CS 432
Fall 2022

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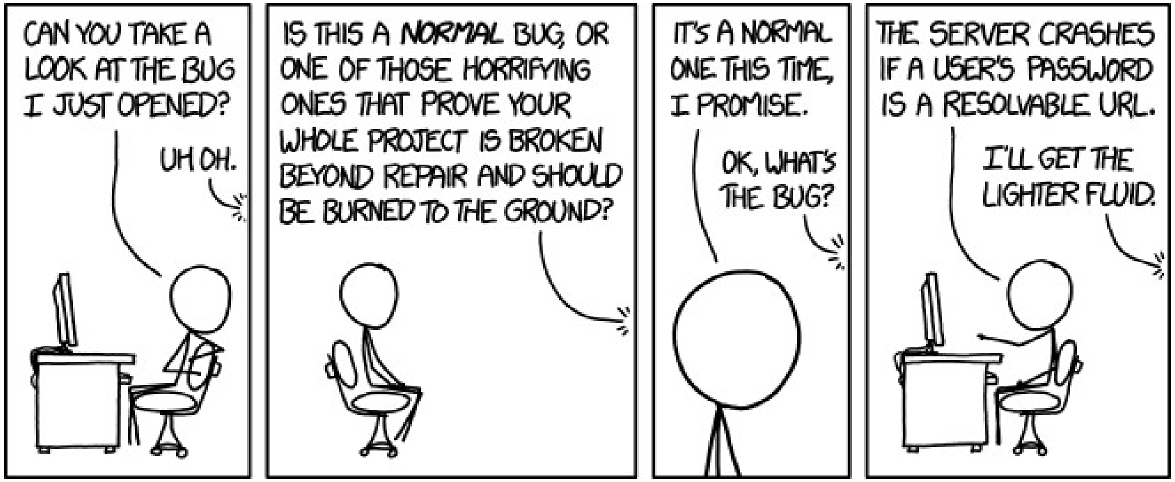
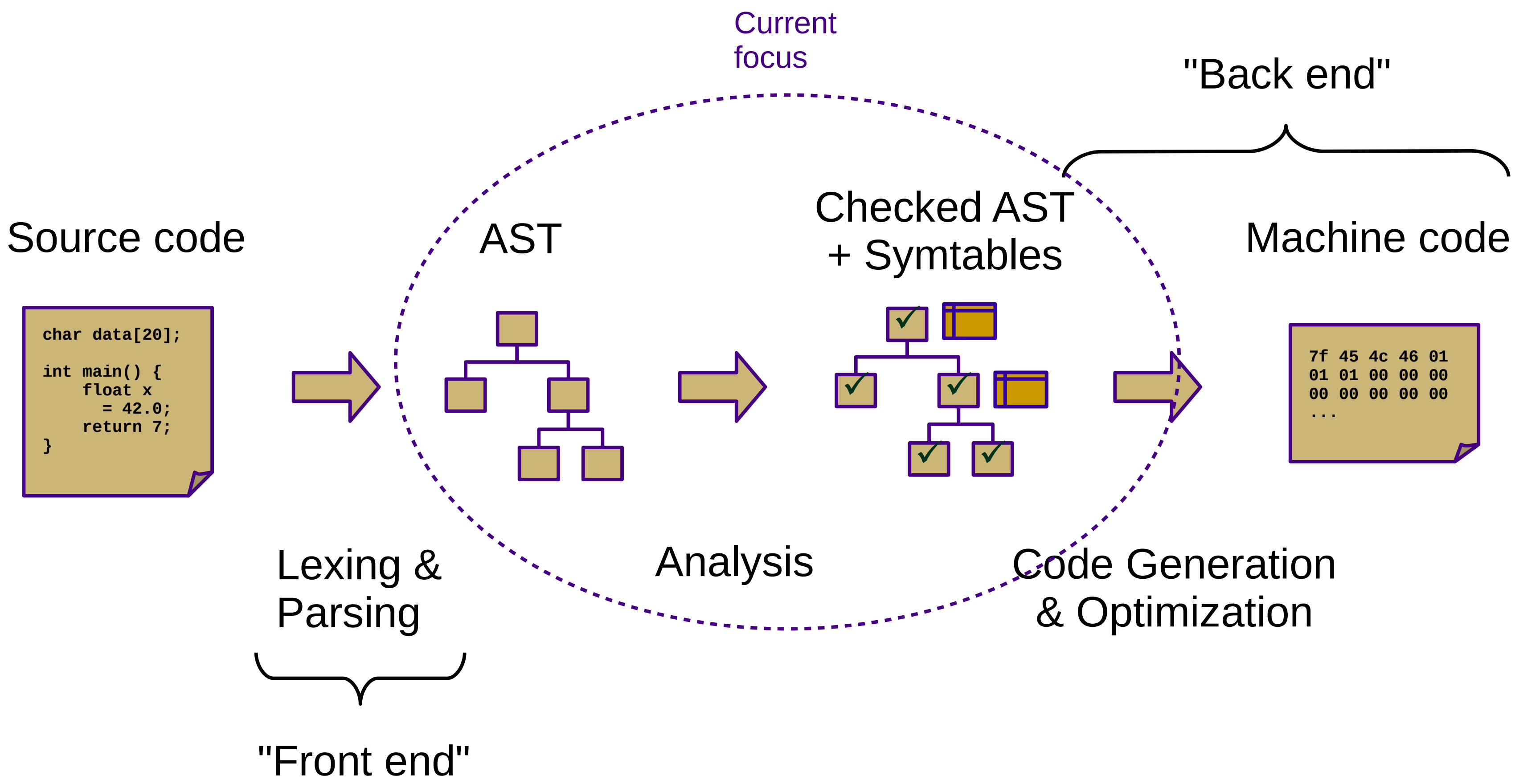


