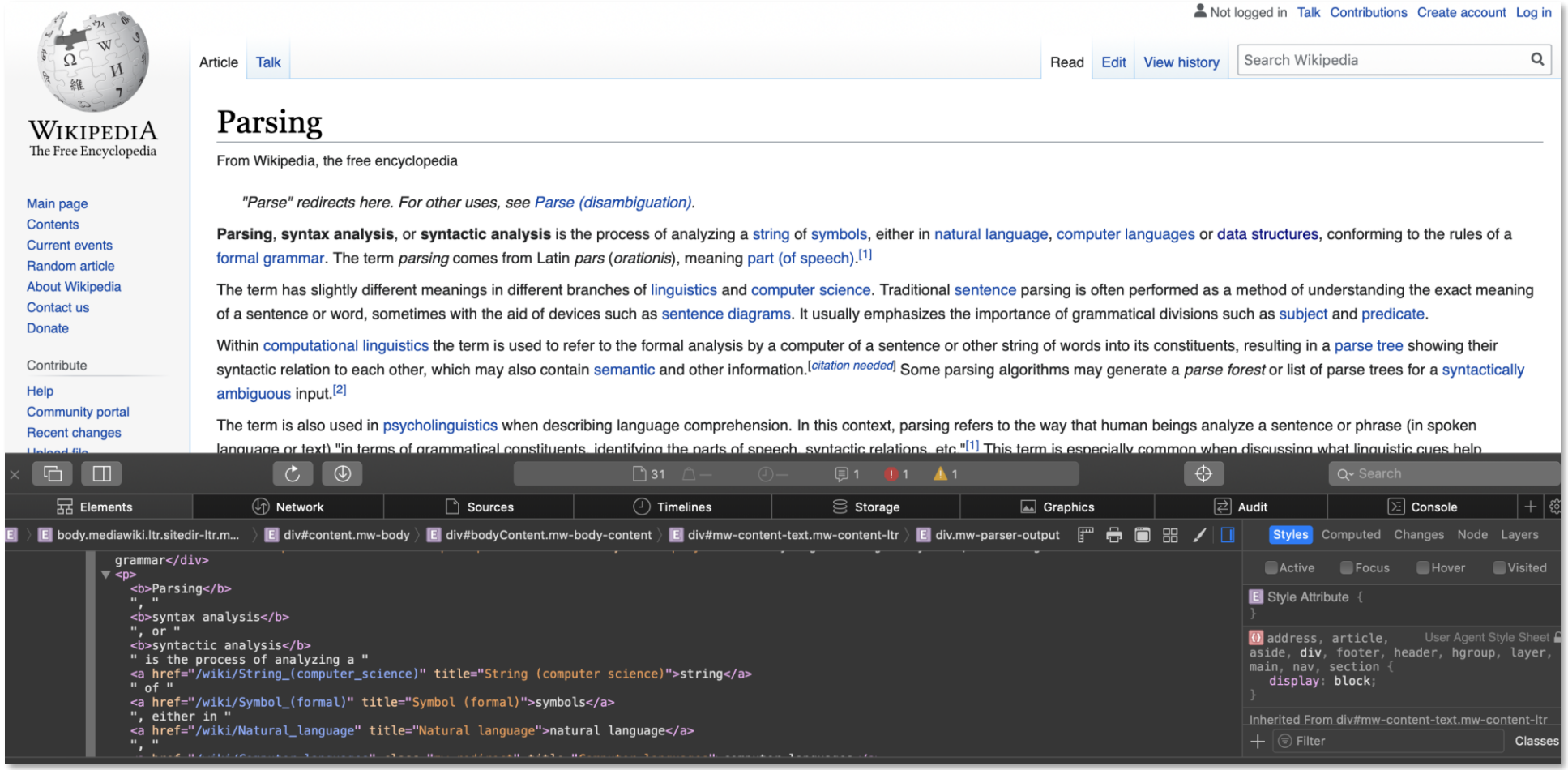
PARSING

Sid Chi-Kin Chau

[Lecture 10]

Unstructured Data



Goals of This Lecture

- Motivation
  - Learn how source codes are interpreted, compiled, and executed
- Tokenization
- Parsing
  - Context-free Grammars
  - Recursive Descent Parsing

