# COMP3048: Lecture 2

## *A Complete (Albeit Small) Compiler*

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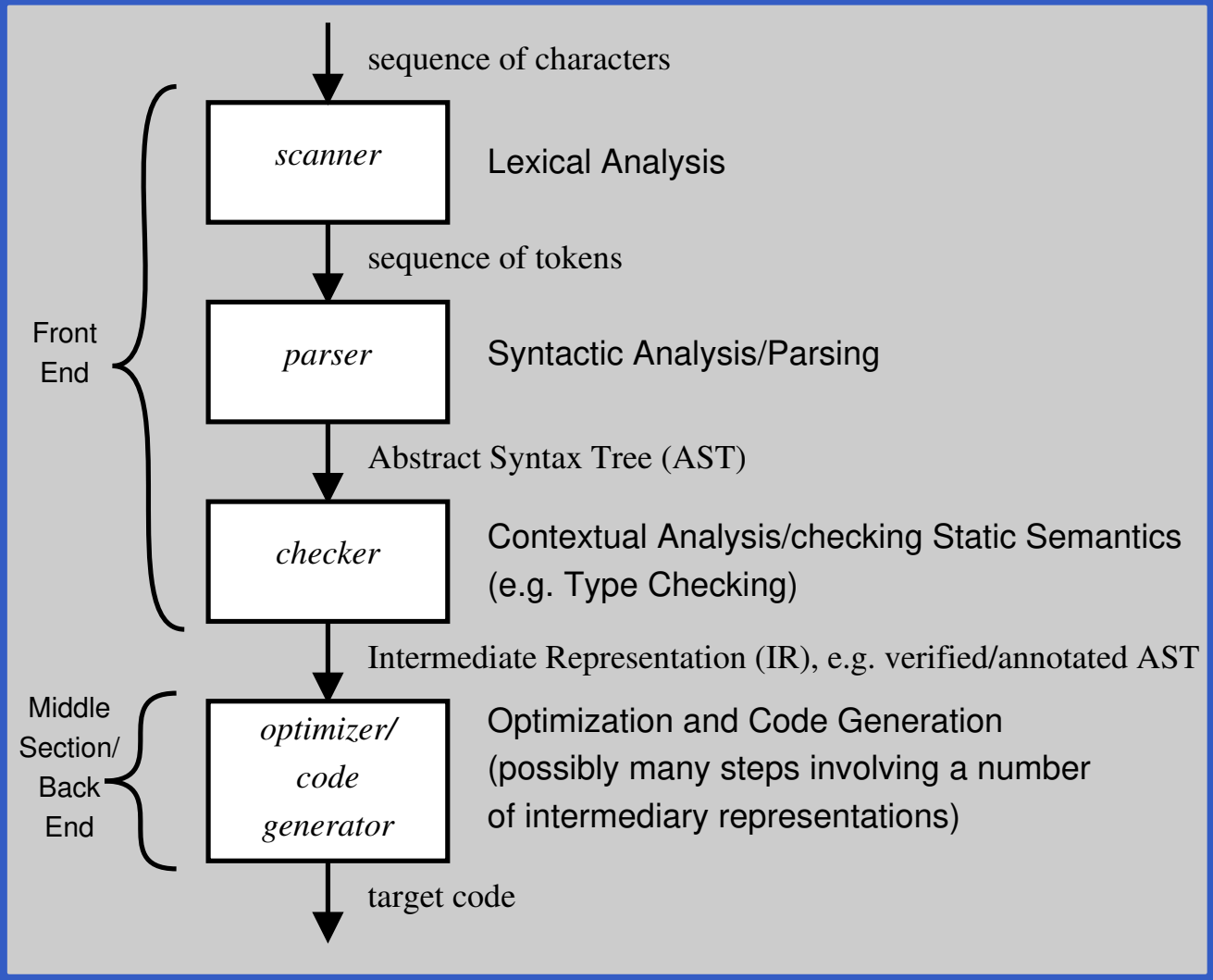
# Recap: Typical Compiler Structure



# This Lecture (1)

In this lecture, we will walk through a rudimentary but complete compiler implemented in Haskell for the *Trivial eXpression Language* (TXL):

- concrete illustration of different compiler phases
- “mental scaffolding”
- brush up your Haskell knowledge

# This Lecture (2)

- TXL by example.
- Lexical aspects.
- Context Free Grammar.
- Static semantics.

# TXL into C compiler

Scenario:

- We wish to develop a compiler for TXL.
- To save ourselves some effort, we are going to compile TXL into C, and then use an existing C compiler (GCC) to translate into executable machine code.