Static Analysis

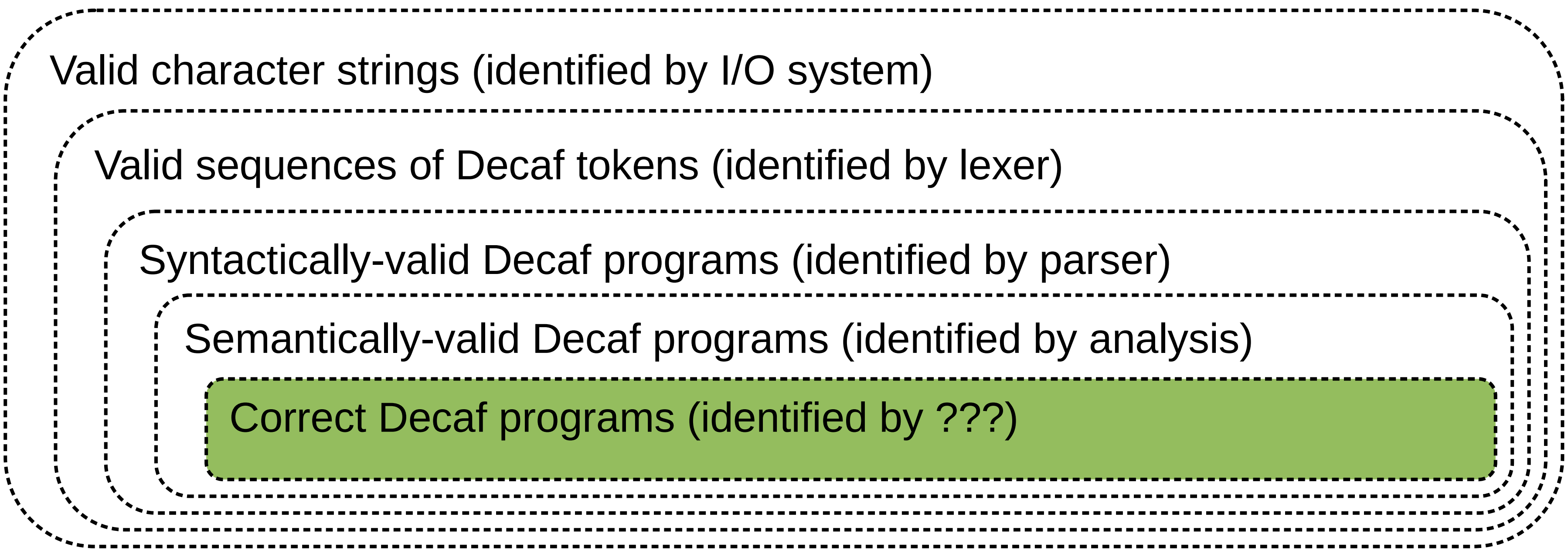
Compilation



Analysis goal: reject as many incorrect programs as possible at the AST level before attempting code generation