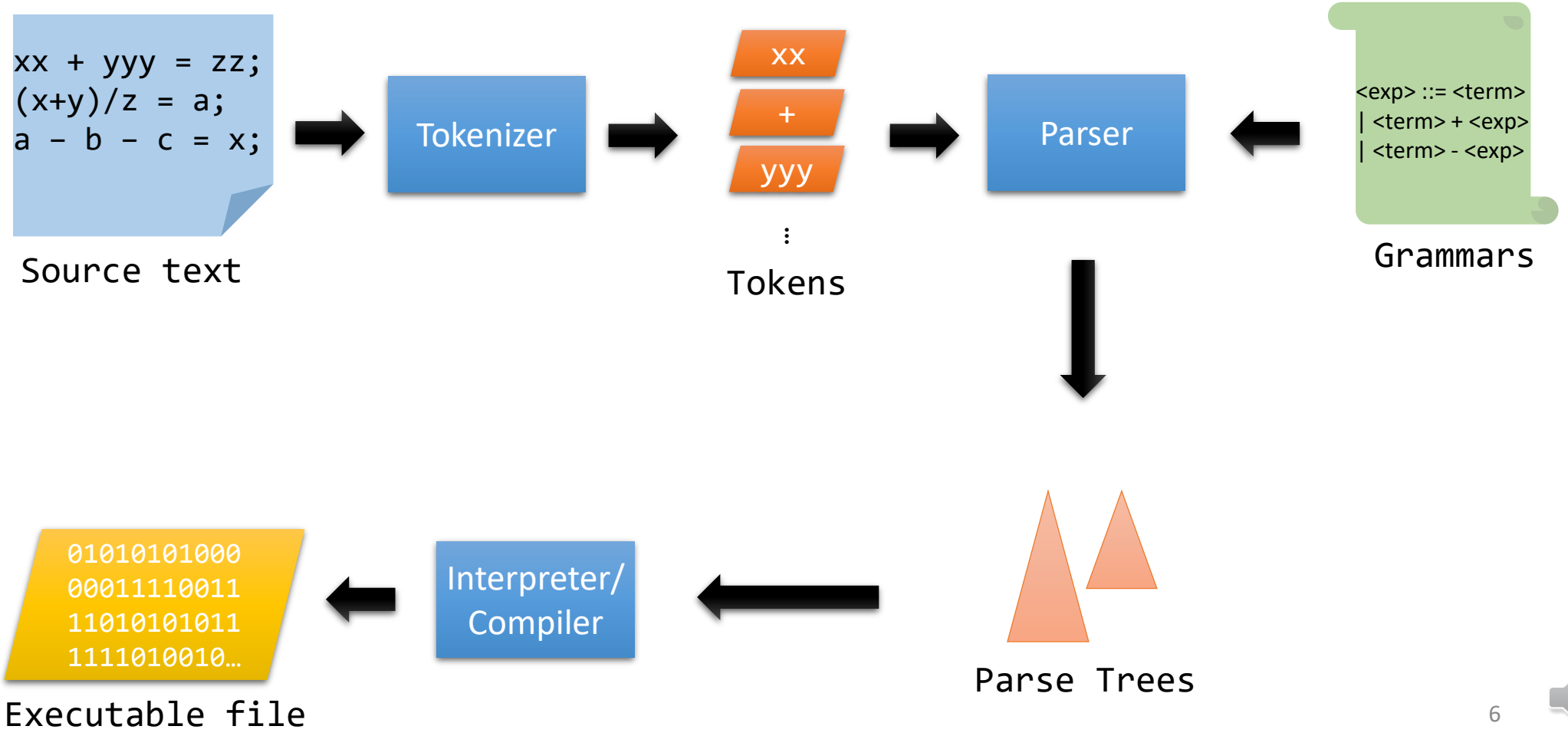
Parsing Text Data

- Modern data is often stored in text files
- Input data to computer via various text files
  - Markup languages: HTML, JSON, XML, Markdown…
  - Programming languages: Java, C, C++, Haskell, Perl, Python, PHP, …
  - Mathematical expressions, e.g., {(2+3)*4}/2
- Need to extract meaningful information for computers
- Need rules for writing and reading

Basic Idea of Parsing

- Also called syntax (syntactic) analysis
- Aim to understand the exact meaning of structured text
  - Resulting in parse tree, a representation of structured text
  - Preceded by a tokenizer
- Need a grammar to generate parse tree
  - Grammar is a set of rules of language in structured text
  - Test whether a text conforms to the given grammar

Parsing Process

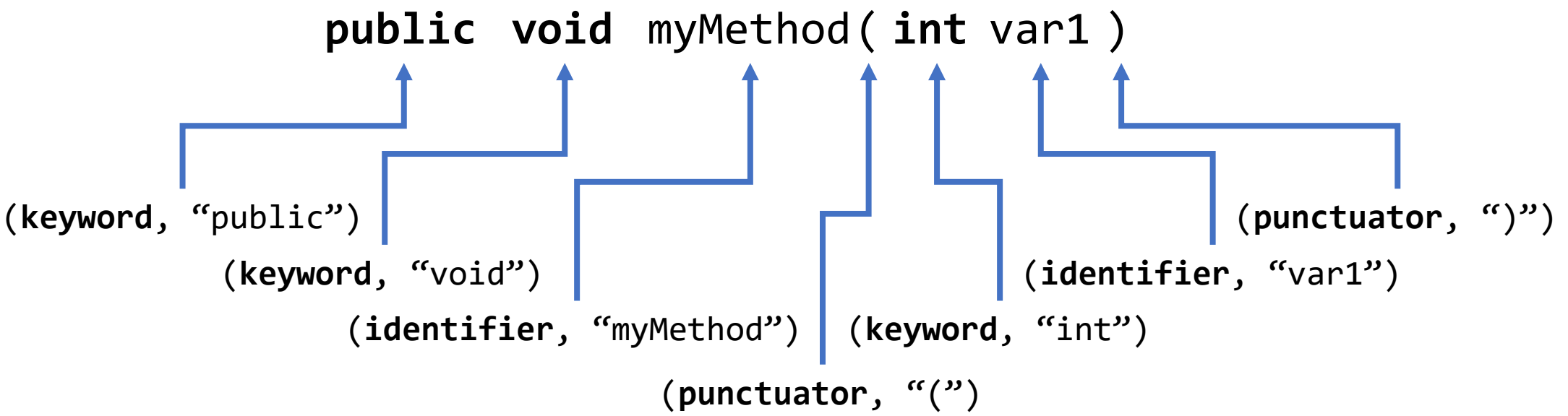


Tokenization

- Tokenization is the process of converting a sequence of characters into a sequence of tokens
- Example, natural language tokenization
  - Input
    - *“I want to tokenize this sentence.”*
  - Output
    - *I / want / to / tokenize / this / sentence /.*
  - In this case, each token is a vocabulary word or a punctuation mark

Tokenization of Structured Text

- A token is a string with an assigned meaning as a pair consisting of a token type and a token value
- Example:



Token Types

- Tokens: type, location, name (if any)

Token Type	Example
Punctuators	( ) ; , [ ]
Operators	+ - * :=
Keywords	begin end if while try catch
Identifiers	Square_Root
String literals	“press Enter to continue”
Character literals	‘x’
Numeric literals (integer)	123
Numeric literals (floating point)	5.23e+2

Punctuators (Separators)

- Typically individual special characters
  - Example: ({ } : . ;
  - Sometimes double characters: tokenizer looks for longest token:
    - /*, //, -- comment openers in various languages
  - Returned as identity (type) of token
    - Plus perhaps location for error messages and debugging purposes

Operators

- Like punctuators
  - No real difference for tokenizer
    - Tokenizers do not “process/execute” tokens
  - Typically single or double special characters
    - Operators
      - + - == <=
    - Operations
      - :=
  - Returned as type of token
    - Plus perhaps location