# Informal TXL Syntax and Semantics

Some examples of TXL programs, ***concrete syntax***, and their intended meaning, ***semantics***:

- `1 + 3`
  Semantics: *4*
- `1 + (3 * (2 + 2))`
  Semantics: ? (*13*)
- `let x = 3 * 7 in x + 3`
  Semantics: ? (*24*)

In TXL, all binary operators have the same precedence and are left associative. See the context-free grammar later.

# Informal TXL Syntax and Semantics

- `let x = 3 * 7 in let x = x * 3 in x - 21`
  Semantics: *???*

Some possibilities:

- Disallow re-definition of entities already in scope.
- Allow nested scopes, decide how to disambiguate; e.g., closest containing scope.
- Recursive definitions or not? I.e., is the defined entity in scope in its own definition?

We opt for nesting, closest containing scope, no recursion. Semantics: *42*

# Informal TXL Syntax and Semantics

- `let x = 3 in y + x`
  Semantics: *???*

Some possibilities:

- Insist all variables be defined. The program can then be ***statically*** rejected as ***meaningless***.
- Catch use of undefined variables ***dynamically***, making the meaning of the program ***undefined***.
- Assume some default value, like 0, for variables that are not explicitly defined.

# TXL Really Is Trivial (1)

- TXL is indeed a trivial language.
- The meaning of a TXL “program” is just a number that could be computed ***statically***, at compile time.
- Thus not ***really*** necessary to generate a program!
- Or we could generate a very simple program of the form

```
print n;
```

# TXL Really Is Trivial (2)

- But we are going to ignore this and generate a program that carries out the evaluation anyway.

# Rough Concrete Compiler Design (1)

Each “box” of the compiler structure diagram corresponds to a function:

```
scanner :: [Char] -> [Token]
parser  :: [Token] -> AST
checker :: AST -> ChkdAST
codegen :: ChkdAST -> Code
```

The compiler can thus be constructed by ***composing*** these functions in sequence. For example, scanning followed by parsing:

```
scanAndParse :: [Char] -> AST
scanAndParse = parser . scanner
```

# Rough Concrete Compiler Design (2)

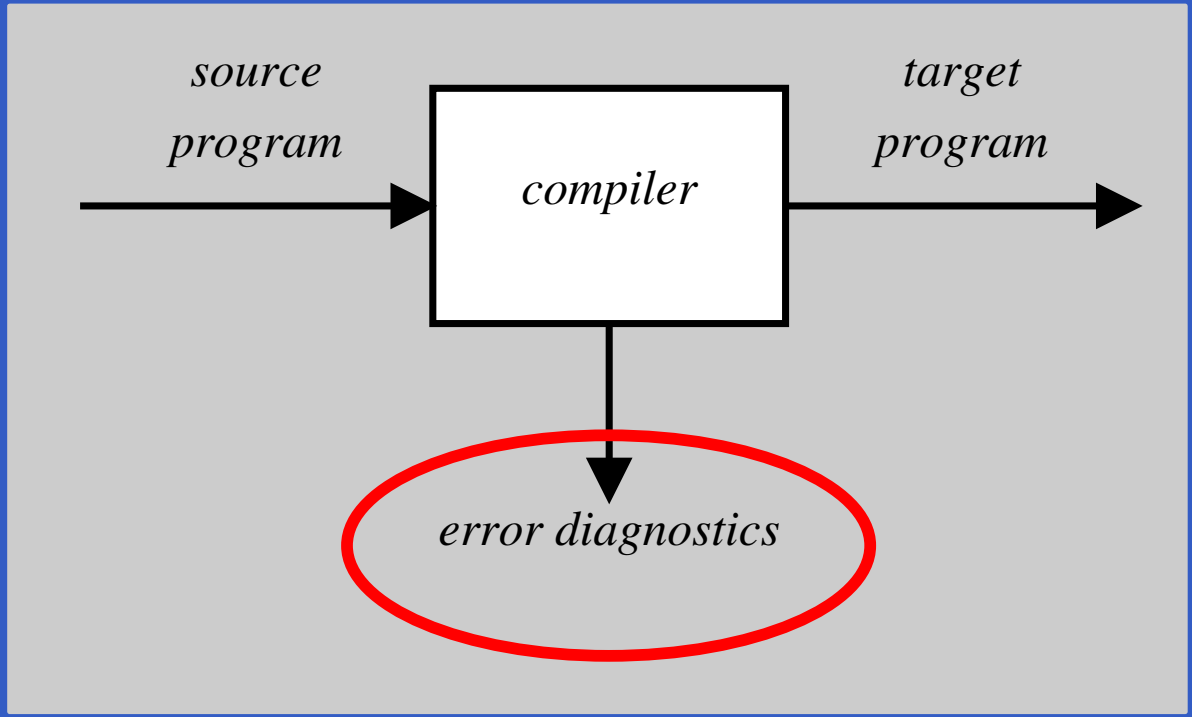
By using ***reverese*** function composition, we can mirror the diagram very closely:

```
-- Reverse function composition
(>>>) :: (a->b) -> (b->c) -> (a->c)

compiler :: [Char] -> Code
compiler = scanner
           >>> parser
           >>> checker
           >>> codegen
```