Overview

- Syntax: *form* of a program
  - Described using regular expressions and context-free grammars
- Semantics: *meaning* of a program
  - Much more difficult to describe clearly
  - Described using type systems and language reference specifications



Static Analysis

- Goal: reject incorrect programs
- Problem: checking semantics is hard!
  - In general, we won't be able to check for full correctness
  - However, some aspects of semantics can be robustly encoded using types and type systems
  - We will also implement other rudimentary correctness checks
    - E.g., Decaf programs must have a “main” function

Static Analysis

- Sound vs. complete static analysis
  - A “sound” system has no false positives
    - All errors reported are true errors
  - A “complete” system has no false negatives
    - All true errors are reported
- Most static analysis is **sound** but not **complete**
  - A lack of type errors does not mean the program is correct
  - However, the presence of a type error generally does mean that the program is NOT correct

Types

- A type is an abstract category characterizing a range of data values
  - Base types: integer, character, boolean, floating-point
  - Enumerated types (finite list of constants)
  - Pointer types (“address of X”)
  - Array or list types (“list of X”)
  - Compound/record types (named collections of other types)
  - Function types: (type1, type2, type3) → type4

Static Analysis

- Type inference is the process of assigning types to expressions
  - This information must be “inferred” if it is not explicit
  - For Decaf, every expression has an unambiguous inferred type!
    - Conclusions of the type proofs – assume the premises are true
- Type checking is the process of ensuring that a program has no type-related errors
  - Ensure that operations are supported by a variable's type
  - Ensure that operands are of *compatible* types
  - This could happen at compile time (static) or at run time (dynamic)
  - A type error is usually considered a bug
  - For Decaf, almost every ASTNode type will have some kind of check

Type Compatibility

- Rules about type compatibility define types that can be used together in expressions, assignments, etc.
  - Sometimes this may require a type *conversion*
- Two types are name-equivalent if their names are identical
- Two types are structurally-equivalent if
  - They are the same basic type or
  - They are recursively structurally-equivalent

C example:

```
typedef unsigned char byte_t;
unsigned char a;        // types of a and b are structurally-
byte_t b;               // equivalent but not name equivalent
```

Type Conversions

- Implicit vs. explicit
  - Implicit conversions are performed automatically by the compiler ("coercions")
    - E.g., `double x = 2;`
  - Explicit conversions are specified by the programmer ("casts")
    - E.g., `int x = (int)1.5;`
- Narrowing vs. widening
  - Widening conversions preserve information
    - E.g., `int → long`
  - Narrowing conversions may lose information
    - E.g., `float → int`

Advanced Type Inference

- Polymorphism: literally "taking many forms"
  - A *polymorphic* construct supports multiple types
  - Subtype polymorphism: object inheritance
  - Function polymorphism: overloading
  - Parametric polymorphism: generic type identifiers
    - E.g., templates in C++ or generics in Java
  - During type inference, create type variables and unify type variables with concrete types
    - Some type variables might remain unbound
    - E.g., `len : ([a]) → int`
    - E.g., `map : ((a → b), [a]) → [b]`

In Haskell:

```
len l = case l of
  []     → 0
  (x:xs) → 1 + (len xs)
```

```
map f l = case l of
  []     → []
  (x:xs) → (f x):(map f xs)
```

Problem

- Inferring the type of an ASTLiteral is easy

$$\text{TDec}\,\frac{}{\vdash \texttt{DEC} : \mathbf{int}} \qquad \text{THex}\,\frac{}{\vdash \texttt{HEX} : \mathbf{int}} \qquad \text{TStr}\,\frac{}{\vdash \texttt{STR} : \mathbf{str}}$$

$$\text{TTrue}\,\frac{}{\vdash \texttt{true} : \mathbf{bool}} \qquad \text{TFalse}\,\frac{}{\vdash \texttt{false} : \mathbf{bool}}$$

- How do we infer the type of an ASTLocation?

$$\text{TLoc}\,\frac{\texttt{ID} : \tau \in \Gamma}{\Gamma \vdash \texttt{ID} : \tau}$$

  - Need information about Γ (type environment)
  - Systems core theme: **Information = Bits + Context**

Symbols

- A symbol is a single name in a program
  - What king of value is it: variable or function?
  - If it is a variable:
    - What is its type? How big is it?
    - Where is it stored?
    - How long must its value be preserved?
    - Who is responsible for allocating, initializing, and de-allocating it?
  - If it is a function:
    - What parameters (name and type) does it take?
    - What type does it return?