Identifiers and Keywords

- Identifiers: function names, variable names
  - Length, allowed characters, separators
- Need to build a name table
  - Single entry for all occurrences of names like `var1`, `myFunction`
  - Typical data structure: hash table
- Tokenizer returns token types
  - Plus key (index) to table entry
  - Table entry includes location information
- Keywords: Reserved identifiers (it can be case-sensitive)
  - e.g., `BEGIN END` in Pascal, `if` in C, `catch` in C++

Literals

- Pre-defined constants in programming languages
- String literals
  - “example”
- Character literals
  - ‘c’
- Numeric literals
  - 123 (Integer)
  - 123.456 (Double)

Free-form vs. Fixed format

- Free-form languages (modern ones)
  - White space does not matter. Ignore these:
    - Tabs, spaces, new lines, carriage returns
  - Only the ordering of tokens is important
  - e.g., C, C++, Java, Javascript, …
- Fixed format languages (historical ones)
  - Layout is critical
    - Fortran, Python, indentation
  - Tokenizer must know about layout to find tokens
  - It was born in 1950's (for punched cards, one statement per card – easy to debug/maintain)

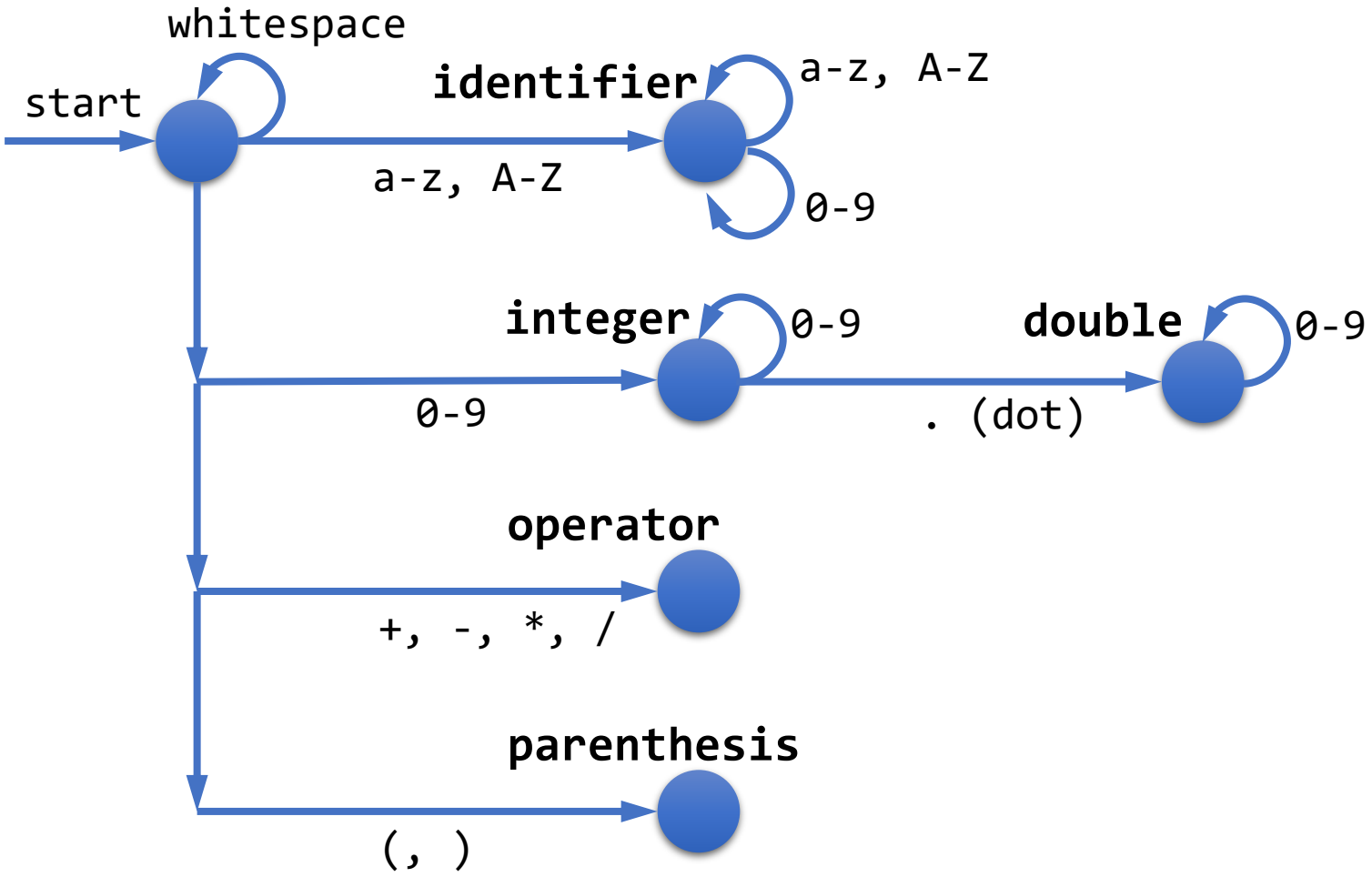
Case Equivalence

- Some programming languages are case-insensitive
  - Pascal, Ada
- Some programming languages are case-sensitive
  - C, Java
- Tokenizer ignores case if configured
  - `This_Routine == THIS_RouTine`
  - Error analysis of tokens may need exact cases

Tokenizer

- Tokenizer carries out pre-processing of the source text
- A finite-state machine (FSM) is used to track the input sequences of characters that can be contained within any recognized tokens
- The first non-whitespace character can be used to deduce the kind of token that follows
- Subsequent input characters are then processed one at a time until reaching a character that is not in the set of characters acceptable for that token

Finite State Machine of Tokenizer



General Strategy for Tokenization

- Tokenization aims to split the words in the source text
- Practical source text contain certain redundant information
- Tokenizer relies on simple strategies:
  - Punctuation and whitespace may or may not be included in the resulting list of tokens
  - All contiguous strings of alphabetic characters are part of one token; likewise with numbers
  - Tokens are separated by whitespace characters, such as a space or line break, or by punctuation characters

General Approach

- Define a set of token types:
  - Enumeration type
    - `tok_int, tok_if, tok_plus, tok_left_paren,` etc
- Tokenizer returns a pair consisting of a token name and an optional token value
  - Some tokens carry associated data
    - e.g. Location in the text
  - Key for identifier table

Abstract Class Tokenizer

```
public abstract class Tokenizer {

        // extract next token from the current text and save it
        public abstract void next();

        // return the current token (without type information)
        public abstract Object current();

        //check whether there is a token remaining in the text
        public abstract boolean hasNext();

}
```


What is a Grammar?

