Recursion (2)

- Different traversals can be implemented via recursive calls on sub-trees

```
public class … {
  public void foo(ASTNode n) {
    …
    else if (n instanceof Mul) {
      // do something - pre-order
      foo(n.e0);
      foo(n.e1);
      // do something - post-order
    }
    …
```

- A possible variation — instead of `void`, have the call return something (e.g. a new, modified `ASTNode`)

Pass in a Class

- Where should the structurally recursive function be located?
  - globally? (not in Java!)
  - on the AST Nodes? Which one?
- No! No! This will not do!
- Each operation / pass gets it's own class
  - We create **exactly one** instance of such a "pass class"
  - Helper functions can be **private** to the class
  - *Pass-local* data can be defined as fields on the class — will only exist while the pass is being executed

Image: Cat in the Hat by Dr. Seuss

Pass-Local Data

- Suppose you're trying to print out the AST, and you want to control *indentation*
  - ✦ How are you supposed to know how many tabs deep you are when traversing a given AST node?
- Approach 1 — change the function signature, e.g.

```
public void print(ASTNode n, int numTabs) {…}
```

  - ✦ This is verbose; every recursive call must supply it
- Approach 2 — store as ***pass-local*** data, and mutate it

```
public class PrintPass {
    private int numTabs;
    public void print(ASTNode n) {…}
```

  - ✦ Much less verbose; but you need to manage it correctly

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My Teacher Told Me..

- …to not use `instanceof` in Java!
- In Java, you're supposed to use **method dispatch** and **inheritance** to let the language control which code gets run

```
public class … {

  public void foo(ASTNode n) {
    if (n instanceof Var) {…}
    else if (n instanceof Add) {…}
    else if (n instanceof Mul) {…}
    else if (n instanceof IfNode) {…}
    else if (n instanceof Assign) {…}
    …
  }
}
```

- But if we do that, we get locality according to AST node, instead of locality according to pass
- The **visitor pattern** is an enhanced version of **pass-in-a-class** that's designed to avoid `instanceof`
- The **visitor pattern** will also help us **factor out code** that's common to multiple passes using inheritance

Double Dispatch

- We need to dispatch on two different *classes*
  - Which **AST Node**, and which **Pass**?
- In "Simple Structural Recursion" the code is located in the pass class, so there's not a good way to use overloading to dispatch on AST Nodes
- In the visitor pattern, each function call turns into two function calls
  - We ask an **AST Node** to **accept** a **Pass** (aka **Visitor**)
  - We ask that specific **Pass** to **visit** the **AST Node**

Double Dispatch Visually

Each **Visitor** defines `visit(Var v)`, `visit(Add v)`, ... methods, one for each AST Node

Each **AST Node** defines a generic `accept(Visitor v)` method, which is only responsible for calling the visitor

	DumpTree	PrettyPrint	TypeCheck	Optimize	LowerToSSA	GenerateASM
Var		●				
Add		●				
Mul		●				
IfNode		●				
Assign		●				
...		●				

An Idea Whose Time Never Came

- OO Languages implement *dynamic* single dispatch
  - i.e. when you call `obj.method(arg1, arg2)`, we decide which implementation of `method` to call by ***dispatching*** on the runtime (dynamic) type of `obj`
- Dynamic Double (or multiple) Dispatch
  - When you call `obj.method(arg1, arg2)`, we decide which implementation of method to call by ***dispatching*** on the runtime (dynamic) type of `obj` ***AND*** on the dyn. type of `arg1` (***AND*** on the dyn. type of `arg2` if multiple dispatch)
- Topic of research at UW(!) in the 1990s
  - Was very complicated and not that useful

Visitor Pattern — Calculator

```
interface Visitor {
  public void visit(Num n);
  public void visit(Add n);
}

abstract public class Expr {
  abstract void accept(Visitor v);
}

public class Num extends Expr { …
  public void accept(Visitor v) {
    v.visit(this);
  }
}

public class Add extends Expr { …
  public void accept(Visitor v) {
    v.visit(this);
  }
}
```

