# CS 432
# Fall 2021

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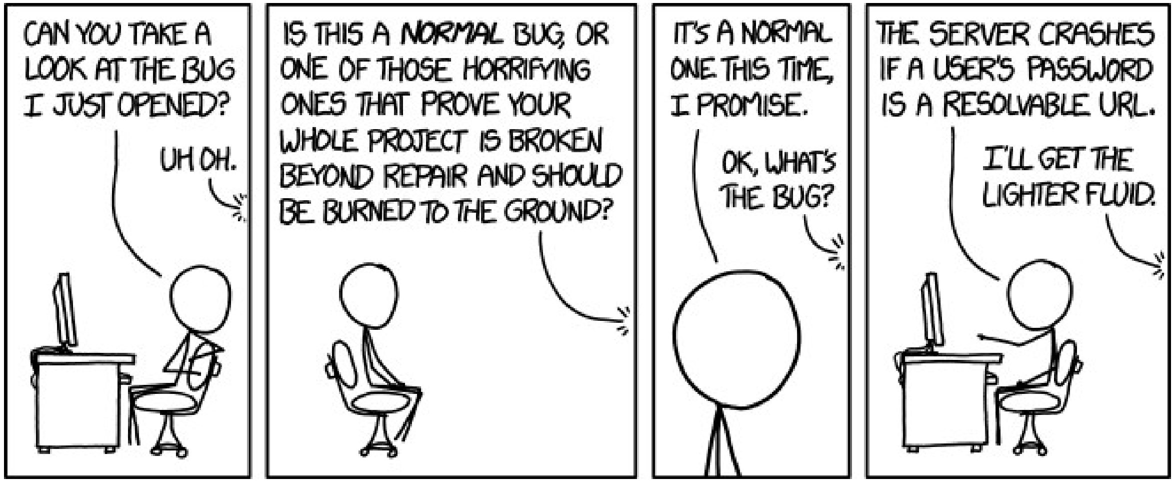
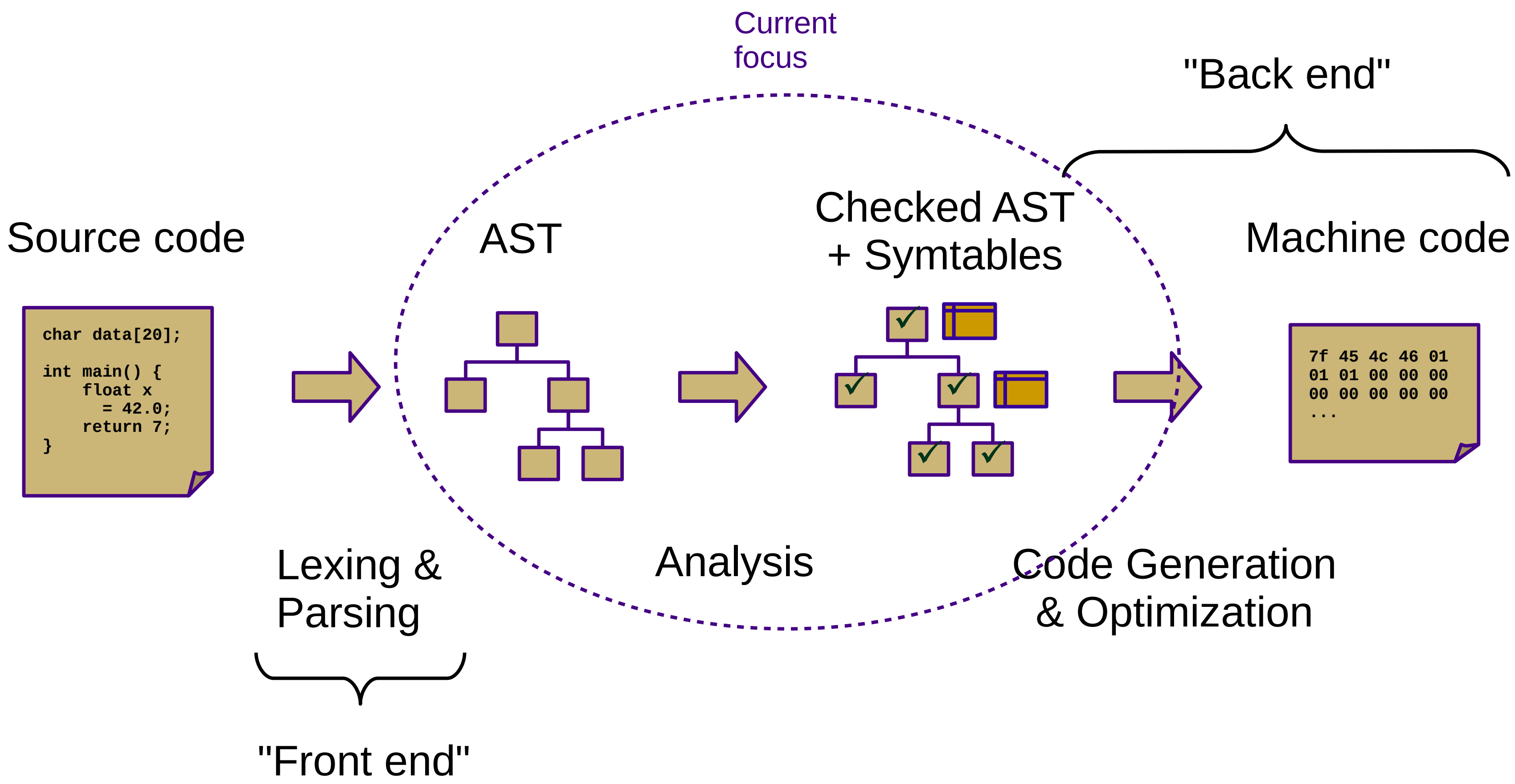