- Grammar is a formal method to describe a (textual) language
- Simple solution: Defining a finite set of all acceptable sentences
  - Problems:
    - Large space/memory complexity
    - What to do with infinite languages?
- Practical solution: a finite recipe to describe all acceptable sentences
  - A grammar is a finite description of a possibly infinite set of acceptable sentences

Grammars

- Grammars formally specify how languages are constructed
  - A grammar specifies the rules of a language
  - Production rule: "*a* → *b*" means that *a* can be rewritten as *b*
- Example, simplified English grammar:

```
<sentence> → <noun_phrase> <predicate>
<noun_phrase> → <article> <noun>
<predicate>  → <verb>
<article> → a
<article> → the
<noun> → cat
<noun> → dog
<verb> → runs
<verb> → sleeps
```


Example

- Derivation of string “the dog sleeps” from the simplified English grammar

```
<sentence> → <noun_phrase> <predicate>
<noun_phrase> → <article> <noun>
<predicate>  → <verb>
<article> → a
<article> → the
<noun> → cat
<noun> → dog
<verb> → runs
<verb> → sleeps
```

Derivation	Grammar Rule
<sentence> ⇒ <noun_phrase> <predicate>	<sentence> → <noun_phrase> <predicate>
⇒ <noun_phrase> <verb>	<predicate> → <verb>
⇒ <article> <noun> <verb>	<noun_phrase> → <article> <noun>
⇒ the <noun> <verb>	<article> → the
⇒ the dog <verb>	<noun> → dog
⇒ the dog sleeps	<verb> → sleeps

Example

- Derivation of string “a cat runs” from the simplified English grammar:

```
<sentence> → <noun_phrase> <predicate>
<noun_phrase> → <article> <noun>
<predicate>  → <verb>
<article> → a
<article> → the
<noun> → cat
<noun> → dog
<verb> → runs
<verb> → sleeps
```

Derivation	Grammar Rule
<sentence> ⇒ <noun_phrase> <predicate>	<sentence> → <noun_phrase> <predicate>
⇒ <noun_phrase> <verb>	<predicate> → <verb>
⇒ <article> <noun> <verb>	<noun_phrase> → <article> <noun>
⇒ a <noun> <verb>	<article> → a
⇒ a cat <verb>	<noun> → cat
⇒ a cat runs	<verb> → runs

Language of Grammar

- Language is all possible derivations from a given grammar
- Example, the language of the simplified English grammar:

L = { “a cat runs”,
“a cat sleeps”,
“the cat runs”,
“the cat sleeps”,
“a dog runs”,
“a dog sleeps”,
“the dog runs”,
“the dog sleeps” }

Chomsky's Grammar Hierarchy

- Type-0: Recursively Enumerable
  - Specified by a Turing machine (any computer)
- Type-1: Context-sensitive
  - Rules: $\alpha A \beta \rightarrow \alpha \gamma \beta$
- Type-2: Context-free
  - Rules: $A \rightarrow \gamma$
- Type-3: Regular
  - Specified by a finite state machine

Context Free Grammars

- Grammars provide a precise way of specifying languages
- A context free grammar is often used to define the syntax
- A context free grammar is specified via a set of production rules
  - Specified by → or ::=
  - Variables (or non-terminals; surrounded with <>)
    - Example: `<noun_phrase>,<verb>`
  - Terminals (symbols)
    - Example: `a, cat, runs`
  - Alternatives (|)
    - Example: `<article> → a | the`

Example

- Grammar for integers
  - {1, 2, 123, 001, 123001, 76860, 00000000, ….}

```
<num> → <digit><num>|<digit>
<digit> → 0|1|2|3|4|5|6|7|8|9
```

  - Exercise: What is the grammar for an unsigned integer number that is not starting with '0' character?

Exercise

- Grammar of matching parentheses:

```
<S> → <S> <S>
<S> → (<S>)
<S> → ()
```

- ()(()()) : Acceptable/Not Acceptable?
- (())()(()())) : Acceptable/Not Acceptable?
- ((())) : Acceptable/Not Acceptable?

```
<S> → <S> <S>
<S> → )<S>(
<S> → ()
```

-))()((: Acceptable/Not Acceptable?
- ())(() : Acceptable/Not Acceptable?
-))()(()(: Acceptable/Not Acceptable?

Online Demo

- Web-based grammar generator
  - https://web.stanford.edu/class/archive/cs/cs103/cs103.1156/tools/cfg/
  - Useful for online learning

Formal Definitions

- Grammar: $G=(V,T,S,P)$
  - V: Set of variables
  - T: Set of terminal symbols
  - S: Start variable
  - P: Set of production rules
- Example
  - V = {<digit>,<num>}
  - T = {0,1,2,3,4,5,6,7,8,9}
  - S = <num>
  - P =

```
<num> → <digit><num>|<digit>
<digit> → 0|1|2|3|4|5|6|7|8|9
```


Grammar for Mathematical Expressions

- Mathematical expressions can be generated by the following grammar:
  - V = {<E>}
  - T = {a, +, *, (,)}
    - Let's assume 'a' can be any number
  - S = <E>
  - P =