Symbol Tables

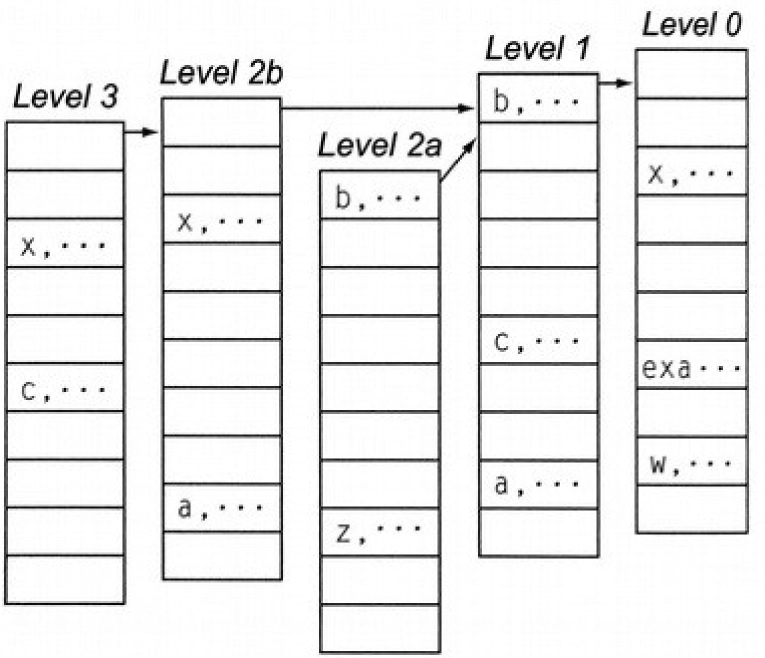
- A symbol table stores info about symbols during compilation
  - Aggregates information from (potentially) distant parts of code
  - Maps symbol names to symbol information
  - Often implemented using hash tables
  - Usually one symbol table per scope
    - Each table contains a pointer to its parent (next larger scope)
- Supported operations
  - Insert (name, record) – add a new symbol to the current table
  - LookUp (name) – retrieve information about a symbol

Symbol Table Example

```
0  static int w;          /* level 0 */
   int x;

1  void example(int a, int b) {
      int c;              /* level 1 */
2a    {
         int b, z;        /* level 2a */
           ...
      }
2b    {
         int a, x;        /* level 2b */
           ...
3        {
            int c, x;  /* level 3 */
            b = a + b + c + w;
         }
      }
   }
```

■ **FIGURE 5.10** Simple Lexical Scoping Example in C.

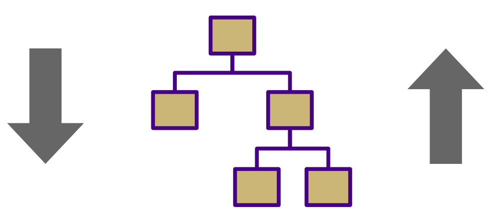
Level	Names
0	w, x, example
1	a, b, c
2a	b, z
2b	a, x
3	c, x

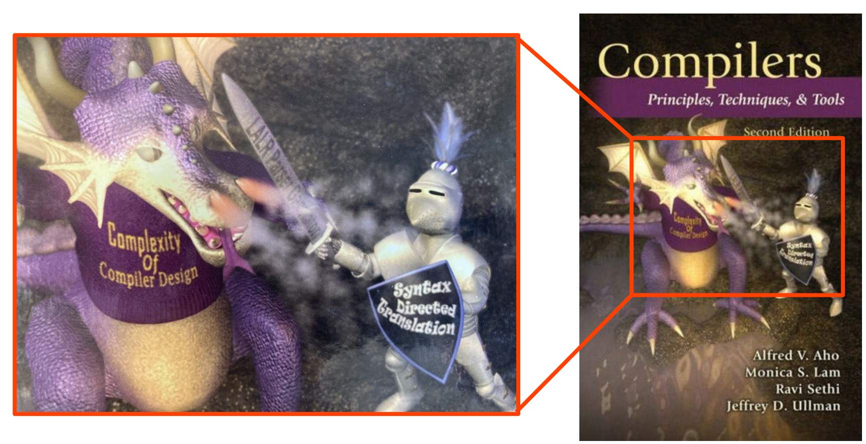


NOTE: For Decaf, we will have two scopes for each function, one associated with the FuncDecl (for parameters) and one associated with the body Block (for local variables).