# Static Analysis

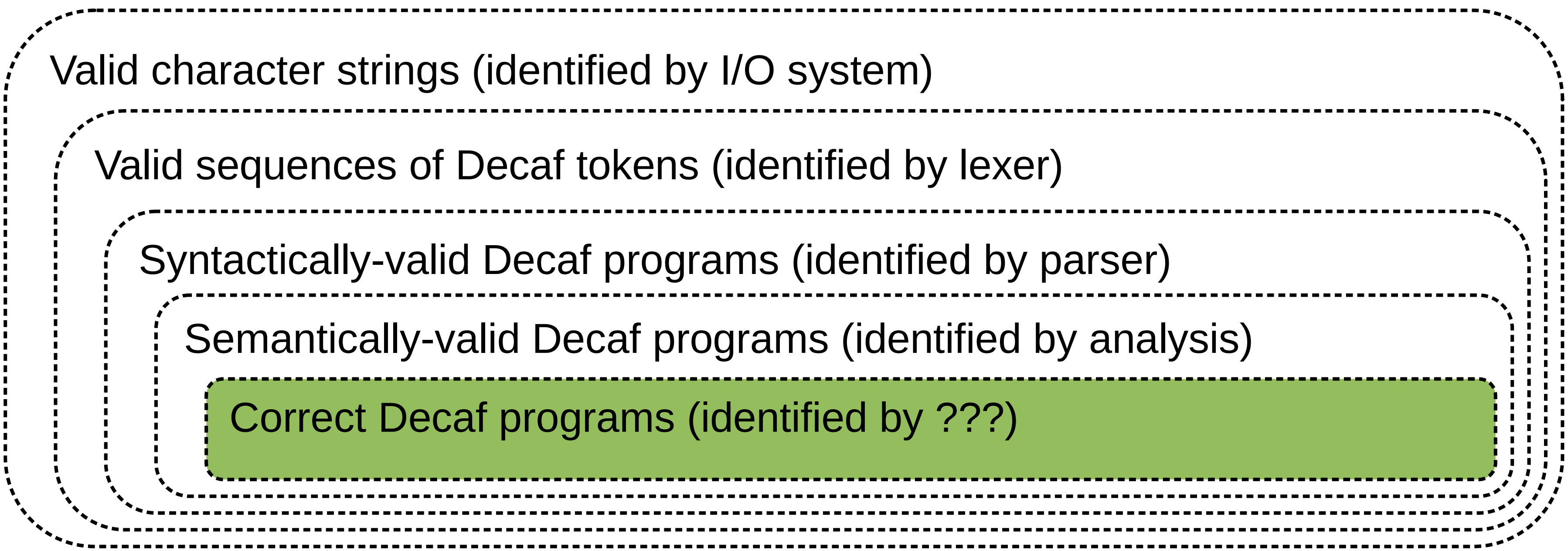
# Compilation




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

# 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 (for static type systems) or at run time (for dynamic type systems)
  - A type error is usually considered a bug
  - For Decaf, almost every ASTNode type will have some kind of check

# 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

# Type Systems

- A type system is a set of type rules
  - Rules: valid types, type compatibility, and how values can be used
  - A type judgment is an assertion that expression **x** has type t
    - Written as "**x** : t" (e.g., "**3** : int" and "**true** : bool")
    - Often requires the context of a type environment (i.e., symbol table)