<E> → <E> + <E> | <E> * <E> | (<E>) | a

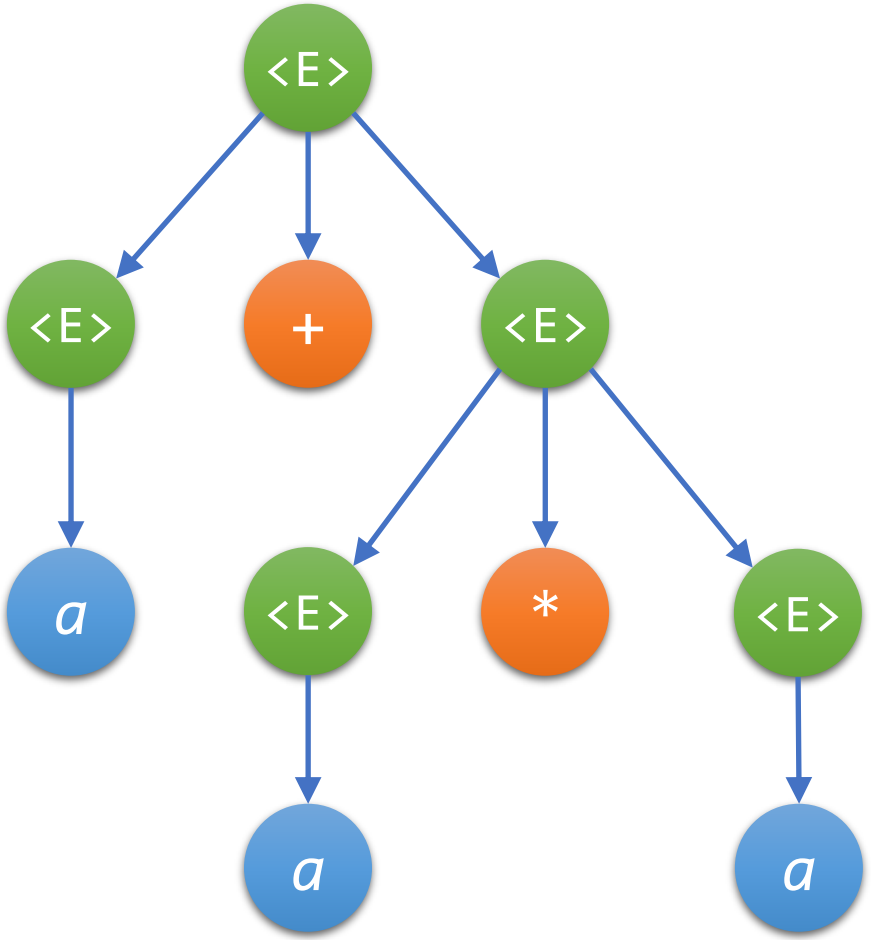
Example

- Derivation of expression "*a + a * a*" from the grammar

<E> ⇒ <E> + <E>
⇒ *a* + <E>
⇒ *a* + <E> * <E>
⇒ *a* + *a* * <E>
⇒ *a* + *a* * *a*