AST Attributes

- An AST attribute is an additional piece of information
  - Often used to store data useful to multiple passes
  - Aside: some translations can be done purely using attributes
    - Syntax-directed translation (original dragon book!)
    - Modern translation is often too complex for this to be feasible
  - Inherited vs. synthesized attributes
    - Inherited attributes depend only on parents/siblings
    - Synthesized attributes depend only on children

Inherited  Synthesized



Attribute Grammars

- Some synthesized attributes can be calculated using post-visit rules in a grammar

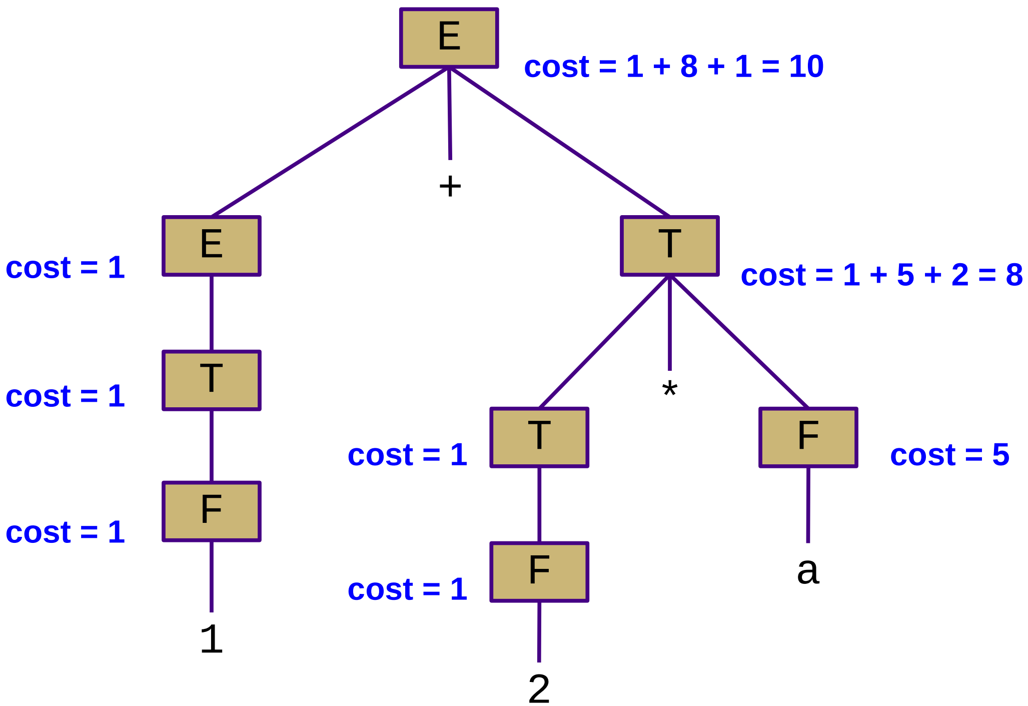
Production	Attribution Rules
$Block_0 \rightarrow Block_1\ Assign$	$\{\ Block_0.\mathtt{cost} \leftarrow Block_1.\mathtt{cost} + Assign.\mathtt{cost}\ \}$
$\quad\mid\ Assign$	$\{\ Block_0.\mathtt{cost} \leftarrow Assign.\mathtt{cost}\ \}$
$Assign \rightarrow \mathtt{name} = Expr;$	$\{\ Assign.\mathtt{cost} \leftarrow \mathtt{Cost(store)} + Expr.\mathtt{cost}\ \}$
$Expr_0 \rightarrow Expr_1 + Term$	$\{\ Expr_0.\mathtt{cost} \leftarrow Expr_1.\mathtt{cost} + \mathtt{Cost(add)} + Term.\mathtt{cost}\ \}$
$\quad\mid\ Expr_1 - Term$	$\{\ Expr_0.\mathtt{cost} \leftarrow Expr_1.\mathtt{cost} + \mathtt{Cost(sub)} + Term.\mathtt{cost}\ \}$
$\quad\mid\ Term$	$\{\ Expr_0.\mathtt{cost} \leftarrow Term.\mathtt{cost}\ \}$
$Term_0 \rightarrow Term_1 \times Factor$	$\{\ Term_0.\mathtt{cost} \leftarrow Term_1.\mathtt{cost} + \mathtt{Cost(mult)} + Factor.\mathtt{cost}\ \}$
$\quad\mid\ Term_1 \div Factor$	$\{\ Term_0.\mathtt{cost} \leftarrow Term_1.\mathtt{cost} + \mathtt{Cost(div)} + Factor.\mathtt{cost}\ \}$
$\quad\mid\ Factor$	$\{\ Term_0.\mathtt{cost} \leftarrow Factor.\mathtt{cost}\ \}$
$Factor \rightarrow \mathtt{(Expr)}$	$\{\ Factor.\mathtt{cost} \leftarrow Expr.\mathtt{cost}\ \}$
$\quad\mid\ \mathtt{num}$	$\{\ Factor.\mathtt{cost} \leftarrow \mathtt{Cost(loadI)}\ \}$
$\quad\mid\ \mathtt{name}$	$\{\ Factor.\mathtt{cost} \leftarrow \mathtt{Cost(load)}\ \}$