- Benefits of a robust type system
  - Earlier error detection
  - Better documentation
  - Increased modularization

# 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

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

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

- 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 type of value is it: variable or function?
  - If it is a variable:
    - 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 does it take?
    - What 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;
       }
    }
  }
```

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

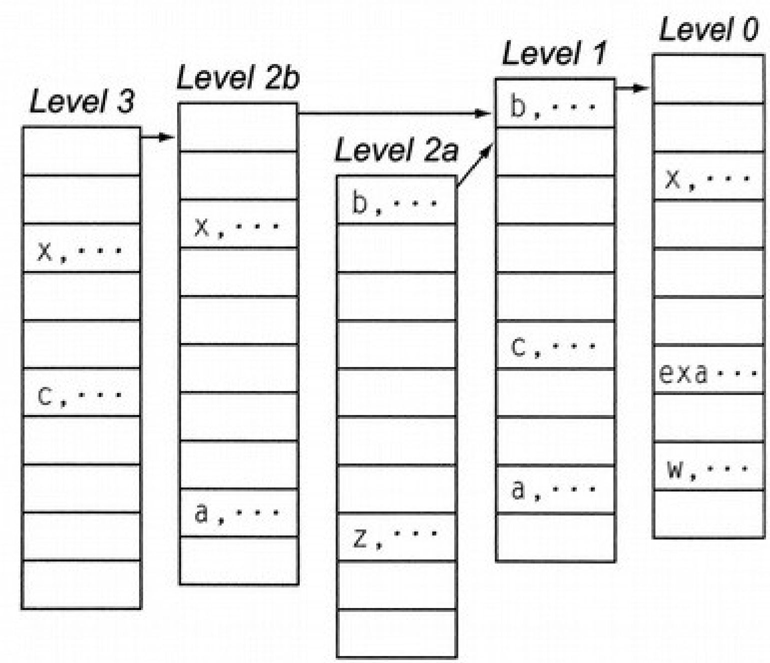
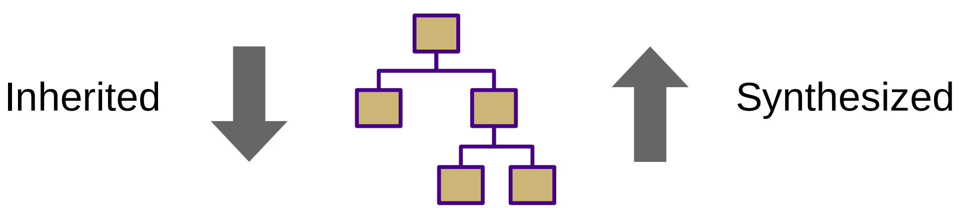