<E> → <E> + <E> | <E> * <E> | (<E>) | *a*

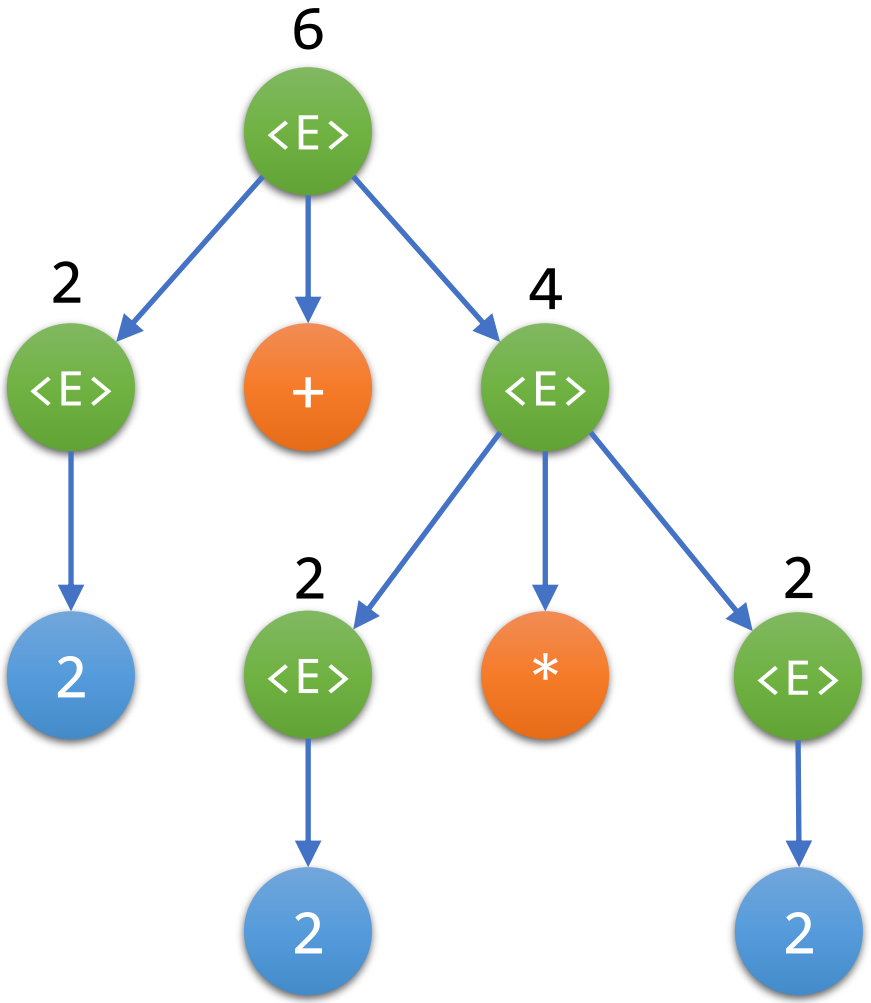
Grammar Production Rule



Parse Tree

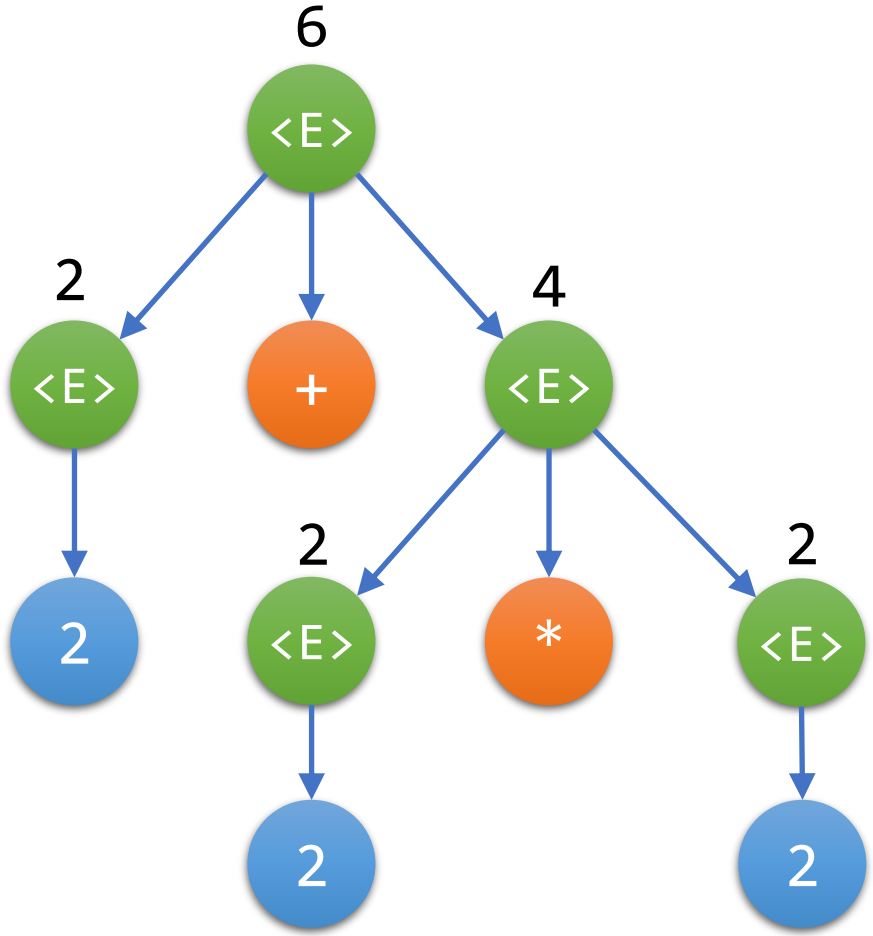
Evaluate Expression via Parse Tree

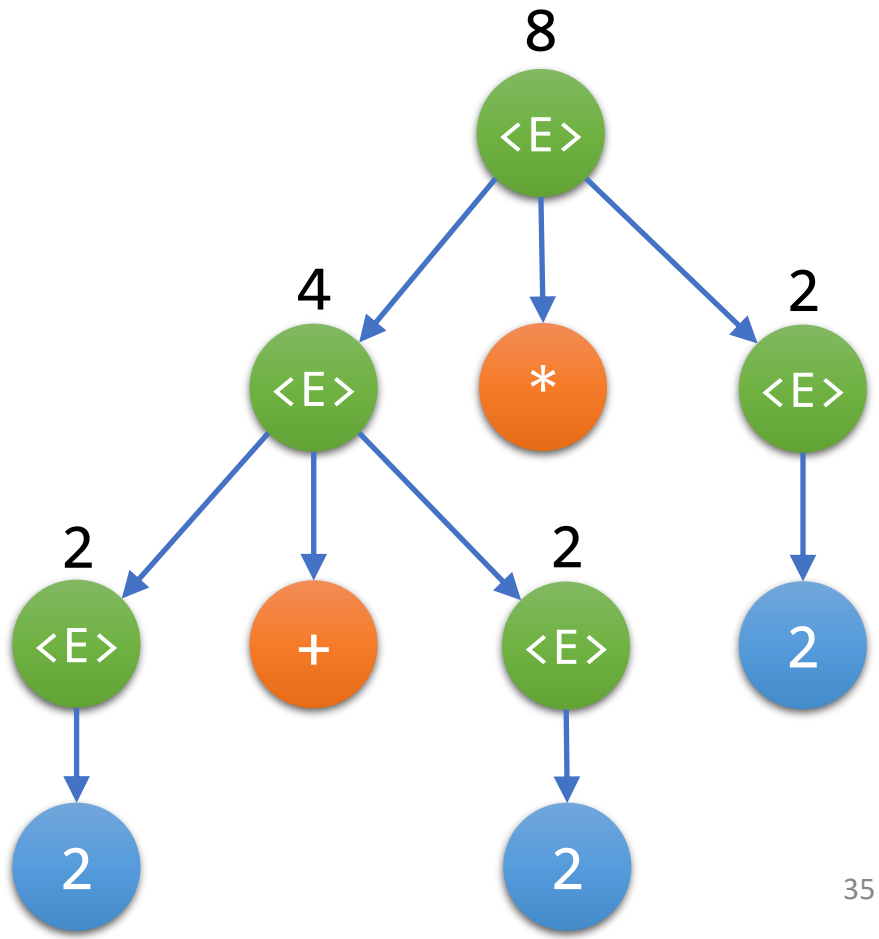
- Parsing tree defines an evaluation order
- Evaluation of expression can be evaluated from leaves to root
- Intermediate variables are replaced by terminal values iteratively



Ambiguity

- It is ambiguous because there are two possible derivations!





Ambiguous Grammar

- A context free grammar *G* is ambiguous
  - If there is a string *w* from language of grammar *G* which has
  - More than one derivation tree
- But it is possible to remove ambiguity by restructuring the grammar

```
<E> → <E> + <E>
<E> → <E> * <E>
<E> → (<E>) | a
```

Ambiguous Grammar

```
<E> → <T> + <E> | <T>
<T> → <F> * <T> | <F>
<F> → (<E>) | a
```