# What Happened to the Errors? (1)

Recall:




Any of the ***front-end phases*** could encounter errors. Thus, each function should return ***either*** the result of transformation ***or*** an error indication.

# What Happened to the Errors? (2)

```
data Either a b = Left a | Right b

scanner ::
    [Char] -> Either [Token] [ErrMsg]
parser ::
    [Token] -> Either AST [ErrMsg]
checker ::
    AST -> Either CheckedAST [ErrMsg]
codegen ::
    CheckedAST -> Code
```

# The TXL2C Compiler Design

However, we are going to cut some corners:

- For scanning and parsing errors, simply stop and print error message. I.e., these functions become ***partial***, but not reflected in their type.
- TXL2C is so trivial, that there is no need to change or annotate the AST: we will use a data type `Exp` throughout.

```
scanner :: [Char] -> [Token]
parser  :: [Token] -> Exp
checker :: Exp -> [String]
codegen :: Exp -> [Char]
```

# Informal Lexical Aspects of TXL

If doing things properly, we would specify the ***lexical syntax*** of the basic language symbols, the ***tokens*** (like integers, identifiers, operators, keywords), using e.g. ***regular expressions***.

Some notes about white space:

- The only significance of white space is to separate tokens.
- Comments starts with `!` and runs to the end of the line.
- Comments are treated as white space.

# TXL Compilation: Lexical Analysis

A small TXL program (the source code):

```
let x = 3 * 7 in
  let x = x * 3 in
    x - 21
```

After lexical analysis (type: `[Token]`):

```
[T_Let, T_Id "x", T_Equal, T_Int 3,
 T_Times, T_Int 7, T_In, T_Let,
 T_Id "x", T_Equal, T_Id "x", T_Times,
 T_Int 3, T_In, T_Id "x", T_Minus,
 T_Int 21]
```

# Context Free Grammar for TXL

$$
\begin{array}{lcl}
\mathit{TXLProgram} & \rightarrow & \mathit{Exp} \\
\mathit{Exp} & \rightarrow & \mathit{Exp}\ \texttt{+}\ \mathit{PrimExp} \\
 & | & \mathit{Exp}\ \texttt{-}\ \mathit{PrimExp} \\
 & | & \mathit{Exp}\ \texttt{*}\ \mathit{PrimExp} \\
 & | & \mathit{Exp}\ \texttt{/}\ \mathit{Primexp} \\
 & | & \mathit{PrimExp} \\
\mathit{PrimExp} & \rightarrow & \underline{\mathit{IntegerLiteral}} \\
 & | & \underline{\mathit{Identifier}} \\
 & | & \texttt{(}\ \mathit{Exp}\ \texttt{)} \\
 & | & \texttt{let}\ \underline{\mathit{Identifier}}\ \texttt{=}\ \mathit{Exp}\ \texttt{in}\ \mathit{Exp}
\end{array}
$$