**FIGURE 5.10** Simple Lexical Scoping Example in C.

**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




# Attribute Grammars

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

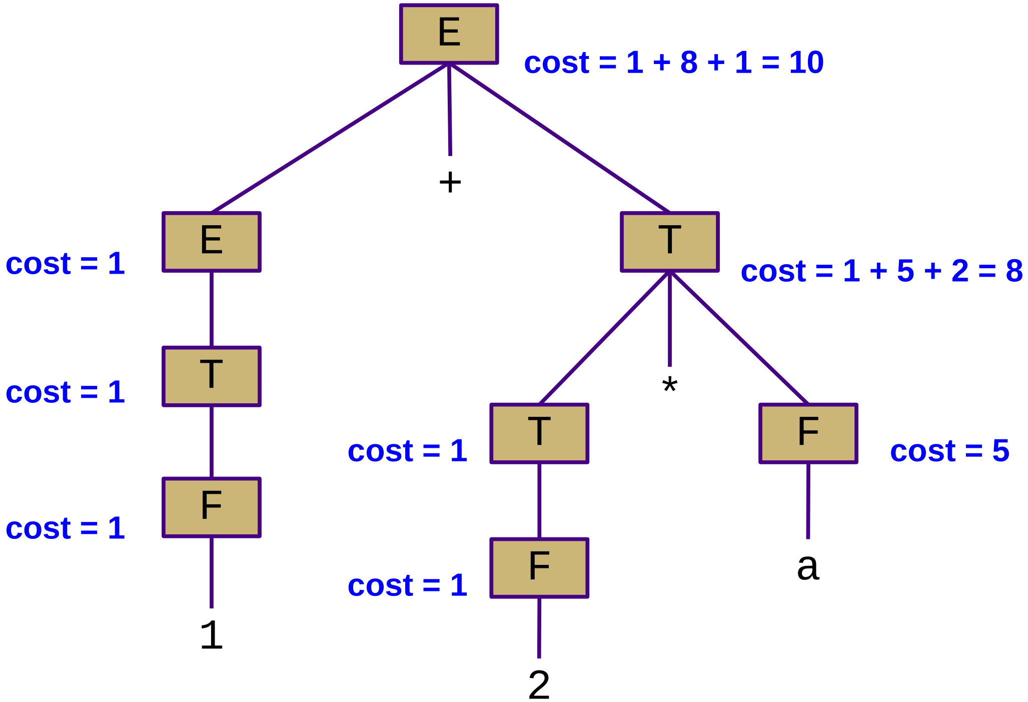
| Production | | | Attribution Rules |
|---|---|---|---|
| $Block_0$ | $\rightarrow$ | $Block_1$ *Assign* | { $Block_0$.cost $\leftarrow$ $Block_1$.cost + *Assign*.cost } |
| | \| | *Assign* | { $Block_0$.cost $\leftarrow$ *Assign*.cost } |
| *Assign* | $\rightarrow$ | name = *Expr*; | { *Assign*.cost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

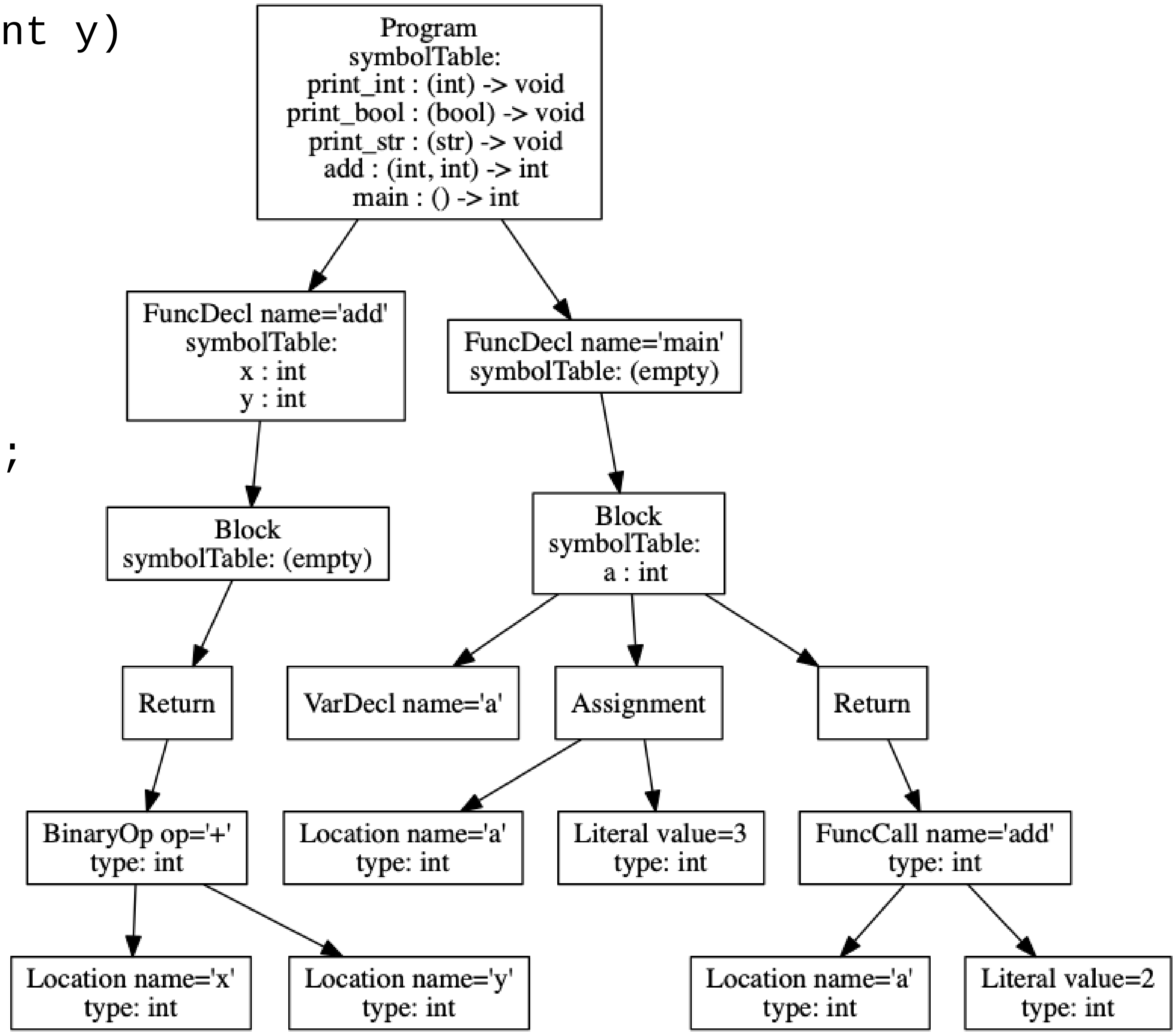
```
def int add(int x, int y)
{
    return x + y;
}