Generic Code for all Passes

```
public class PrintPass implements Visitor {
  public void visit(Num n) {
    System.out.print(n.i);
  }
  public void visit(Add n) {
    System.out.print("(");
    n.e0.accept(this);
    System.out.print("+");
    n.e1.accept(this);
    System.out.print(")");
  }
}
```

Code for a Specific Pass

Visitor Pattern — Calculator

```
interface Visitor {
  public void visit(Num n);
  public void visit(Add n);
}

abstract public class Expr {
  abstract void accept(Visitor v);
}

public class Num extends Expr { …
  public void accept(Visitor v) {
    v.visit(this);
  }
}

public class Add extends Expr { …
  public void accept(Visitor v) {
    v.visit(this);
  }
}
```

```
public class PrintPass implements Visitor {
  public void visit(Num n) {
    System.out.print(n.i);
  }
  public void visit(Add n) {
    System.out.print("(");
    n.e0.accept(this);
    System.out.print("+");
    n.e1.accept(this);
    System.out.print(")");
  }
}
```

1. Call `node.accept(ppass)` (dispatch on **Node**)
2. Call `v.visit(node)` (dispatch on **Pass**)

Visitor Pattern — Calculator

```
interface Visitor {
  public void visit(Num n);
  public void visit(Add n);
}

abstract public class Expr {
  abstract void accept(Visitor v);
}

public class Num extends Expr { …
  public void accept(Visitor v) {
    v.visit(this);
  }
}

public class Add extends Expr { …
  public void accept(Visitor v) {
    v.visit(this);
  }
}
```

```
public class PrintPass implements Visitor {
  public void visit(Num n) {
    System.out.print(n.i);
  }
  public void visit(Add n) {
    System.out.print("(");
    n.e0.accept(this);
    System.out.print("+");
    n.e1.accept(this);
    System.out.print(")");
  }
}
```

Inside the visit method, we make structurally recursive calls by invoking

`child.accept(visitor);`

The Secret Trick of Visitors

- Why can't we just call `visitor.visit(node)` directly?
  - Why does it help to call `node.accept(visitor)` instead?
- In the `visitor.visit(node)` call, the dynamic dispatch is on the `visitor`. We have to statically dispatch on the type of `node`.
  - So we need to be in a snippet of code where the exact type of `node` is known. (This is why `accept` and the whole visitor pattern is fundamentally needed)

Variations on Visitor Pattern

- Instead of having a return type of `void`, we could define a visitor interface generically over return types **`RetT`**

```
interface Visitor<RetT> {
  public RetT visit(Num n);
  …
```

- We could hard code the structurally recursive calls into the `accept` methods as a fixed traversal order

```
public class Add extends Expr { …
  public void accept(Visitor v) {
    e0.accept(v);
    e1.accept(v);
    v.visit(this);
} }
```

Factoring Out Code w/Visitors

- Some compiler passes only need to visit a few types of AST Nodes
  - e.g. a pass to collect all variable names used in a program only needs to visit nodes that store variable names
- If we define a visitor superclass with a default traversal order (e.g. post-order) then we only need to overload a few visitors in a sub-class
- Large compiler projects using visitors will define a few (6-10) types of basic visitors to take advantage of this strategy

Why is this so complicated?

- (Gilbert's opinion) Object-oriented languages got overly focused on the "right way" to do things — requiring the development of confusing "design patterns"
  - Many of these were compensating for missing language features that are slowly and poorly being incorporated (e.g. Java now has pattern matching)
- But a lot of what people call The Visitor Pattern is really about various Pass-in-a-Class strategies
  - This is a fundamentally good idea in compiler design
  - In non object-oriented languages, similar modularity mechanisms are used to encapsulate passes

References on Design Patterns

- Two classic books on design patterns
  - **Design Patterns: Elements of Reusable Object-Oriented Software.** *Gamma, Helm, Johnson, and Vlissides.* Addison-Wesley, 1995. (the classic "Gang of Four" book on design patterns; code in C++ & Smalltalk)
  - **Object-Oriented Design & Patterns.** *Horstmann.* Wiley, 2nd edition, 2005. (code in Java)
- If you want information specifically about the MiniJava AST design, see the starter code and Appel's textbook