FIGURE 4.8 Simple Attribute Grammar to Estimate Execution Time.

Example

E → E_1 + T	{ E.cost = E_1.cost + T.cost + 1 }
| T	{ E.cost = T.cost }
T → T_1 * F	{ T.cost = T_1.cost + F.cost + 2 }
| F	{ T.cost = F.cost }
F → (E)	{ F.cost = E.cost }
| ID	{ F.cost = 5 }
| DEC	{ F.cost = 1 }

1 + 2 * a



Attributes in P3 and P4

Key	Description
`parent`	Uptree parent **ASTNode** reference
`depth`	Tree depth (`int`)
`symbolTable`	Symbol table reference (only in program, function, and block nodes)
`type`	**DecafType** of node (only in expression nodes)
`staticSize`	Size (in bytes as `int`) of global variables (only in program node)
`localSize`	Size (in bytes as `int`) of local variables (only in function nodes)
`code`	ILOC instructions generated from the subtree rooted at this node
`reg`	Register storing the result of the expression rooted at this node (only in expression nodes)

P3

P4

Building Symbol Tables (pre-P3)

- Walk the AST, creating linked tables using a stack
  - Create new symbol table for each scope
    - Every Program, FuncDecl, and Block
    - Caveat: every function contains a function-wide block for local vars, so the function level symbol table will ONLY contain the function parameters
    - Store tables as an attribute (“`symbolTable`”) in AST nodes
  - Add all symbol information
    - Global variables go in Program table (including arrays)
    - Function symbols go in Program table
    - Function parameters go in FuncDecl table
    - Local variables go in Block table

Static Analysis (P3)

- Walk the AST, checking correctness properties
  - Infer the types of all expressions (pre-visits)
    - Use symbol table lookups where necessary
    - Store in “`type`” attribute
  - Verify all types are correct (post-visits)
    - Refer to type rules (section 6 of language reference)
    - May require checking “`type`” attribute of children
    - May require symbol table lookups
    - May require maintaining some state (e.g., current function)
  - Verify other properties of correct programs (post-visits)
    - Example: `break` and `continue` should only occur in while loops
    - **Re-read Decaf reference carefully for these**