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

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

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

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

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

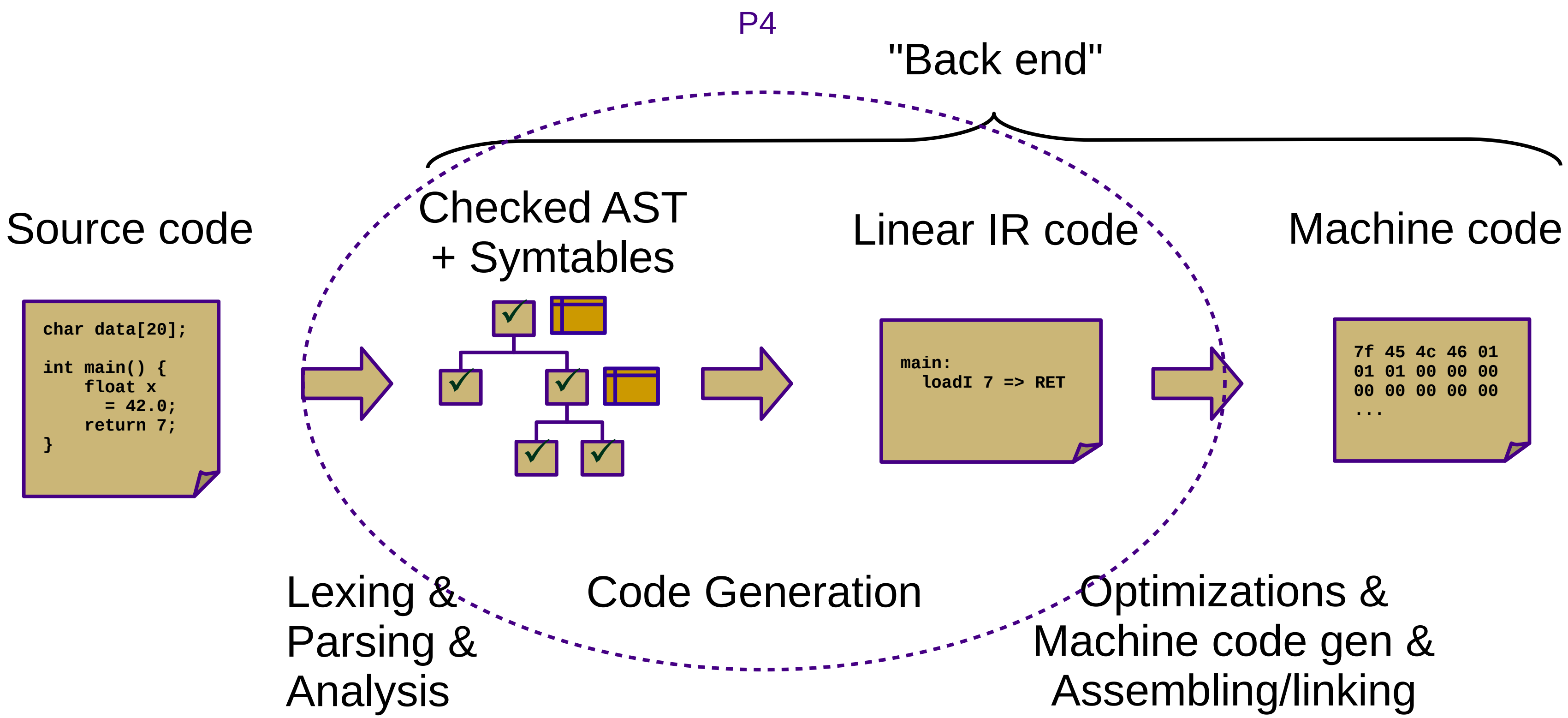


# P3 reminder

- Check your implementation against the reference compiler (`/cs/students/cs432/f21/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