Non-ambiguous Grammar

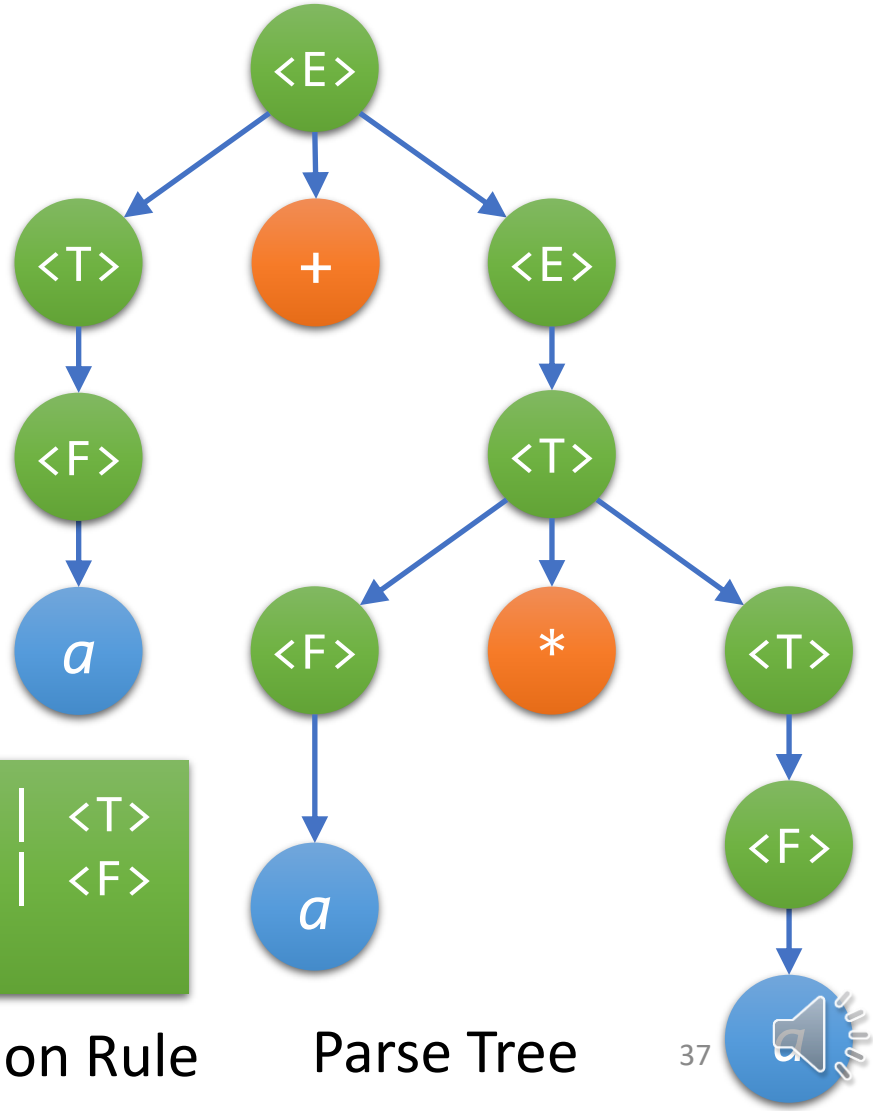
Example

- Derivation of expression "*a + a * a*" from the grammar

<E> ⇒ <T> + <E>
⇒ <F> + <E>
⇒ *a* + <E>
⇒ *a* + <T>
⇒ *a* + <F> * <T>
⇒ *a* + *a* * <T>
⇒ *a* + *a* * <F>
⇒ *a* + *a* * *a*

```
<E> → <T> + <E> | <T>
<T> → <F> * <T> | <F>
<F> → (<E>) | a
```

Grammar Production Rule



Parse Tree

Example

- Check non-ambiguous Grammar
  - https://web.stanford.edu/class/archive/cs/cs103/cs103.1156/tools/cfg/

Test

To test the CFG above, input test strings here, one per line. An empty line corresponds to the empty string. Results will be shown automatically.

2+2*2

Test Results for CFG

#	String	Matches	
1	"2+2*2"	Yes	See Derivation

Rule	Application	Result
Start → S	Start	S
S → T+S	S	T+S
T → F	T+S	F+S
F → a	F+S	a+S
a → 2	a+S	2+S
S → T	2+S	2+T
T → F*T	2+T	2+F*T
F → a	2+F*T	2+a*T
a → 2	2+a*T	2+2*T
T → F	2+2*T	2+2*F
F → a	2+2*F	2+2*a
a → 2	2+2*a	2+2*2

Implementing Parser

- Recursive descent parser
  - Top-down parser
  - Parse from start variable, recursively parse input tokens
  - Create a method for each left-hand side variable in the grammar production rules
  - These methods are responsible for generating parsed nodes

Variable (or Symbol) as a node

- To construct a parse tree,
  - Can adopt ideas from a tree data structure
  - Each variable (or symbol) can be represented as a node in a tree
  - Define a node class for each variable

Implement a Parser

- Given grammar start with Exp

```
<Exp> → <Term> + <Exp> | <Term>
<Term> → <Factor> * <Term> | <Factor>
<Factor> → (<Exp>) | a
```

- We implement based on Recursive Descent Parsing
- Node classes
  - `abstract class Exp`
  - `class Term extends Exp`
  - `class Factor extends Exp`
  - `class Int extends Exp`
  - `class AddExp extends Exp`
  - `class MulExp extends Exp`
- Parse method for each rule in Parse class
  - `Exp parseExp(Tokenizer)`
  - `Exp parseTerm(Tokenizer)`
  - `Exp parseFactor(Tokenizer)`

Implement a Parser

```
public class Parser {

        // parse <Exp> -> <Term> + <Exp> | <Term>
        public static Exp parseExp(Tokenizer tok){ . . . }

        // parse <Term> -> <Factor> * <Term> | <Factor>
        public static Exp parseTerm(Tokenizer tok){ . . . }

        // parse <Factor> -> (<Exp>) | a
        public static Exp parseFactor(Tokenizer tok){ . . . }

}
```


Implement a Parser

- To implement rule "<Exp> → <Term> + <Exp> | <Term>"

```
public static Exp parseExp(Tokenizer tok){
        Term term = parseTerm(tok);
        if (tok.current()=='+'){
                tok.next();
                Exp exp = parseExp(tok);
                return new AddExp(term, exp);
        } else {
                return term;
        }
}
```

This production rule starts with Term

If the next token is +, apply first production rule

Addition between Term and Exp

Implement a Parser

- To implement rule "<Term> → <Factor> * <Term> | <Factor>"

```
public static Exp parseTerm(Tokenizer tok){
        Factor factor = parseFactor(tok);
        if (tok.current()=='*'){
                tok.next();
                Term term = parseTerm(tok);
                return MulExp(factor, term);
        } else {
                return factor;
        }
}
```