Decaf Example

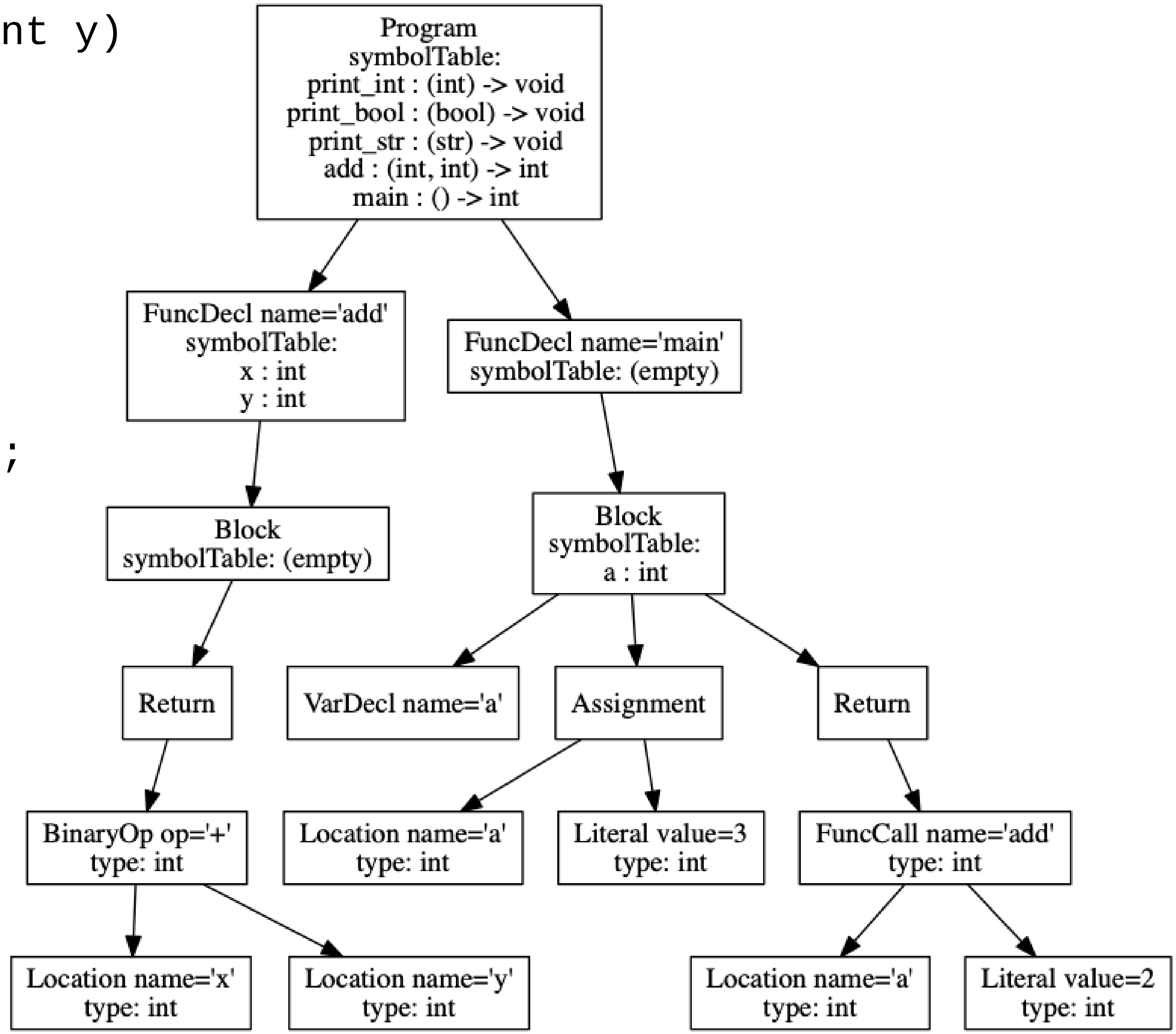
```
def int add(int x, int y)
{
    return x + y;
}

def int main()
{
    int a;
    a = 3;
    return add(a, 2);
}
```

$$\text{TDec}\ \frac{}{\vdash \texttt{DEC} : \textbf{int}}$$

$$\text{TLoc}\ \frac{\texttt{ID} : \tau \in \Gamma}{\Gamma \vdash \texttt{ID} : \tau}$$

$$\text{TAdd}\ \frac{\Gamma \vdash e_1 : \textbf{int} \qquad \Gamma \vdash e_2 : \textbf{int}}{\Gamma \vdash e_1 \text{ `+' } e_2 : \textbf{int}}$$

$$\text{TAssign}\ \frac{\Gamma \vdash \texttt{ID} : \tau \qquad \Gamma \vdash e : \tau}{\Gamma \vdash \texttt{ID} \text{ `=' } e \text{ `;'}}$$