Exercise (home): Draw the ***derivation tree*** for

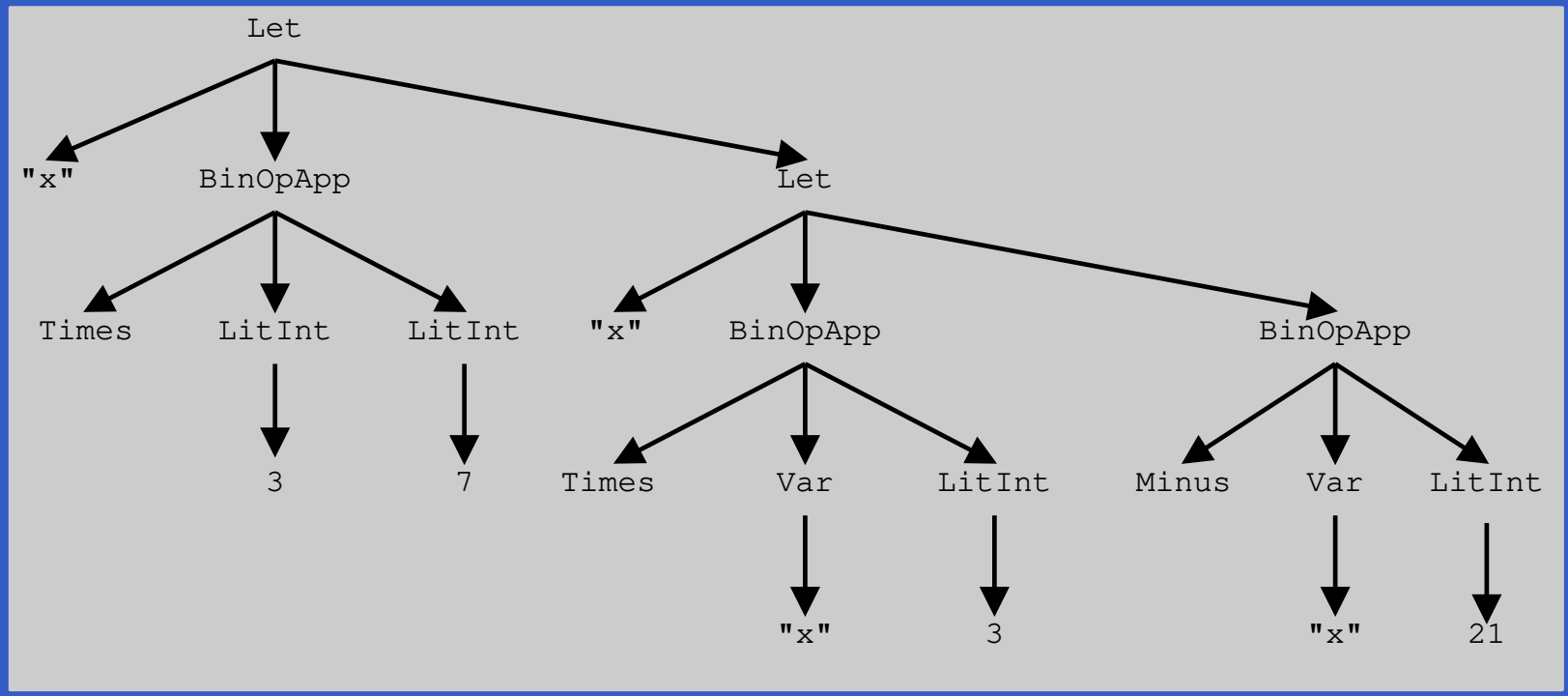
```
let x = 3 * 7 in let x = x * 3 in x - 21
```

Compare with the Abstract Syntax Tree (AST) on next slide!

# TXL Compilation: Syntactic Analysis

```
let x = 3 * 7 in let x = x * 3 in x - 21
```

After parsing, AST drawn as a tree:



# TXL Compilation: Syntactic Analysis

After parsing, AST (type: `Exp`):

```
Let "x"
    (BinOpApp Times
              (LitInt 3)
              (LitInt 7))
    (Let "x"
         (BinOpApp Times
                   (Var "x")
                   (LitInt 3))
         (BinOpApp Minus
                   (Var "x")
                   (LitInt 21)))
```

# Notes on the TXL Parser

- Predictive, recursive-descent parser.
- Parsing function for each non-terminal has type:

```
[Token] -> (Exp, [Token])
```

- As recursive descent parsers cannot handle left-recursion, grammar transformed first to eliminate left-recursion, then systematically transformed into a parser.

# Static Semantics

- TXL has only a single type, integer, so typing is trivial.
- Normal nested scope.
- Only defined variables may be used.
  For example, the following is invalid:

```
let x = 3 in y + x
```

# Compiling the TXL `let`-expression (1)

- The `let`-construct is an ***expression***, and standard rules for nested scope are supposed to be respected.
- This is really the only complication when compiling TXL into C, since C does not have `let`-expressions or anything similar.
- In particular, it is ***not*** possible to directly replace `let` by assignment!

# Compiling the TXL `let`-expression (2)

To see the last point, consider

```
let x = 23 in
    (let x = x * 3 in x - 50)
    + x
```

The meaning should again be $42$.

However, assuming `x` is an `int` variable, the value of the following C expression is $88$:

```
(x = 23, (x = x * 3, x - 50)) + x
```

(Final value of `x` is $69$, $69 - 50 = 19$, $19 + 69 = 88$.)