This production rule starts with Factor

If the next token is *, apply first production rule

Multiplication between Factor and Term

Implement a Parser

- To implement rule "<Factor> → (<Exp>) | a"

```
public static Exp parseFactor(Tokenizer tok){
        if (tok.current()=='('){
                tok.next();
                Exp exp = parseExp(tok);
                tok.next();
                return exp;
        } else {
                Int i = new Int(tok.current());
                return i;
        }
}
```

If the next token is '(', apply the first production rule

Remove ')'

Create an integer

Limitations

- Recursive Descent Parsing: Top-down parser from recursive procedures
  - The Recursive Descent Parsing approach will not work with left recursive grammars. For example,

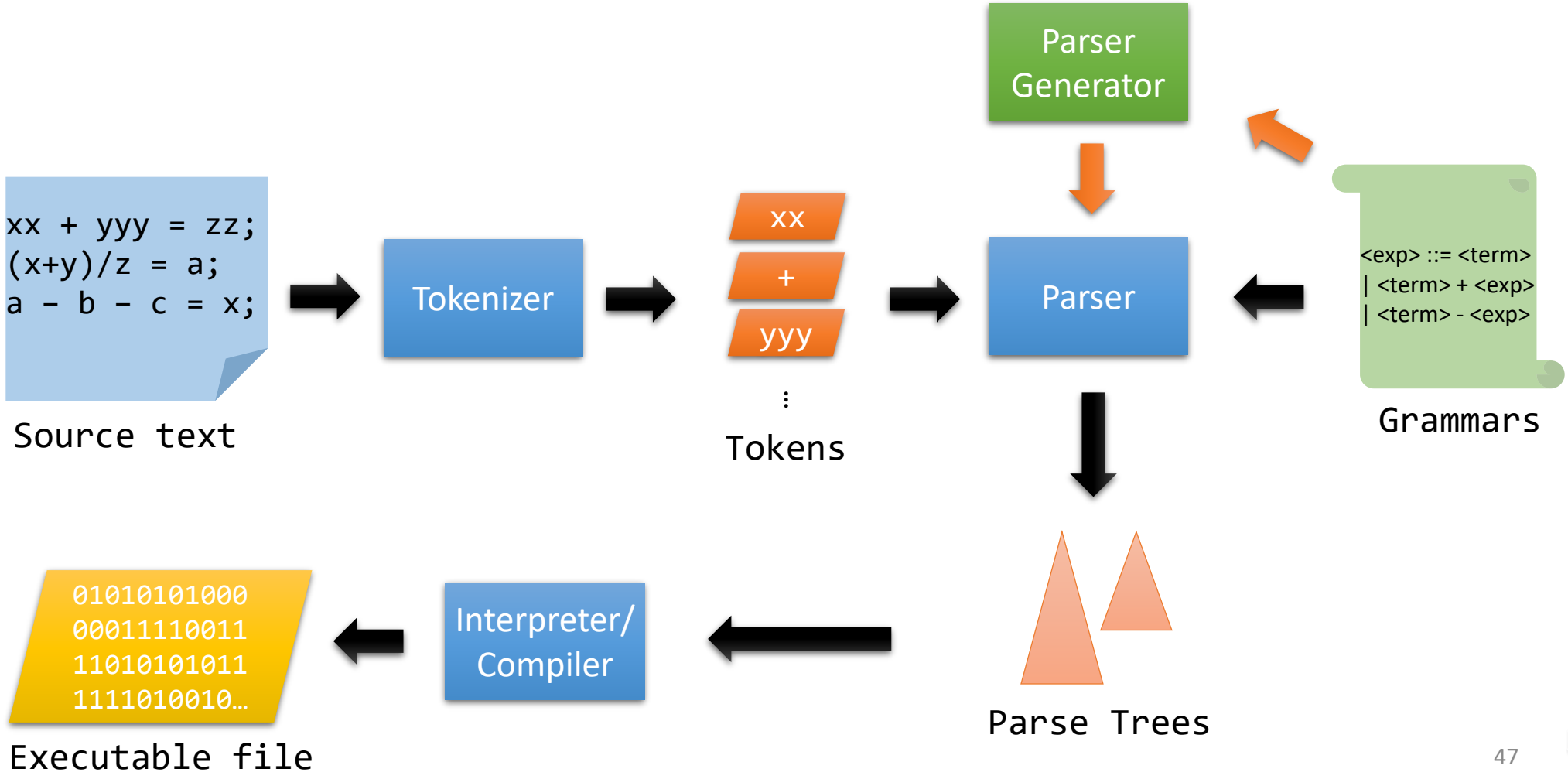
```
<binary> → <binary><digit>|<digit>
<digit> → 0|1
```

  - which cannot be parsed using the recursive descent parser
  - However we could transform the grammar into:

```
<binary> → <digit><binary>|<digit>
<digit> → 0|1
```

  - which represents the same language, but can be parsed by recursive descent parser

Automatic Parser Generation



Automatic Parser Generation

- Parser Generators
  - JavaCC, ANTLR, Yacc/Bison
- Manual Parser Implementation
  - Good error recovery and reporting
  - Flexible combination of parsing and actions
- Automatic Parser Generation
  - Save manual work
  - But more complex and rigid frameworks
  - Error recovery and reporting more difficult

Summary

- Structured data
  - Markup languages: HTML, JSON, XML, Markdown…
  - Programming languages: Java, C, C++, Haskell, Perl, Python, PHP, …
  - Mathematical expressions, e.g., {(2+3)*4}/2
- Tokenization
- Parsing
  - Context-free Grammars
  - Recursive Descent Parsing


DEAR FUTURE SELF,
#
YOU'RE LOOKING AT THIS FILE BECAUSE
THE PARSE FUNCTION FINALLY BROKE.
#
IT'S NOT FIXABLE. YOU HAVE TO REWRITE IT.
SINCERELY, PAST SELF
DEAR PAST SELF, IT'S KINDA CREEPY HOW YOU DO THAT.
#ALSO, IT'S PROBABLY AT LEAST
2013. DID YOU EVER TAKE
#THAT TRIP TO ICELAND?
STOP JUDGING ME!