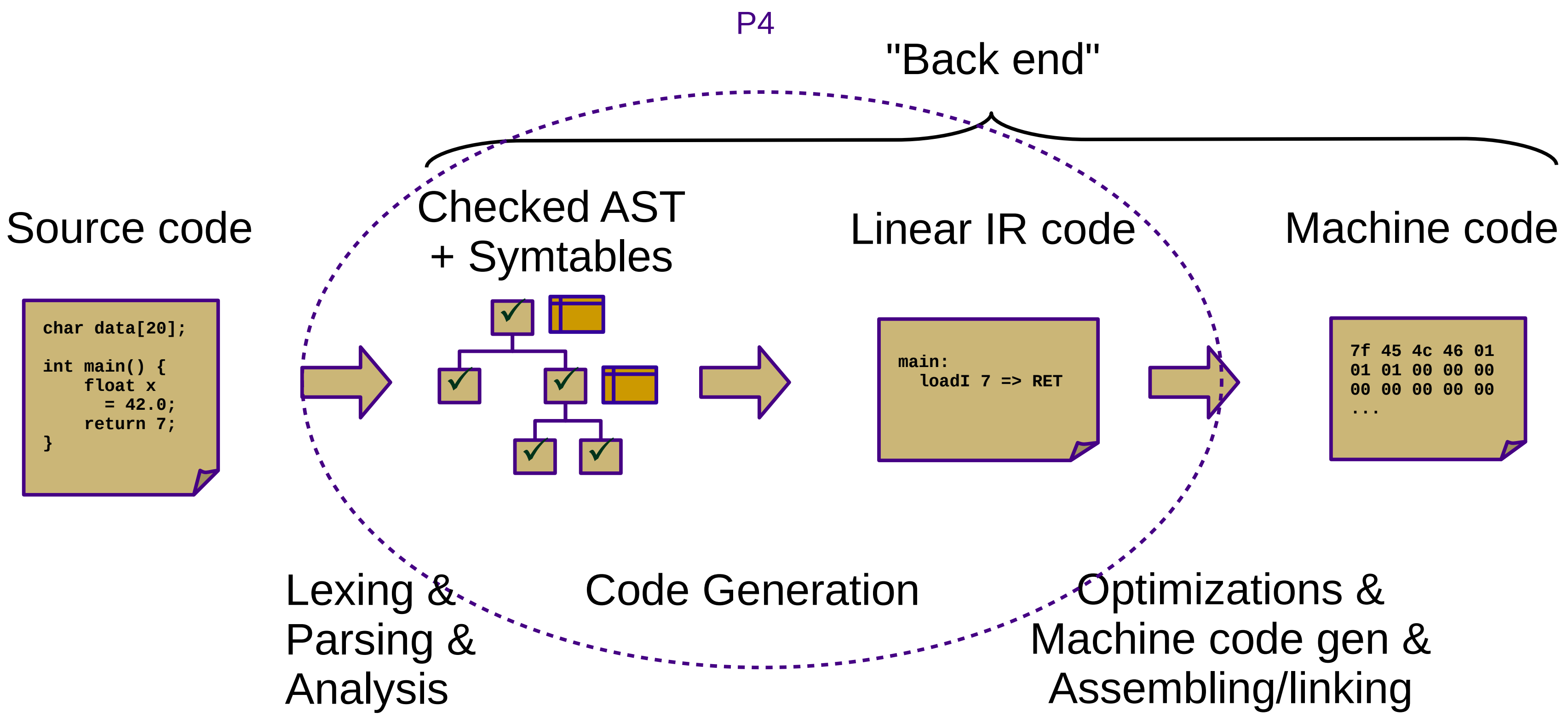


P3 reminder

- Check your implementation against the reference compiler (`/cs/students/cs432/f22/decaf`)
  - If the reference compiler rejects a program, you should too (and vice versa for correct programs)
  - Use "`--fdump-tables`" to print the symbol tables
  - Also, the graphical AST should have the tables now (both in the reference compiler and in your project)

*Optional challenge: write P3 using a "pure" visitor; i.e., the visitor methods perform **no tree traversals**, only symbol lookups and accesses of direct child attributes.*

Preview: P4



P4
"Back end"
Source code
Checked AST
+ Symtables
Linear IR code
Machine code
char data[20];
int main() {
float x
= 42.0;
return 7;
}
main:
loadI 7 => RET
7f 45 4c 46 01
01 01 00 00 00
00 00 00 00 00
...
Lexing &
Parsing &
Analysis
Code Generation
Optimizations &
Machine code gen &
Assembling/linking

Allocating Symbols (pre-P4)

- Walk the AST, allocating memory for symbols
  - Each symbol has a location and offset field
    - This is a form of static coordinates
    - `STATIC_VAR` and static offset for global variables
    - `STACK_LOCAL` and BP offset for local variables
    - `STACK_PARAM` and BP offset for function parameters
  - Track allocated memory
    - `localSize` attribute for each FuncDecl
    - `staticSize` attribute for the Program

Code Generation (P4)

- Walk the AST, generating code
  - Build ILOC instructions for all nodes
    - Refer to operational semantics (section 7 of language reference)
    - Store in "`code`" attribute
    - May require copying "`code`" attribute of children
  - Store expression results in temporary registers
    - Use "`reg`" attribute
    - Need state information to track the next temporary ID
    - Location loads and stores will require static coordinate info